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ABBREVIATIONS

AI	Artificial Intelligence
CSO	Case-Specific Ontology
DPs	Design Parameters
EAM	Engineering-Asset Management
FAST	Functional-Analysis Systems Technique
FMECA	Failure-Modes, Effects and Criticality Analysis
FMEA	Failure Mode and Effect Analysis
FRs	Functional Requirements
HLO	High-Level Ontology
HOT	Hierarchy of Objectives Technique
JTBD	Jobs to be done
KDA	Knowledge Domain Attribute
KR	Knowledge Retrieval
LLFR	Lower-Level Functional Requirement
MUF	Main Useful Function
PVs	Process Variables
RCA	Root-Cause Analysis
TLO	Top-Level Ontology
TO	Technical Ontology
ULO	Upper-Level Ontology

ULFR	Upper-Level Functional Requirement
TOC	Theory of Constraints
TRIZ	Theory of Inventive Problem Solving.

GLOSSARY OF TERMS

The following terms are used in this study and are applicable to this study and not necessarily to other applications.

Case-specific ontology: This is a concept map structured to be specific to the case under consideration.

Concept map: A graphical representation of knowledge.

Explicit knowledge: Knowledge that is communicated (or coded) for purposes of sharing the knowledge.

Functional analysis: A structured matrix containing functional requirements for analysis purposes.

High-level ontology: A second-tier of ontologies and follows at the next hierarchical level after the Top-Level ontology.

Knowledge acquisition: A process of critically reflecting in experiences and prior knowledge.

Knowledge management: The processes whereby knowledge is identified, classified, analysed and restructured for reuse and for storage and retrieval purposes.

Knowledge unit: A knowledge unit is the smallest piece of knowledge which can be used to make decision or to take action.

Logic base: A single platform used to guide a user in the compilation of concept maps, analysing the relationships among concepts and reporting on engineering matters.

Main useful function: The ultimate functional purpose of an entity.

Ontology: A structured, hierarchical classification and organisation of concepts.

Systems engineering: The consideration of all the components and their contributions made towards their combined functioning to achieve a specific purpose or outcome.

Tacit knowledge: Knowledge that resides in an individual and is in the unconscious domain.

Technical ontology: An ontology designed to accommodate technical parameters and is often quantitative in nature.

Taxonomy: A strict hierarchical classification of objects or entities.

Top-level ontology: The highest level of organised concepts.

TRIZ: A Russian acronym for “The theory of inventive problem solving”.

CHAPTER 1: INTRODUCTION

1.1 GENERAL BACKGROUND

Individuals, each with their own personalities and skills, come together in organisations and function as individuals and groups for the benefit of the organisations. Together, individuals and groups bring about an organisational system with distinct dynamics. These dynamics are aimed at doing business, i.e., achieving a common goal or sets of goals, in response to internal and external influences. The development of the necessary skills and the deployment of human resources effectively are important success factors in business. It is also necessary to devise and implement effective strategies for doing business in a changing environment and to respond to changes in an effective way. When considering the development of infrastructure and the status of municipal service delivery in South Africa, Turton (2007, p.1) stated that “Development, like life, is a journey and not a destination! We have not yet arrived and indeed never will. What we have learned in the past is not necessarily relevant to the future, because of the propensity to greater complexity over time. We cannot base tomorrow’s solutions on yesterday’s experiences and today’s science.” However, when a better understanding is obtained about the past, the challenges within the context of the environment of today can be met with today’s science. When knowledge of the past is appropriately selected and analysed, a better understanding is obtained of the context and thought processes that were used in solving the problems of the past. This will give new depths to past knowledge that can only benefit today’s engineers and enable them to meet the challenges. In understanding the problems and solutions of the past, gaps in today’s knowledge and science can be identified and addressed for solving today’s challenges. More knowledge is required to achieve this. With more knowledge, individuals and companies would be in a far better position to respond to challenges in an ever-changing and competitive environment. Experience and learning modify thinking processes. Accumulation and creation of knowledge are enhanced and in this way, competency and value are built. Having regard to the foregoing, this study is focused on designing a model for the acquisition, reuse and the creation of knowledge.

The accumulation of knowledge implies increasing the value of intangible assets. This accumulation is often undermined by a company and people dynamics, because people often change their workplaces or leave a particular industry. Lawless (2005, p.227) attributes the “emptying of the bucket” (pool of engineering staff) to emigration, retirement and people leaving the industry. According to Grundstein (2000, pp.261-262), greater competitiveness often requires cost reduction, and leads to structural changes and personnel cutbacks that result in early retirement, transfer of employees and outright layoffs. Such measures pose risks of dispersion and loss of the knowledge (in both the collective and individual sense) that is the lifeblood of a company. The civil engineering industry in South Africa also suffers from these tendencies, especially due to adverse economic circumstances and the lack in spending on civil infrastructure. In the civil engineering industry, knowledge is mostly kept by individuals. Knowledge is stored in the form of reports and drawings in the archives of organisations, but the underlying knowledge is kept by individuals and not readily shared for reuse. When changes take place, the risk is very high that valuable knowledge would get lost.

1.2 PERSPECTIVES IN ENGINEERING

The business world and South African engineering companies in particular, experience a critical shortage of qualified and experienced engineers. In 2014, the South African minister of higher education and training, Dr Blade Nzimande, MP, gazetted the “National Scarce Skills List: Top 100 Occupations in Demand”, calling for comments from interested parties. Electrical engineers were listed first as a critical skill, followed by civil engineers and then by mechanical engineers (South Africa, 2014).

This deficiency was reported by Lawless in 2005, nine years before the gazette notice in May 2014, implying that the shortage of engineers persisted (Lawless, 2005). Stimie (2008, p.30) reported a slow decline in the number of civil engineering professionals since the infrastructure development heydays of the sixties. Reduced industry demand, reduced number of graduates, emigration, early retirement, low rewards and engineering graduates highly sought after by other economic sectors, have meant that personnel have left the market at a higher rate than those entering through tertiary institutions and immigration (Lawless, 2005, p.3). Benchmarking the tempo of training professionals through tertiary institutions, South Africa graduates 45 engineers for every one million people in the country, lagging far behind China and the USA, graduating 225 to 290 engineers for every one million inhabitants respectively (Stimie, 2008, p.300).

This shortage of suitably qualified and experienced engineers directly affects economic growth and the sustainability of the economic infrastructure. Lawless (2005, p.3) stated that the nation's economy and the quality of life of all its citizens are heavily dependent on the supply and efficient operation of infrastructure.

In an article in the weekly South African publication, "Engineering News", Bonnett, D was reported to have said that "Better infrastructure creates opportunities for the development of businesses and trade within countries in the region, and creates the demand for goods and services that were not previously available at a reasonable price. Better infrastructure can improve trade regarding creating markets and wealth in previously untapped areas" (Cloete, R. 2008, p.1). Building and maintaining infrastructure demand skilled and experienced people as stated below.

Allyson Lawless, the past president of the South African Institution of Civil Engineering in the year 2000, concluded that:

a) Engineering services cannot be effectively conceived, designed or delivered without experienced engineers.
b) Practical engineering decisions cannot be made without experienced engineers – this negatively impacts on spending operations and maintenance.
c) Engineering processes and systems cannot be developed or managed effectively without experienced engineers.
d) Young engineering personnel cannot be trained effectively without experienced engineers.

(Lawless, SAICE, 2008, pp.1-2.)

The effects of the shortage of engineers was stated by the minister of science and technology, Naledi Pandor as follows:

"The shortage of engineering professionals meant there were not enough engineers available for ongoing work, she said. Also, work that required engineering decisions was being done without competent engineering input" (Fin24, 2014).

1.2.1 Closing the gap in knowledge and experience

From the preceding, it can be deduced that the current demand and associated shortage of skills and experience reflect a large knowledge gap. This gap is brought about by the general shortage of qualified and experienced people. The knowledge gap will continue to increase with devastating results unless steps are taken to address the problem from a knowledge management perspective and to design methods of equipping individuals.

1.3 OBJECTIVES OF THIS STUDY

Having regard to the preceding and the strategic role of knowledge, the motivation for this study is to address the needs for the acquisition, reuse and the creation of knowledge in a civil engineering environment. This study therefore focuses on the design of a model to facilitate the acquisition and reuse of knowledge and to stimulate and facilitate knowledge creation. This model is referred to as a “logic base” in this study. The proposed logic base contains particular architecture and ontologies in which logic elements reside, forming an autonomous entity which is sufficiently generic in nature to enhance replication of knowledge. The purpose of the logic base is to lead practitioners into processes of knowledge discovery that could uncover or infer the thought processes behind the engineering solutions, often reported in case studies or lessons learned from previous endeavours. The study is aimed at designing a functional and practical system to lead practitioners in science-based logical processes and to put a logic base in place for practical application in a civil engineering knowledge environment.

The logic of underlying engineering science and thought processes are captured and transformed into a model to enable replication. This study focuses on the background and the analysis of actions or events as reported in case studies. Processes and solutions from case studies are evaluated. An important element of this is to research methods to enhance replication.

1.4 RESEARCH QUESTIONS

1.4.1 The main research question in this study is:

What are the key characteristics of a model (termed a “logic base” in this study) for the acquisition, reuse and the creation of knowledge in a civil engineering environment?

This main research question is answered by answering a series of sub-research and sub-sub-research questions. These are as follows:

a) What are the most appropriate knowledge elements to be considered for inclusion in the proposed logic base?

To answer this sub-research question, the following aspects need to be addressed:

i) What are the most applicable definitions of knowledge for this model?
ii) In what way is knowledge represented in the human mind and how does this relate to the logic base?
iii) What types of knowledge can be identified in the civil engineering environment?
iv) What methods are there for transferring knowledge to individuals, and how would these methods apply to civil engineering?

These questions are answered in Chapter 2 that mainly covers a literature review.

b) **What sources of existing knowledge are available and how does this knowledge relate to the proposed logic base?**

The following sub-sub-research questions pertain:

i) In what form or structure is existing knowledge available?
ii) How usable is existing knowledge to the practicing engineer?

These questions are answered in Chapter 2 as part of the discussions on taxonomies and ontologies.

c) How can existing engineering knowledge be reused?

In answer to this sub-research question, the following questions need to be answered:

i) What methods and processes are there for transferring knowledge to individuals for reuse?
ii) How would one understand or assimilate the context of existing knowledge?

This research sub-question and sub-sub-research questions are answered in Chapter 2.

d) How can knowledge be created?

This sub-research question can be answered by considering the following two questions:

- *i) What stimulates thought processes to create engineering knowledge?*
- *ii) What processes would enhance knowledge acquisition and knowledge creation?*

This research sub-question and sub-sub-questions are answered in Chapter 2.

e) What research methodologies are most applicable for the discovery and application of engineering knowledge?

This sub-research question is answered in Chapter 3.

f) What components are required for the logic base?

- *i) How can knowledge acquisition, reuse and knowledge creation be translated into components of a logic base?*
- *ii) What are the relationships among the various components and how would the components contribute to the functioning of the logic base?*
- *iii) What criteria are required to provide the functionality of knowledge acquisition, reuse and knowledge creation and how can the criteria be satisfied?*

This sub-research and sub-sub-research questions are answered in Chapter 4.

g) What is an appropriate architecture of a logic base to fulfil the Functional Requirements (FRs) for the acquisition, reuse and the creation of knowledge?

- *i) What ontology and taxonomy can form the basis of the design of a logic base?*
- *ii) How sensitive are the ontologies for different applications?*

This sub-research and sub-sub-research questions are answered in Chapter 4.

h) How can one formulate an integrated model, i.e., the logic base, to function as a suitable tool for practical application, incorporating elements of knowledge acquisition, reuse and the creation of knowledge?

i) *How would all the components comprising the logic base interact to provide the required functionality regarding knowledge acquisition, reuse and creation of knowledge?*
ii) *What would be the inputs and outputs of the logic base?*
iii) *What knowledge is required to interact with the logic base?*
iv) *Who would be the target users of the logic base?*

This sub-research and sub-sub-research questions are answered in Chapter 5.

When considering the above research questions, it is essential to put these into the context of knowledge management. A high-level perspective of knowledge management is given in the following section.

(All the research questions, sub-research and sub-sub-research questions are summarised in **Appendix I**. References to the relevant sections where these questions are discussed are also shown.)

1.5 RELEVANCE TO KNOWLEDGE MANAGEMENT

1.5.1 Basic concepts related to knowledge management

At the root of this study lies the knowledge of individuals, groups and organisations. The challenge in this study is to unlock the knowledge and to research the logic of how this knowledge was created and to consider the context and the circumstances in which the knowledge came into being. The field of knowledge management encapsulates and addresses these aspects, as put by Liebowitz (2000, p.1): "The thrust of knowledge management is to create a process of valuing the organisation's intangible assets to best leverage knowledge internally and externally. Knowledge management, therefore, deals with creating, securing, capturing, coordinating, combining, retrieving, and distributing knowledge."

1.5.2 Aspects of gaining knowledge

The distinction between tacit and explicit knowledge is a fundamental aspect of knowledge. Tacit knowledge is knowledge that an individual possesses without knowing it. This type of knowledge is acquired naturally by actions (Polanyi, 1958, p.49; Zack, 1999, p.2). On the other hand, explicit knowledge is knowledge that can be articulated (Sveiby, 1998, p.20).

Nonaka (1994) states that knowledge is initially created by individuals and the knowledge so created becomes organisational knowledge through a process of knowledge conversion as described by the theory. The theory describes four modes in the knowledge conversion as follows:

- tacit to explicit;
- explicit to tacit;
- tacit to tacit;
- explicit to explicit.

Knowledge conversion naturally takes place through a basic human ability to blend the old and well-known with the new, unforeseen or unknown. We would otherwise not be able to live in the world (especially if one considers the current volatile world with almost constant change). “New experiences are always assimilated through the concepts of which the individual disposes and that the individual inherited from other users” (Sveiby, 1998, p.19). It is considered that all our knowledge resides in a tacit dimension.

Individuals make sense of reality by categorising it. “The patterns of categories contain theories, methods, feelings, values and skills that can be used in a fashion that the tradition judges as valid. Switching between tacit and explicit knowledge takes place every second of our lives” (Sveiby, 1998, p.20). Tradition is one way of describing how knowledge is transferred in a social context. As in the master-apprentice relationship, knowledge is transferred to the apprentice when the apprentice does the same things under the guidance, instruction and supervision of the master. To learn by example means that the learner must be willing to follow the example of the master and essentially submit to his authority (Sveiby, 1998, pp.12-25).

There are several mechanisms for transfer of knowledge, described as follows:

- **Mechanism 1:** Imitation, identification and learning by doing. Facts, rules and exemplars are transferred without intermediate storage in a medium. Knowledge does not represent goods that can be moved or transferred. The “receiver” reconstructs his own version of the supplier’s knowledge.

- **Mechanism 2:** Tradition transfers its patterns of action, rules, values and norms. They create a social order because people can foresee both the actions of others and the implied expectations of themselves.

- **Mechanism 3:** The formation of knowledge within a tradition is done both locally (master-apprentice relationship) and in a larger context through professional bodies. A tradition exists outside organisational boundaries. Within organisations, one would find examples of indirect knowledge transfer, such as articulated rule for guiding behaviour, such as texts in manuals or accounting procedures, checklists, handbooks, guidelines for sales people, etc. A successful organisation makes room for the management of both tacit and explicit knowledge (Sveiby, 1998, pp.25-27).

The language of knowledge management is littered with this "thing thinking". "We want to 'capture' knowledge, inventory it, to push it into and pull it out of people" (Wheatley, 2000, p.4). Clear insight is necessary into the processes and attitudes that make knowledge management work. Knowledge is an individual thing – something that is created through engagement with the world. It is important to note that it is not the technology that connects people, but relationships. Relationships are considered to be the key ingredient to knowledge sharing.

The focus in this study will be on experience that was gained by individuals and organisations, in particular, how this came about and how it was structured and what mechanisms existed in practice for the transfer of the knowledge. The study focuses on the underlying logic that supports or drives the creation of such knowledge.

1.5.3 A systems approach

A systems approach integrates the functions and contributions of all the parts comprising a system. This integration enables the understanding of the performance of the whole system. The interactions among the parts of the system are studied so that the performance of the system as a whole can be evaluated and predicted from knowledge of the behaviour of its interacting parts.

The "major premise of a systems approach is that natural laws, once known, could serve as a conceptual framework for understanding relationships within any system and for handling problems or changes encompassed by that system. Consequently, the theory emphasises the values of viewing a system as a whole, of gaining a perspective on the entire 'entity' before examining its parts" (Haines, 1998, p.2).

The logic base is designed within the context of a systems approach. Knowledge elements or concepts are put together in a particular way to contribute and build a complete case or a story.

1.5.4 Applicability of a systems approach to knowledge management

Experience is gained, through application and implementation of processes and monitoring the outcomes thereof. Depending on the outcomes of processes, changes are made to input and process parameters to effect changes in outcomes. (This constitutes a systems approach.) According to Liebowitz (2000, p.19), negative and positive experiences must be considered. This is in fact how learning takes place and how experience is gained. A person or groups of practitioners initiate a process. The process design and outcomes of the processes are done within a set of parameters best known or anticipated by the practitioners. The knowledge of the process and process parameters are derived from the application of appropriate scientific principles and from particular logic processes. These processes have prior knowledge as a basis and may contain new ideas. Both prior knowledge and new ideas have particular risks attached to it, as they may not cause the desired outcomes in a particular process. This is illustrated, for example, when a vehicle approaches an intersection controlled by traffic lights; the scientific principle is that the traffic lights are controlled by computers and the logic is such that conflicts between the various vehicular movements in the intersection are eliminated. This represents prior knowledge with the particular expectation of passing effortlessly and safely through the intersection. However, when a power failure occurs, none of the traffic lights work and a complete new process of crossing the intersection has to be followed, with more effort and risk of collision because drivers assume a continuation of prior knowledge (expectations) rather that expecting new circumstances. The amount of risk depends on the match between the definition of the input and process parameters and the actual outcome of the process. In many instances the progression of the processes can be controlled; however, there are also instances where the controllability is low or even impossible. In such instances, the outcomes of the processes may not meet the requirements.

In this study, various means of discovering and sourcing of knowledge and experience are investigated. The recorded experience is dissected to discover the underlying logic that is used to populate the logic base.

The outcome of the study is a logic base that enables practitioners to interact with it for the discovery of knowledge and to find solutions to problems. This stimulates innovative thinking and solutions to problems. It also assists the prevention of re-inventing the wheel. The logic base acts as an invaluable training tool for enabling the development of skills and to help bridging the gap in the availability of experienced practitioners. When new projects are designed, the logic base will be of particular assistance in avoiding mistakes that were made in the past.

Suggestions are made for the introduction of knowledge management and the integration thereof into the business systems and processes. The introduction of an organisational culture of knowledge management is imperative to ensure the perpetuation of learning and continuously improving the organisation. The example set by Chaparra Steel Mill is observed whereby a learning organisation was established where every day, in every project, additions are made to the knowledge resources (Cross and Israelit, 2000, p.101).

1.6 RESEARCH METHODOLOGY

First of all, various research methodologies are assessed and appropriate methods evaluated to suit this study (Cooper and Schindler, 1998, pp.5-157).

As a next step, a comprehensive literature study is conducted to form a basis for further research. Theories and practice in knowledge management are researched to gain a firm understanding of the available best practices relating to taxonomies and ontologies of knowledge bases. This research is focused on designing the most suitable ontology for the proposed logic base.

The research covers qualitative research methodologies. The focus is on determining the research methodology that will add the most value to the development of the logic base. Of particular interest are action research and case study research.

Knowledge with a sufficient span is considered to ensure a representative sample of the particular portion of the industry being studied. The analysis leads to the basis of the design of the architecture for the logic base. Time and scope limitations does not permit field research and testing of the logic base. This will have to be done in further research.

1.7 IMPORTANCE TO ENGINEERING

Knowledge in the form of lessons learned, processes, checklists, specifications and procedures serve the purpose of alerting the user of such knowledge to experiences or to the identification of risks that may underlie an engineering object or event. However, far more important is the science and logic processes that give rise to such experiences or risks. The logic base facilitates the replication of logic and extends applications into the unknown (which typifies the world of engineering). It can greatly contribute to the reduction of risks. “Lessons learned from old projects could be integrated to improve new projects, thereby reducing risks of unwanted events in new projects. It is also important to preserve and to protect knowledge for future usages. Once knowledge is lost, it could be impossible or very costly or to regain it again” (Grillitsch, Müller-Stingl and Neumann, 2006, p.19). The importance and needs in the civil engineering industry are addressed in this study and are aimed at contributing to the enhancement of skills, thereby contributing to the reduction of the shortage of skills and experience currently experienced in South Africa. When engineers are equipped in the use of the logic base, problems can be addressed in a holistic way and the underlying thought processes can be documented. This may be of great value to inexperienced engineers and for the preservation of valuable knowledge.

1.8 ADVANTAGE TOWARDS THE ENHANCEMENT OF KNOWLEDGE

The logic base facilitates a process to guide users to solutions of particular problems. This is especially important since, although no two situations are the same, the logic that is used for arriving at engineering solutions should be discoverable and should be used as the seed to generate appropriate solutions in other conditions or environments. This study is seen to add an important aspect towards the enhancement of knowledge management in general. The logic base provides an ontology for linking knowledge to a high-level engineering taxonomy that will facilitate discovery of knowledge for reuse. The logic base also integrates ontologies with problem-solving techniques so that knowledge can be discovered and new knowledge created.

1.9 SCOPE AND LIMITATIONS OF THE STUDY

1.9.1 General scope

Knowledge is located at an individual and at an organisational level. There are several disciplines and fields involved in civil engineering. When engineers do analytical work, the focus is more on individual knowledge. When construction, for example, takes place, engineers focus more on group functions and on technical management at an organisational level.

Although the design of the logic base is broad-based, it is confined to civil engineering. It covers both individual and organisational levels.

1.9.2 Theoretical scope

The theoretical study comprises research and identification of individual and organisational knowledge in the field of study. The study involves the processes that are normally followed in conceptualisation, design and implementation of projects and in the operation and maintenance thereof. The knowledge contained in case studies is emphasised. The fundamentals of knowledge acquisition and transfer are researched. The applicability of these fundamentals to applied sciences, and in particular to civil engineering, is researched. Thought processes are considered and how these relate to civil engineering. A model (logic base) is designed.

1.9.3 Empirical scope

The logic base is based on the knowledge derived from case studies, representing real life situations and incidents. Many case studies report on successes and failures, thereby providing valuable lessons.

As a follow-up and in support of this study, computer software may need to be developed (or existing software be customised) to enable the effective operation of the logic base. The development of software is not within the scope of this study.

1.9.4 Overview of chapters

The following summary is given of the chapters in the study:

Chapter 1: Introduction and study objectives
Chapter 2: Literature review
Chapter 3: Research methodology
Chapter 4: The design of a logic base
Chapter 5: Application of the logic base
Chapter 6: Summary and conclusions

A more detailed description of the proposed objectives of each chapter is as follows:

Chapter 1:

In this chapter, an introduction and orientation is given of the study. The need for the study is discussed, and the significance of the research is explained. Consideration is given to knowledge management and its role in an organisational context. The scope and limitations of the research are outlined. The methodology followed in the study is discussed. Most importantly, the various research questions are structured to form the basis of this study.

(A complete summary of all the research questions is given in **Appendix I**.)

Chapter 2:

In this chapter, a literature review is conducted. The chapter starts with the theory of knowledge, including consideration of tacit and explicit knowledge. Knowledge conversion is studied, as well as the theories regarding knowledge acquisition and reuse. Problem-solving as part of knowledge creation and knowledge acquit ion and reuse is covered. A selection of problem-solving techniques is discussed as well as its relevance to the application in the logic base. Taxonomies and ontologies are reviewed and how these relate to the proposed logic base. Consideration is also given to systems engineering.

A diagrammatic layout is given in **Appendix H,** which summarises the literature review in Chapter 2. **Figure H1** shows how the various parts of the literature study contribute to the design on the logic base.

Chapter 3:

In this chapter, various research methodologies are researched. Appropriate research methods are evaluated and chosen to suit various aspects of this study. The results of the preceding research and analysis in Chapter 2, lays the foundation for further development work.

Chapter 4:

In this chapter, the logic base is designed. Knowledge processes in case studies are analysed and an ontology is designed using the typical topics of case studies as a basis. Concept maps are used, the interrelationships among concepts are investigated and the relevance thereof are discussed.

Chapter 5:

In this chapter, concept maps are expanded and further design is done on the logic base. Concept maps are discussed in greater detail, relationships among concepts are elaborated on and further attention is given to problem-solving techniques. The way relationships are treated in the logic base are discussed. The operation of the logic base is discussed and a framework is given of a model, illustrating the functioning of the logic base. Some practical examples are given of the functioning of the logic base.

Chapter 6:

This chapter is a summary of the study and addresses the research questions as stated in Chapter 1. Suggestions are made for further research, including the refinement of the logic base and the applications thereof.

1.10 REFERENCES:

A reference list pertaining to this study is provided, covering all the chapters.

1.11 APPENDICES:

Specific supporting documentation in support to the text is attached in the appendices.

In particular, a summary of the layout of this study is given in **Appendix H** (**Figure H1**) and a summary of the research questions and sub-questions is provided in **Appendix I**, Table I1.

CHAPTER 2 : LITERATURE ANALYSIS

2.1 INTRODUCTION

In this chapter the emphasis is on gaining the required background knowledge for the design of the proposed logic base. The relevant research questions are contextualised within the research literature. The research literature was chosen accordingly. This chapter deals with the theory of knowledge and the creation of knowledge. Knowledge acquisition and problem-solving techniques are covered. Taxonomies and ontologies are reviewed and their relevance to the logic base are discussed. Consideration is also given to systems engineering.

2.2 RESEARCH QUESTIONS APPLICABLE THIS CHAPTER

From Chapter 1 the main research question is:

What are the key characteristics of a model (termed a "logic base" in this study) for the acquisition, reuse and the creation of knowledge in a civil engineering environment?

To answer this research question, sub-research questions numbers (a) to (h) need to be answered. In this chapter only sub-research questions (a) to (d) will be addressed and the remainder will follow in subsequent chapters of this study.

a) What are the most appropriate knowledge elements to be considered for inclusion in the proposed logic base?

To answer this sub-research question, the following aspects need to be addressed:

- *i) What are the most applicable definitions of knowledge for this model?*
- *ii) In what way is knowledge represented in the human mind and how does this relate to the logic base?*
- *iii) What types of knowledge can be identified in the civil engineering environment?*

iv) What methods are there for transferring knowledge to individuals and how would these methods apply to civil engineering?

These questions are answered in Chapter 2 that mainly covers a review of the literature.

b) What sources of existing knowledge are available and how does this knowledge relate to the proposed logic base?

The following sub-sub-research questions pertain:

i) In what form or structure is existing knowledge available?
ii) How useful is existing knowledge to the practising engineer?

These questions are answered in Chapter 2 as part of the discussions on taxonomies and ontologies.

c) How can existing engineering knowledge be reused?

In answer to this sub-research question, the following questions need to be answered:

i) What methods and processes are there for transferring knowledge to individuals for reuse?
ii) How would one understand or assimilate the context of existing knowledge?

d) How can knowledge be created?

This sub-research question can be answered by considering the following two questions:

i) What stimulates thought processes to create engineering knowledge?
ii) What processes would enhance knowledge acquisition and knowledge creation?

(A complete summary is given in **Appendix I** of all the research questions. It also shows in which sections these questions are discussed. **Appendix H** shows a diagrammatic layout of the literature study in Chapter 2. It also shows how the various parts of this chapter contribute to the design on the logic base.)

2.3 OVERVIEW OF KNOWLEDGE AND KNOWLEDGE MANAGEMENT

2.3.1 Definitions of knowledge

First, some of the more commonly known dictionary definitions are given below, and after that comments are made about definitions from other literature sources.

Knowledge as a noun:

a) Oxford English Dictionary (OED, 2010) online:

“1 Facts, information and skills acquired through experience or education; the theoretical of practical understanding of a subject.

1.1 The sum of what is known.

1.2 Information held in a computer system.

1.3 Philosophy True, justified belief; certain understanding, as opposed to opinion.”

There are numerous other definitions of knowledge as mentioned by Tobin (2006, p.2). After Tobin considered all the definitions in his study, he quoted a statement made by the British Standards Institute that says “there is no single agreed definition of knowledge; any definition is controversial.” In his dissertation, Tobin (2006, p.2) provided a summary of definitions of knowledge given by various authors and selected the definition of knowledge as being “the capacity to act”. The definition provided by Zack (1999, p.2) is deemed to be relevant to this research. The definition states: “knowledge is commonly distinguished from data and information. […] Knowledge is that which we come to believe and value on the basis of the meaningfully organised accumulation of information through experience, communication or inference.” Furthermore – the ‘capacity to act’ is seen as the result of possessing knowledge.

From the above definitions by the OED (2010) and Zack (1999), the following definition is derived to best describe the term “knowledge” for this research:

Knowledge is an awareness, consciousness, familiarity, perception or understanding that causes the possessor to have a practical command of, or competence, skill or expertise in, or capacity to act. It is acquired through learning, erudition, instruction, study or practise (actions).

The preceding definition answers the first sub-research question, No. a) i).

This definition describes in essence what knowledge is, how it is acquired and what the effects are of possessing it (its application). Haines (1998, p.30) stated that, "A person can only become aware of his or her possession of knowledge in an indirect way, i.e., when actions are required. These actions can be the solving of problems, making decisions and understanding of causes and effects." The knowledge that was acquired gives rise to a competency to do things. The acquisition of knowledge leads to the establishment of new insights and the enrichment of existing knowledge.

The underlying science of knowledge and knowledge acquisition by the human mind can be found in cognitive psychology. This is briefly discussed in the following section.

2.3.2 Cognitive aspects of knowledge

a) Cognitive psychology

In the field of cognitive psychology, human mental processes are studied as it plays an important part in the behaviour of people and the way in which people think and feel. According to Kellogg (2002, p.4), the broad categories of this field incorporate things like "perception, memory, the acquisition of knowledge and expertise, comprehension and production of language, problem-solving, creativity, decision making and reasoning." The human interfaces with its environment and as such with knowledge sources that need to be understood. (Refer to the field of distributed cognition as briefly discussed later.) According to Smith (1998, p.15), researchers in various fields, such as psychology, artificial intelligence, philosophy and neuroscience, developed the cognitive account of the human mind. Cognitivism holds that whenever one is thinking about something, a mental representation of that thing is being processed in some or other way. Cognitivists claim that thinking is information processing that transforms informational inputs into conclusions. The discipline of cognitivism considers the human mind as a processor of information, analogous to that of computers. However, the human mind does more than just processing of information. The human mind adds meaning to information and hence changes the content and induces different interpretations or meanings that lead to various actions by individuals. An example is given of tossing a coin. Information is transmitted about the outcome of the toss, but the event, in itself, is meaningless. However, if money is introduced to the game of tossing a coin, such as winning R50 for throwing heads, meaning is added and the objective of the game changes (Kellogg, 2002, p.5).

A fundamental part of cognitive psychology is to explore how knowledge of the world is represented in the mind. The topic of mental presentations comes to the fore, because it deals with objects, events and ideas (Sternberg, 1999). An important reason for considering mental presentation is that “human behaviour cannot be explained without specifying how individuals present the world to themselves” (Sternberg, 1999, p.115). A mental representation is an unobservable internal code for information. There are two schools of thought, namely cognitivism and connectionism. According to cognitivism, the mental representation could be an image or symbolic model. It assumes that the mind functions as a digital computer and that those mental representations are serially processed by conforming to a set of rules of a programme. As an alternate model, the connectionist model does not compare the human mind with that of a computer, but compares it to a model of the working of the brain. Instead of operating to a set of rules, the model is based on numerous associations among simple units, called neurons. (Neurons, in this case, are not the same as in the medical definition, but rather groups of associative units.) Connectionists argue that mental presentations are distributed over a population of neurons and not as per symbolic model theory, using localised symbols. Connectionism reflects the convergence of cognitive science with neuroscience, the physiological study of the brain (Dinsmore, 1992; Kellogg, 2002; Sternberg, 1999). Knowledge and knowledge processes are therefore embedded in the thought processes and the working of the human mind. The view of researchers is that thinking involves the processing of mental representations in one’s mind. For example, declarative knowledge might be organised into semantic networks that connect different items of information by relational links. “Semantic networks shade into schemas, elaborate knowledge structures that people activate in relevant situations.” These knowledge structures form mental models and are powerful ways of representing certain kinds of knowledge. An example is that a person’s ability to solve problems could be improved if the knowledge about problem-solving was represented in the appropriate way when it was taught (Smith, 1998, p.18).

A further perspective is given to cognition through the field of study of distributed cognition. Individuals interact in a multimodal way with artefacts, agents and other people. A complex set of dynamic relationships exist between an individual or a group of persons whereby their cognitive processes are influenced. The cognition of an individual is the product of the interaction process. The cognitive dynamics can be described as a complex system

(Hutchins, 2006, p.375-377). An example is the working together of a group of people to investigate and endeavor to solve shared problems. The roles of organisations where interaction takes place with individuals and artifacts as part of the business are of importance.

The multimodal interaction involves both internal (to the individual himself) and external artifacts or representations. External representation can be by way of individuals' memories. External representation can also be by way of software, the internet, by social media, cellphones, paper-based documents, or any other media (Harris, 2018, pp.1-7). The patterns of information flow can alter cognition. Representation is of direct application in this study as concept maps that will be discussed in later sections of this study are in fact cognitive distribution tools (or artefacts) that provide models for interaction in cognitive processes.

b) Concepts

Smith (1998, p.18) remarks that concepts are the simplest elements of thought and correspond to words in a natural language and kinds of things in the world. "Concept formation is the process by which people develop a new notion or unit of meaning" (Smith, 1998, pp.18,19). Theories of concepts by Kellogg (2002, p.210) states that […] "a concept is embedded in and consistent with people's background knowledge and folk theories." According to Howard (1987, p.2), "A concept is a mental representation of a category, which allows one to place stimuli in a category by some similarities between them." It allows a person to place stimuli in or out of the category. Experience in dealing with other class members suggests how to deal with new members in this category. "A fundamental aspect of concepts is that they are generally *abstractions* from experience" (Howard, 1987, p.3). This means that one or more essential relevant aspects are singled out and other aspects are ignored. Concepts enable people to make enough sense of the world to live adaptively. The infinite complexity is broken up into categories. How we look at the world depends on our individual concepts, how we categorise it and what knowledge we use to understand it.

Howard (1987, p.9) states that concepts and stimuli can be allowed to be related through taxonomies and partonomies. The characteristic of the taxonomy is that it consists of various layers when viewed in a vertical dimension. The upper-level concepts subsume those directly below it (vertical level). On a horizontal level, different concepts are mutually exclusive. A related structure is a partonomy, where concepts in partonomy are linked by part-whole relations rather than class inclusion. An example is the concepts "eye", "nose", "lips" and "forehead" which are components of one's face. The face is part of the human body which is part of humanity. The relation between face and body is "part of a whole". The face is therefore not an instance of the body, but a part of it. "All the concepts that a person knows ultimately connect to each other in a maze of taxonomies, partonomies and other structures. All this knowledge constitutes a person's cognitive structure" (Howard, 1987, p.11). Kellogg (2002, pp.204-231) deals with semantic memory and distinguishes between the following different kinds of concepts:

- Rule-governed concepts: each and every feature must be present for an object to fit the concept.
- Object concepts: refer to natural kinds or biological objects and artefacts or human-made objects: often organised hierarchically – boundaries between class memberships can be fuzzy.
- Schemas: cognitive structures that organise related concepts and integrates past events.

c) More on categorisation

In the process of mental representation, the human mind categorises concepts and is, therefore, part of the human mind's thought processes. "There is nothing more basic than categorisation to our thought, perception, action and speech. Every time we see something as a *kind* of thing, for example, a tree, we are categorizing" (Lakoff, 1987, p.5).

There is a difference between the terms "categorisation" and "classification" (Jacob, 2004). However, for the purposes of this study it is not considered essential to refine the study to that level of detail. The terms are therefore used interchangeably.

Sternberg (1999, p.206) mentions "concepts and categories" in a sub-heading in his discourse on prototype versus exemplar models in cognition and says that a concept is a mental presentation of a class (e.g., dogs, trees, etc.), which includes our knowledge about such things. A category is introduced as "the set of examples picked out by a concept" (Sternberg, 1999, p.206). "Concepts or sub-concepts can thus the picked and classified into various categories. An example would be the concept of a bird. Fruit-eating birds would be a category of the concept 'bird'." Sternberg describes two prominent ways of classification of things into different categories. The two ways are the prototype view and the exemplar view. Both these methods compare features of some unfamiliar thing with features of a familiar base reference. In the case of the prototype view, the reference base would be one's general knowledge about the thing and then compares an unknown object to that familiar base and then decides upon a classification. On the other hand, according to the exemplar view, the reference base is the similarity of something to what is in one's memory about specific cases. A combination of the prototype and exemplar models is advocated (Sternberg, 1999, p.231). Classifications of concepts can be done mathematically and/or statistically to compare the variation of features from the bases to come to a decision about the classification. This implies that a particular classification can vary according to weights attached to the importance of certain features. It is interesting to note regarding classification of concepts that it is context-dependent. Sternberg (1999, p.231) mentions that "A concept can be coherent even when there are no obvious perceptual or functional similarities among its instances." The example is given of the concepts 'children', 'money', 'photo albums' and 'pets' that do not seem to have anything in common. However, if one considers these in the context of what one needs to take out of a house if the house is on fire, one would have no difficulty in classifying the concepts in the same category. The above suggests that the category boundaries are flexible. When considering the classification of concepts of case studies (discussed in Chapter 4), the categorisation of concepts is mostly based on functional features and should be flexible. Lakoff (1987, p.12) explains that in contrast to the classical theory of categorisation, where category boundaries are rather inflexible, the current prototype theory regard categories to be much different. The themes in categorisation that are dealt with by Lakoff (1987) describes a significant departure from the classical theory. The following concept classifications are discussed by Lakoff (1987, pp.12-19).

(Only the relevant aspects relating to this study are shown and briefly discussed.)

- Family resemblance: Members of a category may be related to one another without all members having any properties in common that define the category.
- Centrality: Some members of a category may be "better examples" of that category than others.
- Polysemy as categorisation: Related meanings of words form categories and their meanings bear family resemblances to one another.
- Membership gradience: At least some categories have degrees of membership and no clear boundaries.
- Conceptual embodiment: Properties of certain categories are a consequence of the nature of human faculties and of experience of functioning in a physical and social environment.

- Functional embodiment: The idea that certain concepts are not merely understood intellectually*;* rather, they have been used tacitly. Concepts used in this way have a different, and more important, psychological status that those that are only thought about consciously.
- Basic-level categorisation: The idea that categories are not merely organised in a hierarchy from the most general to the most specific, but are also organised so that categories that are cognitively basic are in the middle of a general-to-specific hierarchy. Generalisation proceeds upward from the primary level and specialisation proceeds downward.
- Reference-point or metonymic reasoning: Part of a category or subcategory can stand for the whole category in certain reasoning processes.

The above ideas of categorisation (or classification) are of particular significance in the structuring of concept maps and will be expounded on in later sections.

Sternberg (1999, p.228) states that, "In addition to classification, category knowledge plays a critical role in a variety of other cognitive activities, such as explanation, conceptual combination, communication and inference. The use of categories for inference is particularly important [...] we view prediction as a simple but common inference." Concepts allow one to make inferences. An example is when a doctor makes a diagnosis of an illness and he categorises the illness. In so doing he may have more knowledge about the illness.

d) Schemas

A schema is "a cognitive structure that organizes related concepts and integrates past events" (Kellogg, 2002, p.211). Howard (1987, p.31) says that a schema represents a mental representation of a set of related categories. Howard defines it as "an organized body of knowledge, a mental structure that represents some part of some stimulus domain." Schemas are important in understanding the constructive aspects of perception and memory.

Howard (1987) refers to stimuli and uses this term mostly for instantiations. A schema consists of several parts or elements and is called variables or "slots". A face schema consists of the slots in a schema that are filled with instantiations, such as eyes, nose, mouth, etc. Kellogg (2002) talks about frames and define it as schemas that represent the physical structure of the environment. Frames are also used in generating mental maps of the environment and other forms of remembering and imaging. The essence of a frame is a detailed structural description that specifies the concepts and the relations among concepts that define the physical environment. The terms “frames” and “slots” are mentioned again in subsequent sections regarding knowledge representation in computing.

e) Perception

This is the process whereby people acquire information of the outside world. It culminates in recognition, matching a perceptual input with information stored in memory. Perception is context-sensitive and affected by prior beliefs and expectations. “Perception permeates human activity, including problem-solving. Its role is critical in problem identification, where failure to pick up relevant information or to recognize a situation as problematic can be disastrous” (Smith, 1998, pp.16, 17). Perception mapping is presented by Mann (2007b, p.149) which is a tool designed to manage emotional and perceptual complexities present in business-problem situations involving people. It seeks to obtain mutual understanding and appreciation between parties with potentially conflicting views. Perception mapping has some commonality with concept mapping as will be discussed in detail in Chapter 4 of this study.

f) Propositions

Sternberg (1999, p.113) explains that according to one class of theories, human knowledge is represented in an abstract format, called “propositions” (single-code theories). “A proposition is defined as the smallest unit of knowledge that can stand as an assertion, the smallest unit that can be true or false” (Sternberg, 1999, p.117). Propositional networks can be drawn where the first word in each proposition expresses a relation and the next one or two words the arguments of the proposition. This is illustrated in **Figure 2.1**.

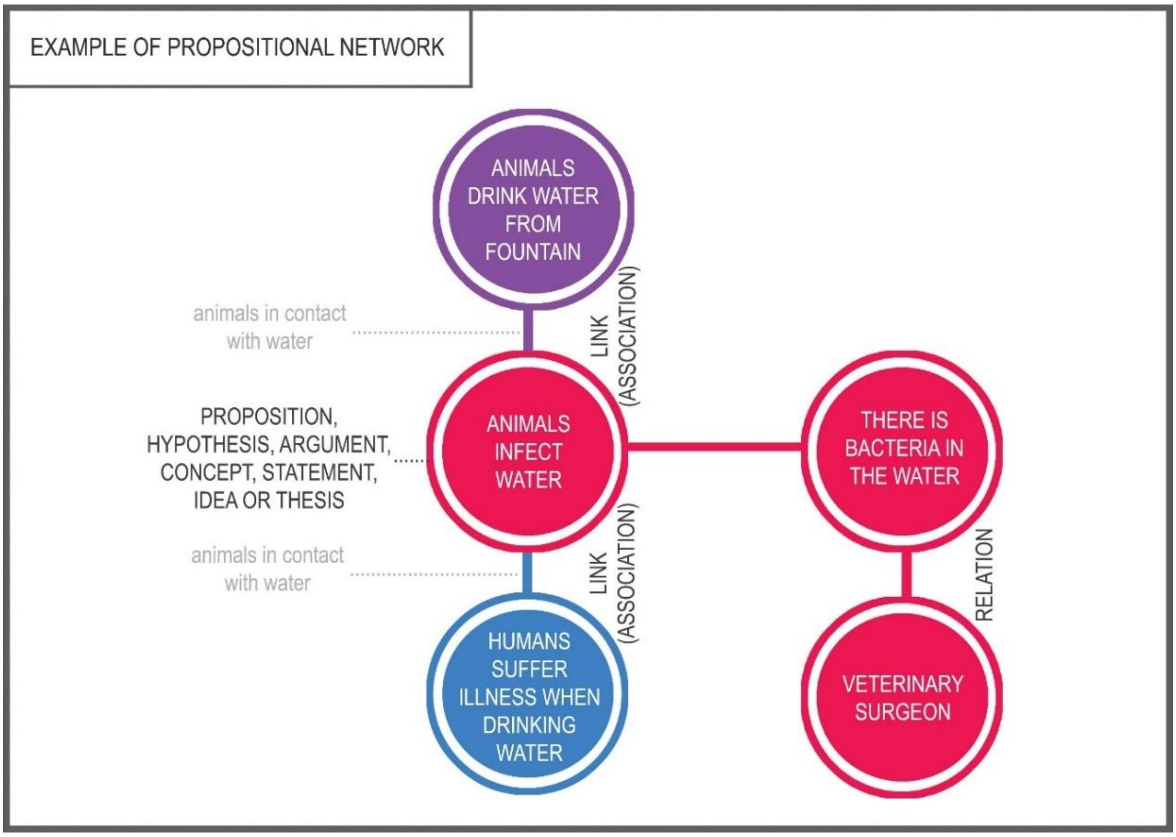

Figure 2.1 Example of a propositional network

In the above propositional network, the nodes or objects or statements are linked to the proposition that animals infect water. The proposition is made that "animals infect water". This proposition can be tested and it can be found as false. There is another proposition, namely, "there is bacteria in the water". This proposition is true. The veterinary surgeon has a relation with the humans and the animals, and is linked to the bacteria count in the water. The network can therefore be adjusted to reflect the true and false propositions. "There are many retrieval schemes associated with proportional networks, but most are based on a concept spreading activation […] the activation of a node spreads through the links to other nodes in the network" (Sternberg, 1999, p.120).

Another view of propositions can be used, which are "statements about something, object or event in the universe. Propositions contain two or more concepts and are connected by using linking words or phrases to form meaningful statements. Sometimes these are called semantic units or units of meaning" (Novak, 1998, p.26). This view suggests that relationships between concepts can be generalised to include any meaningful relationship.

(This is the way that relationships will be treated in the logic base in Chapters 4 and 5 of this study.)

The other class of theories accepts that knowledge can be represented propositionally, but advocates that knowledge is, however, also represented in perceptual format, often referred to as images or more generally as analogical representations (multiple-code theories). Studies suggested that visual imagery is functionally the same as visual perception. Also, a change in mental image ought to be analogous to experiencing a change in perception (Kellogg, 2002, p.220). From the above discussion, it is deduced that the way these symbolic models and associations are represented in the human mind, resembles and strongly suggests that visual images are produced. This suggests that concept diagrams (or maps), as discussed in Chapter 4, are analogous to images formed in the human mind. This offers potential advantages in that concept diagrams could be formulated into appropriate images that are meaningful in remembering certain knowledge or lessons learned. This aspect may present interesting possibilities and should be covered in the future research.

In summary, cognitive psychology seeks to explain the various processes that take place in the human mind. Various models were developed and are still being developed to explain the immense complexities of the human mind. Cognitive psychology describes the mental representation of, amongst others, the acquisition of knowledge and expertise which makes it very relevant in the field of knowledge environment. The most important aspects covered in the brief treatise above are the mental representation by way of concepts and schemas and the categorisation thereof. These are considered essential building blocks of knowledge and the proposed logic base.

Concept diagrams, as a direct outflow from cognition are further discussed and expounded on in Chapter 4 in the development of the logic base. Reference is also made to the above in the development of ontologies in later sections of this chapter.

(The preceding section answers the second sub-sub-research question, No. (a) (ii).)

2.3.3 The knowledge hierarchy

Wallace (2007, p.13) describes the relationships among data, information, knowledge and sometimes wisdom in a hierarchical arrangement. This was part of the language of information science for many years. Although it is not quite clear when and by whom it was first presented, the acronym “DIKW” is used as shorthand for data-to-information-to-knowledge-to-wisdom. Wallace (2007, p.14) explained that many authors have attempted to define the distinctions between data, information, knowledge and wisdom. His comments are included in the exposition below. An appropriate definition was formulated by Ackoff (1989, pp.170-172), stating five categories, namely:

- **Data**: Symbols that represent the properties of objects and events.
- **Information**: Processed data, where the processing is directed at increasing usefulness. It also answers questions such as “who”, “what”, “where” and “when”. Classically, **information** is defined as data that are endowed with meaning and purpose.
- **Knowledge**: Is the application of data and information and answers the “what” questions. It is connected in relationships, may be described as knowledge.
- **Understanding**: The application of “why”.
- **Wisdom**: Evaluated understanding. It is the ability to make sound judgments and decisions apparently without thought.

Zack (1999, p.2) states that, “Knowledge is commonly distinguished from data and information. Data represents observations or facts out of context, and therefore not directly meaningful. Information results from placing data within some meaningful context, often in the form of a message. Knowledge is that which we come to believe and is value-based on the meaningfully organised accumulation of information (messages) through experience, communication or inference.” Pomerol and Brézillon (2011, p.2), aptly put it that “knowledge is information incorporated in an agent’s reasoning and made ready either for active use within a decision process or action.” It is the output of a learning process. Thus, the roles of knowledge are to “(1) transform data into information, (2) derive new information from existing ones, and (3) acquire new knowledge pieces” (Pomerol and Brézillon, 2011, p.2).

From the above definitions, the conclusion is made that knowledge forms in a person’s mind when data and information are placed in context and processed through reasoning processes thereby obtaining an understanding, enabling a person to act or to make decisions. Understanding is part of knowledge. The viewpoint of Pomerol and Brézillon (2001, p.2) and their 3 statements are considered very important in this study as it relates to *knowledge acquisition* (the transformation of data into information), the *creation of new* *knowledge* (from the derivation of new information from existing) and to *acquire new knowledge* pieces. By implication the reuse of knowledge also applies.

A philosophical paradox results from the fact that one has to have prior knowledge (also referred to as meta-knowledge) to be able to transform data into information and information into knowledge.

Bajaria (2000) provides several examples showing how important it is to integrate knowledge creation and knowledge management. If data is correctly collected (as part of knowledge management) and is unbiased and trustworthy, it can be beneficially used to indicate trends or can reveal potential root causes of problems. Data then becomes information and can be converted to knowledge about something. Wisdom results when the correct and best solutions to problems are developed from the enquiry on the available knowledge.

This is one of the important aspects and a fundamental reason for the development of a logic base. It is seen to be part of the function of a logic base to establish knowledge for purposes of generating new knowledge. Furthermore, the purpose of a logic base is to provide, among other things, a learning tool through the organised accumulation of relevant information. The relevancy of information to an individual is highly influenced by the level of prior knowledge, experience (tacit knowledge) and context. Impartation of external (explicit) information adds to a person's knowledge memory and helps a person to define the processes involved to produce a particular outcome. The tacit knowledge is then contained in concepts that are formed in the mind.

The content of knowledge as described above is dependent on the context and what a person comes to believe. This belief is also value-based. Since these aspects can differ widely from one individual to another, it is contended that the knowledge derived from the same set of data and information will differ from one person to another. This deduction is necessary when it comes to the process of creating knowledge. This will lead to different individuals producing different contents of knowledge, even if the same data and information are accessed as the basis for generating knowledge. As circumstances change, so does the context, which leads to the creation of further (or different) knowledge.

As will be seen in later sections in this research, regarding the acquisition of knowledge, socialisation is one of the acquisition methods. Socialisation places great emphasis on context (Pomerol and Brézillon, 2001).

This is further illustrated by the theory of constructivism which is found in an educational theory, dating back to 1668. “The constructivism learning theory argues that people produce knowledge and form meaning, based upon their experiences. Two of the key concepts within the constructivism learning theory which create the construction of an individual’s new knowledge are accommodation and assimilation. The process of assimilation causes individuals to incorporate new experiences into the old experiences. This causes the individual to develop new outlooks, rethink what were once misunderstandings and evaluate what is important, ultimately altering their perceptions. Accommodation, on the other hand, is reframing the world and new experiences into the mental capacity already present. Individuals conceive a particular fashion in which the world operates. When things do not function in that context, they must accommodate and reframe the expectations of the outcomes” (Online Teacher Resources, 2012, p.1).

According to Smith, DiSessa, and Roschelle (1994, p.2), the basic premise of the theory of constructivism is that students build more advanced knowledge on prior understandings. Sfard (1998, p.4) states that “The idea that new knowledge germinates in old knowledge has been promoted by all the theoreticians of intellectual development.” The role of prior knowledge and understandings can also be seen against the previous discussions on the prototype and exemplar viewpoints regarding categorisation. This reinforces the important role in contextualisation of knowledge.

The development of knowledge, as discussed above, leads to the quest to organise or discover what the different types of knowledge are and is discussed in the following section.

2.3.4 Different types of knowledge

In examining what *knowing* is, Polanyi (1958, p.49) philosophised on skills (seen as a part or component of knowing). In his deliberations, he referred to the practising of a skill and remarked that “a skillful performance is achieved by the observance of a set of rules which is not known to the person following them” (Polanyi, 1958, p.49). Polanyi philosophised regarding the role of implicit or tacit knowledge in performing certain tasks. He describes the acquisition of language skills which illustrates the principles of tacit knowledge in a very special way. When speaking a language one is not aware of all the grammatical rules, but focuses on the message that needs to be conveyed. The grammatical rules are embedded tacitly and are made explicit during speaking. Further examples are given by Polanyi where tacit knowledge plays a major role. Such examples are swimming, riding a bicycle or playing the piano. In all these cases, persons are not aware of the rules that govern the physics of the actions. By performing the acts, the person is capable of doing the correct things.

According to Prosch (1973), Polanyi made a unique contribution to philosophy and pioneered the notion of tacit knowledge. Sanders (1988, p.1) states that there are other related notions which bear the same meaning as tacit knowledge. Words such as "unconscious" and "unconscious ideas" (S Freud), "unconscious inference" (F Brentano), "implicit knowledge" (H L F von Helmholtz) and "knowing how" (G Ryle). (The relevant names of authors are shown in brackets.)

Sanders (1988) criticised Polanyi's work. This criticism was reviewed by Cannon (1996). However, it is considered beyond the scope of this study to provide a detailed exposition on the matter. Suffice to say that it seems that there is sufficient support for the notion of tacit knowledge, as defined by Polanyi, to refer to the concept of tacit knowledge in this research. In summary, important aspects of tacit knowledge are the following:

- "We can know more than we can tell."
- "We can tell nothing, without relying on our awareness of things we may not be able to tell."
- "All knowledge is either tacit or rooted in tacit knowledge" (Sanders, 1988, p.3).

Crowley (2001, p.568) described tacit knowledge as follows:

- "personal in origin;
- valuable to the possessor;
- job specific;
- related to the context;
- difficult to fully articulate;
- both known in part and unknown in part to the possessor;
- transmitted, where transmission is possible, through interpersonal contact;

- operative on an organisational level;
- applied, in part, through "if-then" rules (*if* certain conditions exist, *then* apply the following);
- intertwined with explicit knowledge along unstable knowledge borders;

poorly reflected in contemporary literature."

Wallace (2007) remarked that tacit knowledge is divided into two dimensions:

- "First, the technical dimension which encapsulates the term 'know-how' that closely correlates with Polanyi's (1958, p.49) statement that we know more than we can tell.
- The second dimension is the cognitive dimension and consists of schemata, mental models, beliefs and perceptions so ingrained that we take it for granted" (Wallace, 2007, pp.30-31).

Cannon (1996, p.2) states that the Theory of Tacit Knowledge (TTK) is intended as a non-explicit theory of, or as an informal logic of science and knowledge in general. Three theses are mentioned:

- "First, true discovery, exemplified particularly by the progress of science, cannot adequately be accounted for by a set of wholly explicit rules or algorithms, either for finding or for testing theories.
- Second, knowledge, though public and social, is to varying degrees also inherently personal.
- Third, not only is it impossible to make all knowledge explicit but the knowledge that cannot always be specified underlies, i.e., is more fundamental than, explicit knowledge."

Polanyi's philosophies of the terms focal knowledge and subsidiary awareness are given in "Personal Knowledge" (1958, pp.54-55). He uses the example of a person driving a nail with a hammer. One's mind will be focused on the hammer hitting the nail, but one will be only vaguely aware of the hammer's handle and the action of the handle on one's hand and of one's muscles acting on the hammer. Polanyi also mentions that if a pianist's attention shifts from the piece he is playing to what he is doing with his fingers, he gets confused and may have to stop playing. Polanyi states that "Subsidiary awareness and focal awareness are mutually exclusive" (Polanyi 1958, p.56). Focal knowledge is the knowledge of the phenomenon or object that is in focus. Knowledge that is used as a tool to handle or to improve what is in focus, is referred to as tacit knowledge: Tacit knowledge functions as the background and assists in accomplishing a task that is in focus. The above can be clarified by noting that tacit knowledge plays a role in the background of actions as well as in the tasks at hand. However, the focus, having the immediate actions in mind, can only be on one or the other.

Zack (1999, p.2) describes tacit knowledge as "knowledge that develops naturally as a by-product of action." Actions can, therefore, be seen as the means of gaining experience. The capacity to act implies the possession of certain skills or know-how (familiarity).

It is also important to note that the basic requirement of knowledge is to actually apply it in unfamiliar or unknown, varied and uncertain circumstances (Bennet and Bennet, 2008).

In summary, having regard to the discussions above, the following are deduced:

- That there are two fundamental types of knowledge, namely explicit and tacit knowledge.
- That there is more knowledge in the tacit dimension that can be made explicit.
- That tacit and explicit knowledge always co-exist.
- Knowledge is inherently personal in nature.
- That more advanced knowledge is built on prior understandings.
- Tacit and explicit knowledge are fundamental and essential for discovery (as exemplified by the advances made in science).
- Knowledge creation is initiated by action and is a repetitive process – better described as an iterative process.
- Knowledge is required for use in uncertain and varied circumstances.

2.3.5 Different types of explicit knowledge

It is valuable also to consider some further types of explicit knowledge. These different types of knowledge are relevant to this study because it provides an understanding of the possible classification of knowledge which can be beneficial to the development of a logic base.

The different types of knowledge from the work of Zack (1999, p.2) that can be made explicit are summarised as follows in **Table 2.1**.

Table 2.1 Different types of knowledge

Type of knowledge	Description
Knowledge about something (explicitly knowing what – events, facts & concepts).	• Declarative knowledge.
Knowledge of how something occurs or is performed (implicit or tacitly).	• Procedural knowledge.
Knowledge of why something occurs - general knowledge.	• Causal knowledge. • Broad. • Often publicly available. • Independent of particular events.
Specific knowledge.	• Context-specific.

Zack (1999, p.2) remarked that "knowledge may be of several types, each of which may be made explicit. Knowledge *about* something is called declarative knowledge and is explicit. […] A shared, explicit understanding of concepts, categories and descriptors lays the foundation for effective communication and knowledge sharing in organizations." Knowledge of *how* something occurs or is performed is called procedural knowledge" (Kellogg, 2002, p.150). (This can be done through the use of taxonomies, as discussed later on in this chapter.) Markus (2001) also defines factual knowledge, analytical knowledge and rationale knowledge in addition to procedural knowledge. This is a useful addition and adds a dimension of "know-how" to the aspect of "procedural" knowledge.

"Shared explicit procedural knowledge lays a foundation for efficiently coordinated action in organizations. Knowledge of *why* something occurs is called causal knowledge. Shared explicit causal knowledge, often in the form of organizational stories, enables organizations to coordinate strategy for achieving goals or outcomes" (Zack, 1999, p.2).

When one, for example, reads a technical article, the understanding of the context presupposes a certain amount of tacit knowledge regarding the subject, e.g., the basic rules of science and a certain level of tacit knowledge regarding the subject is presupposed when reading a technical article. (Some technical articles may be difficult to understand because the reader may not yet have the same level of tacit knowledge as the writer of the article. This makes it difficult for the reader to fully comprehend or to contextualise the information.)

The above is very significant in this research as the purpose of the logic base is to record experience in such a way that it can be understood and reused and thereby add new knowledge to the user.

Knowledge may also range from general to specific (Sveiby, 1998). General knowledge is broad, often publicly available and independent of particular events. Specific knowledge, in contrast, is context-specific. General knowledge is commonly shared and can be more easily and meaningfully codified and exchanged, especially among communities of practice. Codifying specific knowledge to be meaningful across an organisation requires its context to be described along with focal knowledge. This, in turn, requires explicitly defined contextual categories and relationships that are meaningful across knowledge communities.

Knowledge representation in knowledge bases and Artificial Intelligence (AI) is cognisant of the various types of human knowledge. In cognitive science, the different types of knowledge that people commonly use, is recognised. AI systems then implement some of these types using similar knowledge-representation techniques (Gašević and Devedžić, 2009, p.11).

The description of different knowledge types is an important building block for the development of a logic base's ontology and taxonomy. The development of the taxonomy of the proposed logic base will be done after the determination of the characteristics and the attributes of the knowledge base.

To further contextualise knowledge, the following section describes what the management of knowledge entails.

The preceding section answers the third sub-sub-research question, No. a) iii).

2.3.6 What is knowledge management?

Knowledge management is mostly seen in the context of something that exists within individuals in an organisation. Ahmed, Lim and Loh (2002, p.3) summarise that "Many practices attempting to manage individual and corporate learning have, over time, converged into what is now labelled 'knowledge management'." Disciplines such as psychology and management sciences were involved, and this diversity "culminated in the development of a range of terms such as 'the learning organization', 'intellectual capital management', intellectual asset management' and 'knowledge management'." Ahmed, Lim and Loh (2002, p.3) conclude that "knowledge management is an umbrella for capturing a range of organizational concerns and that there is a common understanding that knowledge management encapsulates a more organic and holistic way of understanding and leveraging people within work processes for business benefit" (Ahmed, Lim and Loh. 2002, p.3). The prime reason for knowledge management in the commercial context is for improvement in market competitiveness and sustainability. In this context, Davenport and Prusak (2000, p.3) describes knowledge management as an "overt activity" performed within firms. Knowledge management is described by Wallace (2007, p.1) as "an innovative approach to redirect the energies and activities of organisations by enhancing the generation, flow and use of internal knowledge." Seemann *et al.* (2000, p.92) say that "management needs to make specific efforts to build intellectual capital in an organisation to ensure that new business strategies can be supported. Such strategies could include the hiring of new talent, job rotation and altering the organisational structures to enable knowledge flow between old and new business activities."

A definition for knowledge management that was adopted after much deliberation by Jennex and Olfman (2009, p.i) is as follows:

"KM (Knowledge Management) is the practice of selectively applying knowledge from previous experiences of decision making to current and future decision-making activities with the express purpose of improving the organization's effectiveness." (Parentheses added.) The selective application of knowledge from previous experiences should be understood against the background of the different types of knowledge as described in **Table 2.1**, and in the discussions thereof. Various types of knowledge should be identified and selected as the most appropriate. Skills or know-how, such as analytical and rationale knowledge, are equally important to harness knowledge and previous experience for making decisions and for improving effectiveness. Jennex and Olfman (2005, p.i) describes knowledge management as an action discipline that is results oriented. For knowledge management to be successful, the impact from knowledge reuse must be measurable. "Decision-making is the ultimate application of knowledge" (Jennex and Olfman, 2005, p.iv). This can be directly related to the quality of decision making, which can be measured and judged. Organisations can tell if they are referring similar matters for making decisions over and over and if they are using the experience to make decisions quicker and better.

In the following section, the approaches and processes of accumulation, organising and getting acquainted with and gaining knowledge are discussed.

2.3.7 Management of knowledge – the knowledge unit

In the quest to identify "knowledge" it was considered prudent to find or to delineate something that can be described as "knowledge" and can be used. This was researched and is described below.

Zack (1999, pp.2-4) describes different types of knowledge (tacit and explicit), but in the context of reusability. In his discussion, he emphasises the need to manage the articulation of knowledge to make it manageable regarding explicit knowledge.

Kellogg (2002, p.222) says that a proposition is the smallest unit of knowledge which one can judge as true or false. Zack (1999, p.4) deliberates the architecture of knowledge repositories. He identifies structure and context as essential requisites of knowledge architecture. He defines the basic structural element as a "*knowledge unit"*, a formally defined, atomic packet of knowledge content that can be labelled, indexed, stored, retrieved and manipulated. (A proposition can be seen as a manipulation and therefore, would also qualify as a knowledge unit in line with Zack's definition.) The format, size and content of knowledge units may vary depending on the type of explicit knowledge being stored and the context of their use. Knowledge units are the elements of knowledge obtained after a hierarchical decomposition at several levels of detail. "The relevant knowledge is subdivided into knowledge units related in such a way that a few ideas (concepts or statements) in a unit are elaborated by further description through 'subordinate' (or 'next-lower-level') units" (Zack, 1999, p.4).

Sfard (1998, p.5) writes that "concepts are to be understood as basic units of knowledge that can be accumulated, gradually refined, and combined to form ever richer cognitive structures." Knowledge units lend themselves to the compiling of a "repository structure that includes the schemes for linking and cross-referencing knowledge units. These links may represent conceptual associations, ordered sequences, causality or other relationships depending on the type of knowledge being stored" (Zack, 1999, p.5).

When considering Zack's description of the "knowledge unit" and the architecture for knowledge management, it can be inferred that the following characteristics hold true for knowledge units:

- Knowledge units are the shortest possible meaningful description of a particular concept.

- Significant and meaningful concepts, categories and definitions (declarative knowledge).
- Processes, action and consequences of events, including analysis (procedural knowledge).
- Rationale for actions and conclusions (causal knowledge).
- Circumstances and intentions (specific contextual knowledge).
- Linkages among the above.

When considering the needs of the logic base, the following additional characteristics can be identified:

- A separately identifiable concept.
- An identifiable activity or action.
- An element of a system having preceding and/or succeeding elements.
- An occurrence or incident.
- A case subject or topic with what or on what something is happening.
- A phenomenon that has or is taking place and that influences other things.
- A concept that defines or describes an operation or elements thereof.

The above definitions will become relevant when consideration is given to the logic base and taxonomies and ontologies where knowledge units will be extracted from existing knowledge bases for further knowledge creation.

2.4 KNOWLEDGE CREATION

2.4.1 Definition of knowledge creation

Organisations exist to provide products and services to people at their desired quality. The quality of services or products is the result of the behaviour and performance of all the organisation's workers, functioning as individuals and as groups within an organisational structure (George and Jones, 2000, p.238). In response to a world of interdependence and change, and to ensure continued, sustained existence, organisations have to develop the continuous capacity to adapt and change. Such organisations are also referred to as "learning organizations" (Robbins, 2001, pp.559-562). In such organisations, knowledge creation plays a central role and knowledge is understood to be the most valuable resource or even "the only meaningful resource" (Fong, 2003, p.1) to support the organisational goals.

While knowledge resides in and is developed by individuals, organisations play a critical part in articulating and amplifying the knowledge (Nonaka, 1994).

2.4.2 The roles of organisations

Organisations have been understood to be processors of information and solvers of problems. The question is how efficiently and effectively an organisation can deal with information and decisions in an uncertain world. One suggested way of dealing with the uncertainty is to follow an input-process-output sequence of hierarchical information processing. However, this viewpoint sees organisations as passive and static, and information processing is seen to be a problem-solving activity based on what is given to the organisation and not what the organisation created (Nonaka,1994). A further perspective is provided by Robbins (2001, p.559) where the concepts of single and double-loop learning are described in the learning processes of organisations. When errors are detected, single-loop learning involves a corrective action process that relies on past routines and present policies. In double-loop learning, corrective action requires the modification of the organisational objectives, policies and standards methods. Double-loop learning challenges deep-rooted assumptions and norms within an organisation. In double-loop learning opportunities exist for radically different solutions to problems and dramatic jumps in improvement. This process of double-loop learning tends to be closer to Nonaka's (1994) point of view that knowledge creation through innovation does not merely lay in information processing or problem-solving, but rather in establishing what problems there are or can occur (anticipative problem-solving techniques, such as TRIZ – see later in this chapter) and to develop the necessary knowledge to solve the problems. This new knowledge in one department can cascade or influence other departments and trigger further knowledge creation. The question now is, how does an organisation create the knowledge?

Takeuchi and Nonaka (2004) discuss the current trend in management in a fast-changing world. Knowledge management is at the heart of managing change. In a new global society, the world has become more complex and more paradoxes are found. In the previous industrial era, paradoxes were "killed" by sticking to old routines which were part of past successes. In the new breed of successful companies, paradoxes are embraced. Takeuchi and Nonaka (2004) refer to these companies as “dialectic” companies. They describe a dynamic process for the resolution of paradoxes or conflicts, summarised in the “thesis-antithesis-synthesis” spiral. The starting point in the dialectic process is a thesis that shows itself as inadequate or inconsistent. This is opposite or negating the thesis and is known as an anti-thesis. This antithesis also shows itself as inadequate or inconsistent. To reconcile the opposing theses, a synthesis takes place. The synthesis may turn out to be adequate or inadequate and takes the place of the thesis as before, and the process repeats itself (Takeuchi and Nonaka, 2004, p.5). Takeuchi and Nonaka see tacit and explicit knowledge also as opposing or paradoxical concepts, although they are interdependent and interpenetrating. The resolution of paradoxes, and in particular tacit and explicit knowledge, found its way to the Nonaka and Takeuchi’s SECI Model for knowledge creation. This is shown in **Figure 2.2** and described in the following sections. Also refer to the process of inventive problem-solving (TRIZ) in later sections, where contradictions play a key role in problem-solving (Mann, 2007a).

Nonaka (1994) describes knowledge creation as the continuous interplay or dialogue between tacit and explicit knowledge. An example is when ideas are formed in individuals, knowledge is created when the individuals share their ideas (also referred to as socialisation). The concept of “communities of interaction” is mentioned as a fruitful way of sharing ideas and therefore of creating or developing new knowledge (Nonaka, 1994, p.17). These interactions may also take the form of formal or informal targeted discussions with knowledgeable individuals or groups.

When Nonaka (1994, p.16) and Takeuchi and Nonaka (2004) discuss tacit knowledge, they distinguish between two elements, namely the cognitive and the technical elements. The cognitive elements comprise working mental models in which analogies are created and manipulated in a person’s mind. These models comprise paradigms, schemata, viewpoints and beliefs that provide “perspectives” that help individuals define their world. It also includes a person’s images of reality and visions for the future. Technical elements, in turn, comprise know-how, crafts and skills. Nonaka (1994) and Takeuchi and Nonaka (2004) contend that the “articulation of tacit perspectives” – in a kind of mobilisation process – is a key factor in the creation of new knowledge.

Senker (1995, p.427) differentiates between knowledge and skills. “Knowledge implies understanding. The acquisition of knowledge is a perceptual, cognitive process. Skill implies knowing how to make something happen; it involves cognition, but also involves other aspects such as manual dexterity or sensory ability." Senker stated that this differentiation between knowledge and skills differs fundamentally from Nonaka's views In some cases, skill is entirely based upon tacit knowledge, whereas in other cases it is based upon a thorough understanding of the scientific principles involved. However, in most cases, skill draws on a combination of tacit and explicit knowledge. "Skills based on appropriate combinations of tacit and formal knowledge in specific context may better be defined as 'expertise' " (Senker, 1995, p.427).

It should be remembered that skill can only become real or can only be acknowledged when expression is given to it by way of actions. Skills may be developed by the combination of prior tacit knowledge and by adding to it either by internalising explicit knowledge or by gaining experience by practising the skills (assimilation and accommodation). A skill cannot be demonstrated other than by exercising or practising it.

Senker's differentiation between skills and knowledge is not seen to be fundamentally different from Nonaka's point of view. Senker only extends the meaning of skill also to include manual dexterity or sensory ability. These attributes are also capable of being learned or acquired and in essence form part of the tacit dimension.

As an example, when confronted with an unknown situation, one's first response is to use tacit knowledge to attempt to understand the situation or to resolve or overcome a problem. When unsuccessful or when further obstacles are encountered, one would analyse the situation by using scientific knowledge (explicit). A combination of tacit and explicit knowledge is therefore applied.

The concept of "skill" is important in this research since it was reported in the public domain that South Africa experienced a slow decline in the number of civil engineering professionals a decline in as a result of skilled people emigrating to other countries or leaving particular professions. (Refer to Chapter 1, section 1.2.2 and Stimie 2008, p.30.)

The intention of this research is to establish a logic base that would assist in recording or capture knowledge and therefore also the skills to reuse and thereby endeavour to not losing knowledge when skilled people depart from their workplace.

Nonaka and Tacheuchi (1994) noted that commitment underlies human knowledge-creating activities. Three basic factors induce commitment, or enabling conditions, viz.:

Intention	Purposeful activity. Knowledge is created within the context of and with a purposeful activity as a vehicle.
Autonomy	In the context of an organisation, removes limitations for self actualisation and promotes and motivates knowledge creation.
Fluctuation	Chaos or discontinuity leads to re-evaluation and re-creating ideas and paradigms.

For example, information is obtained from the environment and is focused on by an individual. Relevant aspects are comprehended and consciousness is developed regarding certain aspects. However, a person cannot grasp the meaning of information without some frame of value judgment. This value judgment lies in the tacit dimension.

Anderson (1996, pp.1-22) worked in the field of cognitive psychology. Anderson's ACT model discusses four different patterns of interaction between tacit and explicit knowledge. Anderson hypothesises that declarative knowledge has to be converted to procedural knowledge to develop a particular cognitive skill. Nonaka (1994) accepts Anderson's exposition and proceeds on the assumption that knowledge is created through a process of knowledge conversion. This is discussed in more detail below.

2.4.3 Knowledge conversion

Nonaka (1994) states that individuals initially create knowledge and that the knowledge generated becomes organisational knowledge through a process of knowledge conversion as described by the theory. The theory describes four modes in the knowledge conversion as follows:

Conversion from:

- tacit to tacit knowledge
- explicit to explicit knowledge
- tacit to explicit knowledge
- explicit to tacit knowledge

These knowledge conversion processes are discussed and summarised in **Figure 2.2**.

2.4.4 Discussions on each conversion process

a) Conversion from tacit knowledge to tacit knowledge (Socialisation)

This takes place when typically a master, possessing a wealth of tacit knowledge, shows an apprentice how things are done or made. Experience is the key to the apprentice's acquisition of tacit knowledge. In essence, it is the shared experience that is important. This can also be a bi-directional process where individuals learn from each other. Language is not a necessity to transfer the knowledge. (Declarative knowledge is converted to procedural knowledge.)

b) Conversion of explicit knowledge to explicit knowledge (Combination)

By way of a social process, different bodies of explicit knowledge held by individuals are combined. Through various exchange mechanisms such as meetings, telephone conversations, etc., existing information (and knowledge) is reconfigured, categorised, re-contextualised, sorted and through combination, new knowledge is created.

c) Conversion of tacit knowledge to explicit knowledge (Externalisation)

This conversion process is also referred to as "externalisation". This takes place when persons with tacit knowledge discuss certain topics and write reports (narratives) about something. Also, declarative knowledge is converted to procedural knowledge.

d) Conversion of explicit knowledge to tacit knowledge (Internalisation)

This is also seen as a learning process. Internalisation takes place. The action is "deeply rooted" in the internalisation process.

Figure 2.2 illustrates the modes of conversion of knowledge (Nonaka, 1994, p.19).

The above knowledge conversion processes are relevant to this research since the population of a knowledge base is done via several knowledge acquisition methods. It is the intention that the proposed logic base be able to facilitate knowledge conversion processes. For example, when experience is recorded, actions of other people are revealed and assimilated. These actions can then contribute to the user's creation of tacit knowledge. Furthermore, people convert tacit knowledge to explicit knowledge when writing reports or brief narratives. These can then be captured electronically and retrieved as useable knowledge. The availability and implementation of electronic media are of particular importance, such as:

- Impartation of certain skills through video training.
- By doing modelling and simulation techniques.
- By contact and discussion, by way of Internet-based discussions and conferences.
- By writing narratives.
- By way of actions and observing outcomes.

The knowledge conversion process is shown in **Figure 2.2. (SECI model)**

(SECI is the acronym for **S**ocialisation, **E**xternalistion, **C**ombination and **I**nternalisation.)

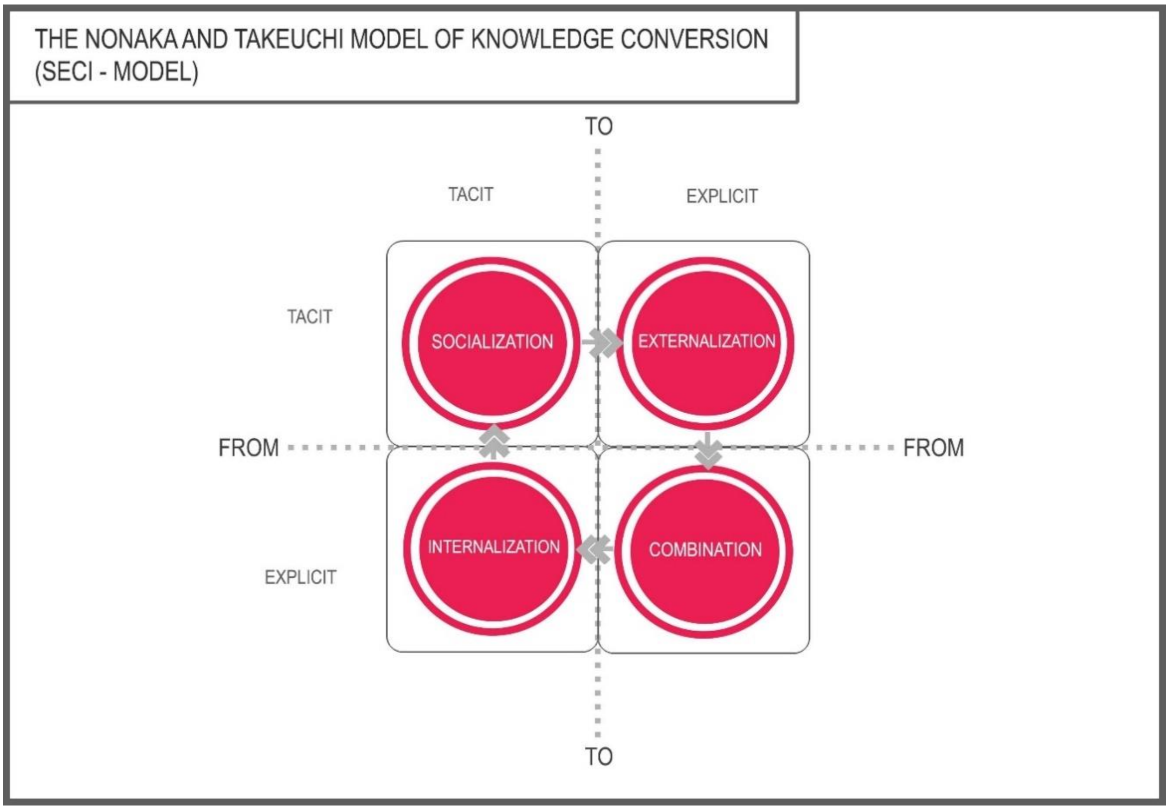

Figure 2.2 The Nonaka and Takeuchi model of knowledge conversion

(SECI Model)

The above model is also referred to as the Nonaka and Takeuchi model which was published in 1995. Other models also exist namely the revised Nonaka and Takeuchi model (Harsh, 2009), and the three-dimensional model. In the three-dimensional model, knowledge reusability is added as a third axis on the above model by Nonaka and Takeuchi (Harsh, 2009). Knowledge reusability will be discussed in subsequent sections.

The question is whether the Nonaka and Takeuchi model is a valid model. A very useful evaluation of Nonaka and Takeuchi's theory was done by McLean (2004). The assessment was done to see if, and to what extent the theory of Nonaka and Takeuchi's model constitutes a real "theory". The theory was evaluated from two perspectives, viz.: Firstly, on how it was derived at and developed. "The quality of the way in which the theory was created (i.e. the process) speaks to the quality of the product (i.e. the theory) and how much credibility it should be given" (McLean, 2004, p.1). Secondly, the quality and maturity of the theory were assessed. The conclusions of the evaluations by McLean (2004) can be summarised as follows:

- That the theory of organisational knowledge creation put forward by Nonaka and Takeuchi is indeed a theory, but that it is an emerging one that it will grow more robust over time.
- The theory is well-conceptualised and draws on an extensive review of the literature and significant data from the field in the form of case studies. "In its current state, the theory is important and fruitful in contributing to the existing body of knowledge on organizational knowledge creation" (McLean, 2004, p.8).

The work done by Takeuchi and Nonaka (1994) is important for purposes of this study since the model for knowledge creation depicts a process that will form an essential basis for the development of the proposed logic base. This will be expounded in chapter 4, where concept maps are discussed. The drawing process of concepts maps resembles knowledge conversion processes.

Each of the above conversion modes is capable of generating new knowledge on its own, but it is most important to note that it is the continuous interaction among the four modes that creates knowledge. Individuals initially create knowledge. The interaction between individuals in an organisational context creates what is referred to as organisational knowledge. Nonaka (1994) argues that organisational knowledge creation takes place when all four modes of knowledge creation are organisationally managed to form a continuous cycle. "The cycle is shaped by a series of shifts between different modes of knowledge conversion. There are various 'triggers' that induce these shifts between ways of knowledge conversion" (Nonaka, 1994, p.20). The first mode of socialisation starts with building a team, thereby doing "field" interaction. Members would share their experiences and perspectives.

The second mode or externalisation mode is triggered by successful dialogue. Metaphors can be used to articulate individuals' perspectives and thereby reveal hidden tacit knowledge. "Concepts formed by teams can be combined with existing data and external knowledge in a search of more concrete and shareable specifications" (Nonaka, 1994, p.20). The combination mode is facilitated by such triggers as "coordination" between team members and other sections of the organisation and the documentation of existing knowledge. "Through an iterative process of trial and error, concepts are articulated and developed until they emerge in a concrete form. This experimentation can trigger internalisation through a process of learning by doing" (Nonaka, 1994, p.20). Tacit knowledge held by individuals lie at the heart of the knowledge creation process and the interaction among people facilitates externalisation which is amplified through the dynamic interactions between all four modes of knowledge conversion. "Tacit knowledge is thus mobilized through 'entangling' of the different modes of knowledge conversion in a process which will be referred to as a 'spiral' model of knowledge creation" (Nonaka, 1994, p.20).

This is depicted in **Figure 2.3**:

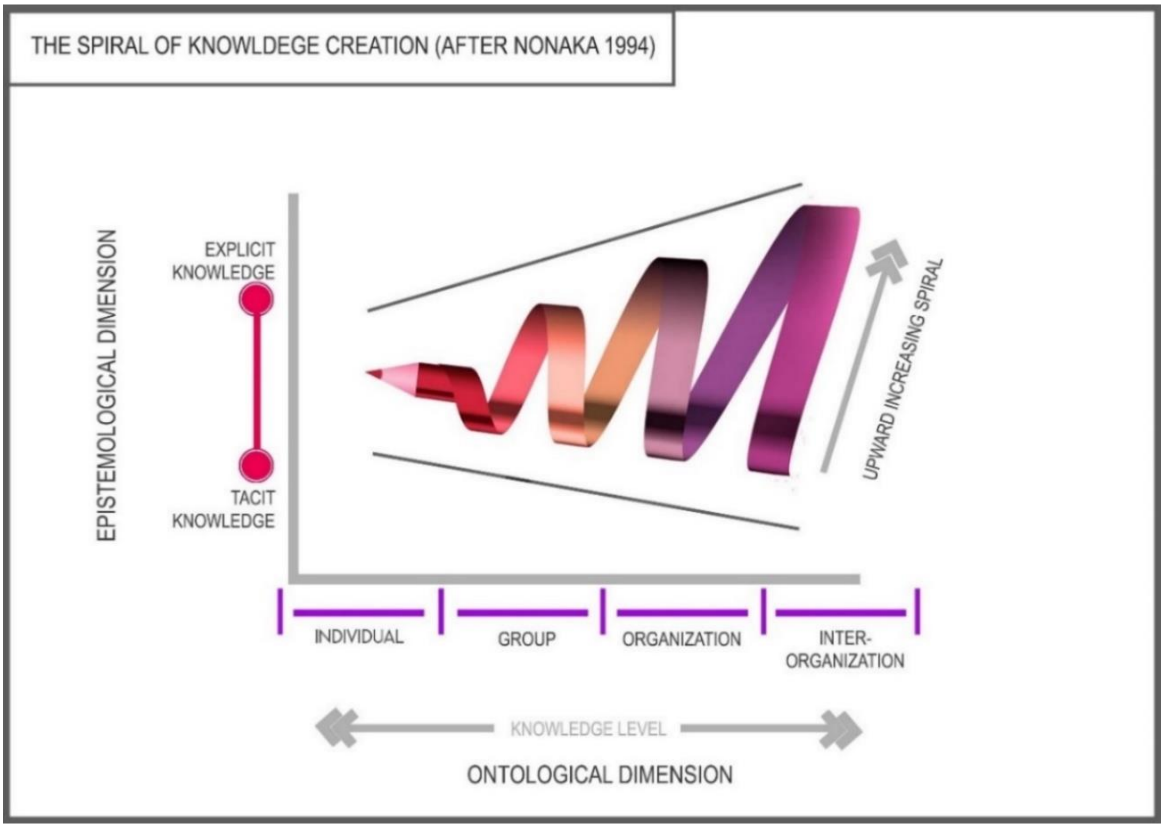

Figure 2.3 The spiral of knowledge creation (after Nonaka, 1994)

The question of knowledge reuse will be covered in a subsequent section dealing with the topic.

2.4.5 The use of metaphor

Nonaka (1994, p.20) describes the use of metaphor as a way of converting tacit knowledge into explicit knowledge (externalisation). Sfard (1998, p.1) writes that "Indeed, metaphors are the most primitive, most elusive, and yet amazingly informative objects of analysis." The use of metaphors is most interestingly described in an article by Nonaka (1991) where the term "Tall Boy" was used as a metaphor in the description during the development of the Honda Civic urban motor car. The word "Tall Boy" encapsulated some concepts that drove the development of a new model. "The unique power of metaphors stems from the fact that they often cross borders between the spontaneous and the scientific, between the intuitive and the formal. Conveyed through language from one domain to another, they enable concept osmoses between every day and scientific discourses, letting our original intuition shape scientific ideas and the formal conceptions feed into intuition" (Sfard,1998, p.4).

Metaphors constitute the primary vehicles to attach through images, more real knowledge of intuitive or abstract matters that inevitably support the creation of new knowledge. Nonaka (1994) makes the statement that metaphors are not only a first step in converting tacit knowledge into explicit knowledge, but that it also constitutes a method of creating networks of concepts used to create knowledge about the future from existing knowledge. He defines a metaphor as two contradicting concepts incorporated into one word. However, a metaphor can also limit the creation of new knowledge if the metaphors permeate the intuitive domain and provide barriers to new knowledge that may contradict the metaphor.

Forming analogies may resolve this contradiction (Nonaka, 1994, p.21). Analogies are used to explain or explore new operations, systems and concepts by referencing to existing knowledge and things already understood. The analogy in this sense assists in bridging the gap between image and logic.

The illustration in **Figure 2.4** sums up and shows how tacit knowledge is transformed into explicit knowledge. This happens firstly by recognising contradictions through metaphor, then by resolving the contradictions through analogy and concepts which can then be transferred through consistent logic.

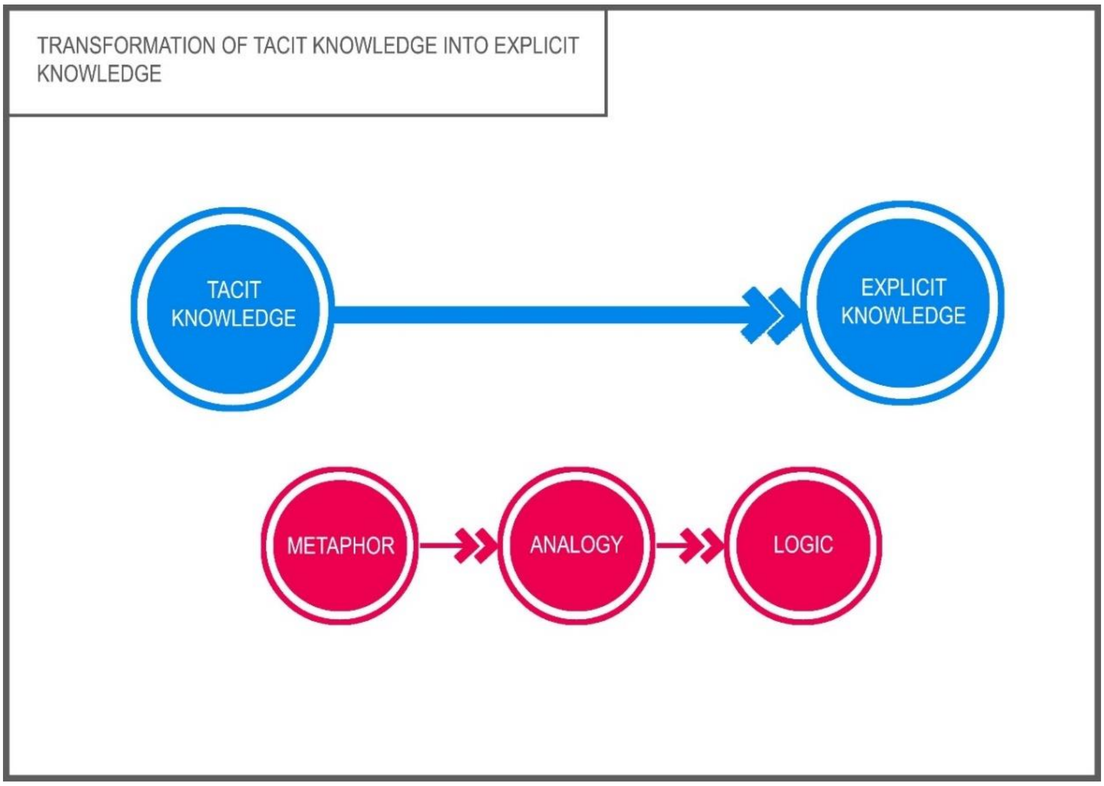

Figure 2.4 Transformation of tacit knowledge into explicit knowledge

Nonaka (1994) describes the need to combine bodily experience with rational experience. Nonaka argues that the Western world has its focus primarily on rationality, while the Eastern world focuses more on social experience than the rational. The combination of bodily experience (also referred to as an intentional self-involvement) and rationality should be well-balanced. One has to reflect (rationalisation and logical thinking) while experiencing.

Self-organising teams are useful vehicles for knowledge creation. Through a process of development of mutual trust, socialisation leads to the articulation of tacit knowledge. In the process of continuous dialogue, knowledge is articulated (made explicit), ideas are verified, criticism is given and the knowledge synthesised to create new knowledge.

Figure 2.5 was developed from the text of Nonaka (1994). It shows the different kinds of reasoning processes. Induction and deduction are shown vertically and increases the depth of knowledge about pre-existing concepts. (Induction – "Logic: the inference of a general law from particular instances". Deduction – "Often contrasted with induction"; "the inference of particular instances by referencing to a general law or principle".) (Refer also to Soanes and Hawker, 2008.) Abductive thinking leads thoughts away and represents lateral thinking processes and creates entirely new concepts.

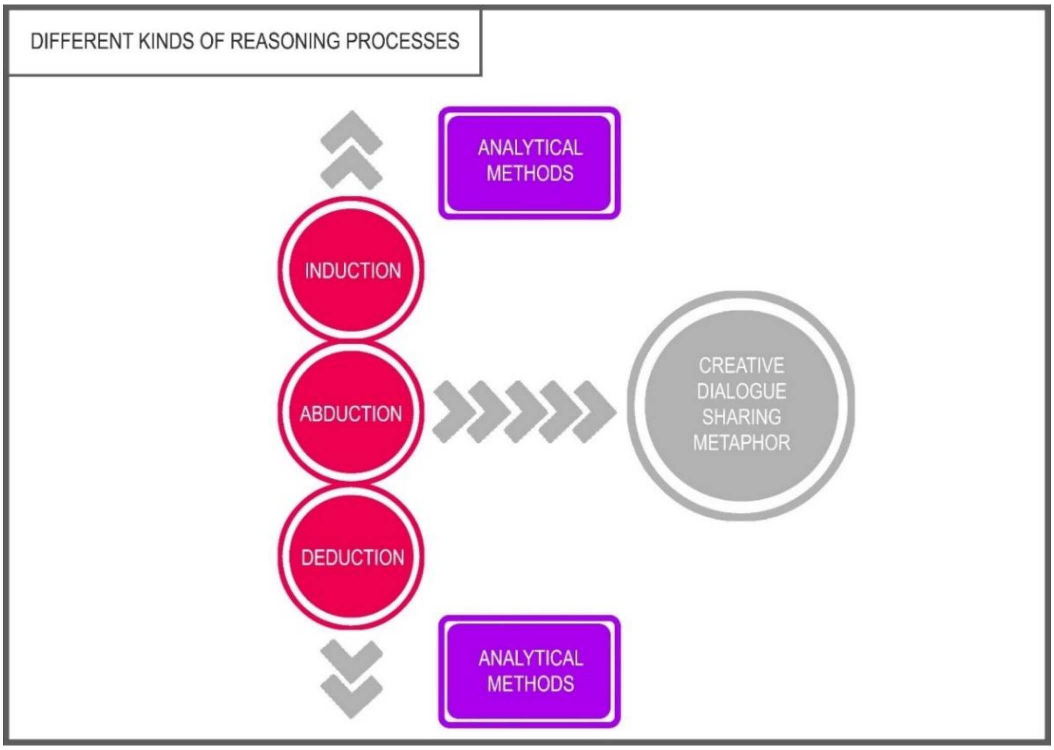

Figure 2.5 Different kinds of reasoning processes

Whereas induction and deduction can be used to generate new concepts, it may not be sufficient to create more meaningful or radical concepts. For that to happen, creative dialogues and sharing will add value. The use of metaphor, invoking more from the tacit dimension, may be more meaningful.

Nonaka (1994) essentially explains how knowledge is created in self-organising teams. The knowledge creation is facilitated by a socialisation process that shares and enriches tacit knowledge. Knowledge conversion also takes place by conversion of explicit knowledge into tacit knowledge through a process of internalisation. A certain concept is developed and crystallised by internalisation.

2.4.6 Redundancy of information

Nonaka and Takeuchi (1995) also touch on the subject of “redundancy of information”. Turner and Keegan (2000) report on the redundancy in organisations. Nonaka and Takeuchi (1995) define as a conscious or intentional overlapping of company information, business activity and managerial responsibilities. Redundancy helps to create a common cognitive ground and thus encourages sharing of knowledge and therefore the transfer of tacit knowledge. It also reduces the impact of managerial hierarchy that tends to limit information sharing between hierarchical levels. (One can also add that redundancy of information also applies to the so-called “working in silos”, where one department in a company does not liaise sufficiently with others.) Redundancy acts as a vehicle for problem identification and solving, as well as for knowledge creation which follows procedures that are different from specified official organisational structures.

Redundancy also spreads explicit knowledge through an organisation so that it can be internalised (Nonaka and Takeuchi, 1995, p.14). Nonaka explains how redundancy increased the speed of product development where there are less strict departmental boundaries in a company and even interaction with external parties such as suppliers and customers. A product (especially when developing new products) works as a trigger to articulate tacit knowledge.

Turner and Keegan (2000, pp.131-148) report on organisational redundancy in a project-based organisation and noted that redundancy and slack are important in fostering innovation. Organisational flexibility is required, because without redundancy systems are fixed and static. Organisational redundancy causes flexibility and creates a favourable environment for the flow and sharing of knowledge. This ties into the following section on organisational knowledge.

Nonaka (1994, p.27) sums up the process of organisational knowledge creation as depicted in **Figure 2.6.**

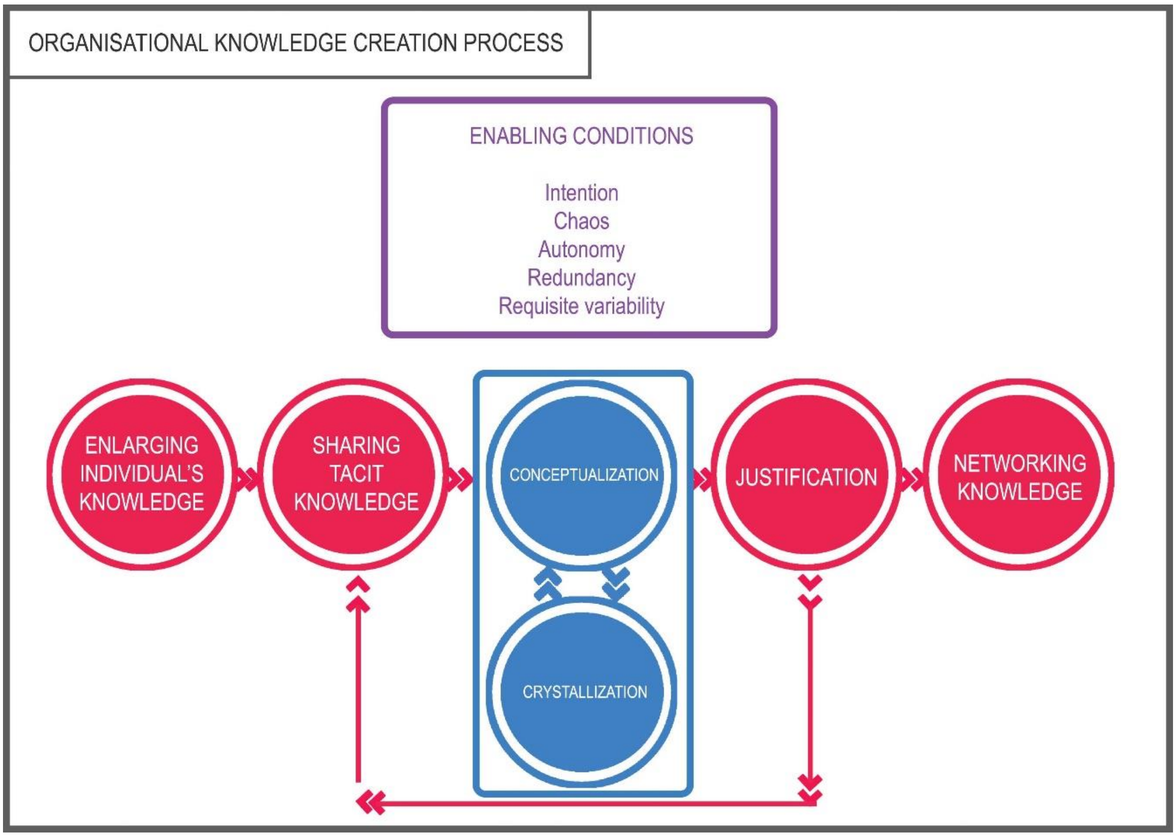

Figure 2.6 Organisational knowledge creation process

Nonaka (1994, p.27).

In the business organisation, middle managers can play a pivotal role in synthesising tacit knowledge of both frontline and top management, making it explicit and incorporating the knowledge of new technologies and products. Middle managers mediate between “what is” (front line employees’ knowledge) and “what ought to be” (top managers’ vision).

This dichotomy between the two perspectives creates tension and in the resolution of the tension, a basis is formed for knowledge creation. Middle managers are in the best position to mediate and are the true knowledge engineers of the knowledge-creating organisations. Nonaka (1994) describes this management form as “middle-up-down” management and how it benefits the process of organisational knowledge creation. This constitutes organisational learning – active communities of practice combine routine job dimensions of everyday activities with active learning and innovation (Nonaka, 1994, p.34). According to Stuhlman (2010, p.6), “Knowledge creation is the process that results in new knowledge or organises current knowledge in new ways making techniques to use existing knowledge.

Once knowledge is created, the organisation has a knowledge flow, which is the way knowledge travels, grows and is stored and retrieved.

Knowledge flows:

a) “Up and down from management;
b) Within circles of sharing (such as shared interests between staff performing similar or complementary roles);
c) Through planning, investigation, and training; or
d) Through common sources such as books, reports, data bases or knowledge bases.”

The model depicted in **Figure 2.6** is of significance in this research since it describes processes of knowledge creation. In the preceding sections, in summary, the following significant aspects of knowledge were established:

- That a credible model for knowledge creation exists, describing the various modes of knowledge creation. (Nonaka and Takeuchi model as augmented by Harsh for inclusion of knowledge reuse.)
- That organisations play very important roles in amplification and sharing of knowledge and the conversion of knowledge from one form to another.
- The organisational form should be flexible and the structure should foster knowledge creation.
- Middle management plays a pivotal role in knowledge management in an organisation.
- Redundancy of information provides a vehicle for problem identification and knowledge creation.

When developing the logic base, all the knowledge creation processes will have to be taken into consideration. The strengths and shortcomings of different processes under different circumstances have to be understood. This also relates to business processes in the civil engineering environment.

2.4.7 Sense-making

Sense-making is a subject that looks at the components and human attributes that influence the outcome of a process for the development of understanding a situation.

When a person or organisation encounters a notable event or surprise, the natural reaction is to analyse the preceding events and circumstances leading up to the event. (The surprise or unusual event can also be seen as a contradiction to what was expected or planned.)

Weick (1995, p.11) states that "People start with an outcome at hand, a verdict, a choice, and then render the outcome sensible by constructing a plausible story that produced it. A crucial property of sense-making is that human situations are progressively clarified, but this clarification often works in reverse. It is less often the case that an outcome fulfils some prior definition of the situation and more often the case that an outcome develops that prior definition."

Weick (1995, pp.17-18) describes that there are at least seven distinguishing characteristics "that set sense-making apart from other explanatory processes such as understanding, interpretation, and attribution.

Sense-making is understood as a process that is:

- "Grounded in identity construction
- Retrospective
- Enactive of sensible environments
- Social
- Ongoing
- Focused on and driven by extracted cues
- Driven by plausibility rather than accuracy."

When a story is told, or an account is given of certain experiences, the audience or reader naturally wishes to make sense of specific events. The sense-making process is however, highly dependent on the person or his or her environment. By introducing certain stimuli, thought processes are influenced and can be more productive or innovative.

In the earlier Cynefin framework (or model), discussed in the following section, a emphases is placed upon the factual account of events and cause-and-effect relationships are emphasised. In the updated Cynefin model, the emphasis shifted to the handling of chaos and complexity. In Weick's model, the emphasis is placed upon retrospective events and on plausible explanations rather than facts.

According to Browning and Boudès (2005), there is considerable overlap between the Weikian and Cynefin models. (Based on the earlier Cynefin model.)

When documenting experience in a knowledge base, it is important to realise that there were certain processes or perceived processes that led to the compilation of the experiences. The presentation of the experience is highly influenced by the sense which the audience or reader makes out of the presentation. By understanding more of the processes related to sense-making, better guidance can be given in the logic base to stimulate thinking processes.

Sense-making as described in the Cynefin Model and in Weick's model leads to actions. As described by Weick, Sutcliffe and Obstfeld (2005, p.409), "Explicit efforts at sense-making tend to occur when the current state of the world is perceived to be different from the expected state of the world." This means that sense-making is activated by the question, "same or different?" If it feels different, a situation of a discrepancy is experienced. An expectation of continuity is breached. The response to the situation demands "continued redrafting of an emergent story so that it becomes more comprehensive, incorporates more of the observed data and is more resilient in the face of criticism" (Weick, Sutcliffe and Obstfeld, 2005, pp.414-415). When considering the exposition of Weick's work, sense-making has much in common with problem-solving. Situations are identified, and "bracketed" and attention is then given to a particularly observed matter. In the process of formulating a response to the bracketed situation, actions are taken. These actions equate to the formulation of solutions to the particular problem, solving a particular contradiction. As described in the Cynefin Framework, there need not be any clear cause-and-effect relationships. In this regard, one can state that problem-solving is not an exact science. It is more the process of solving problems that are important and not necessarily the outcomes. Problem-solving can also be seen as a continuous process with a multitude of outcomes and various domains. "Problems must be bracketed from an amorphous stream of experience and be labelled as relevant before ongoing action can be focused on them" (Weick, Sutcliffe and Obstfeld, 2005, p.415).

2.4.8 Sense-making: The Cynefin Framework

Kurtz and Snowden (2003) developed the so-called "Cynefin framework". The framework is derived from research on "the use of narrative and complexity theory in organisational knowledge exchange, decision making, strategy, and policy-making. […] The application of the framework lies in group sense-making and discourse" (Kurtz and Snowden, 2003, p.462). The Cynefin framework developed from work in knowledge management, cultural change and community dynamics. It is a decision and analytical framework used, among other things for decision theory, for knowledge management, IT (Information Technology) design and project management. It expanded into product development, market creation and branding and, in recent years, in the area of national and organisational strategy.

The complexities of the world and the interaction of organisations with this global, fast-changing world cannot be adequately dealt with by simple information processing and simplistic models. Furthermore, vast differences in individual perspectives further complicate matters. The Cynefin framework endeavours to establish a dynamic framework to make sense of these complexities. It is against this background and application that the process of "sense-making" is considered relevant to this research as it constitutes a method of knowledge creation, whereby complexities in data, information and knowledge elements are resolved to provide focused information and knowledge.

An interesting approach was used by Kurtz and Snowden (2003, p.462) in developing the Cynefin framework by challenging three basic assumptions. The assumptions are seen to form constraints about the body of data, information and knowledge. When these constraints are relaxed, the context changes and provides new insights into the available knowledge. The relaxation of the constraints also assists in sense-making by moving from a state of disorder to order. The assumptions are as follows:

a) "The assumption of order: that there are underlying relationships between cause and effect in human interactions and markets, which are capable of discovery and empirical verification."

b) "The assumption of rational choice: that faced with a choice, human actors will make a 'rational' decision based only upon minimizing pain and maximizing pleasure."

c) "The assumption of intentional capability: that the acquisition of capability indicates an intention to use the capability, and that actions from competitors, populations, nation states, communities, or whatever collective identity are under consideration are the result of intentional behaviour" (Kurtz and Snowden, 2003, p.462).

(In a paper by Kurtz and Snowden [2003], it is contended that although these assumptions are true within some contexts, they are not universally true, although the tools and techniques used assume they are.) It is by the challenging of the constraints that people can see things in different perspectives, thereby opening their thoughts to see opportunities for change. (In sections below comments are given on the above challenges.) It is foremost necessary to discuss the Cynefin framework in more detail.

The original Cynefin framework is summarised in Fi**gure 2.7**, and further explanations are given of the various domains that are shown in each of the four blocks of the square. It must be noted that this framework was significantly changed recently and further discussions on the new models are part of the discussion on the original model.

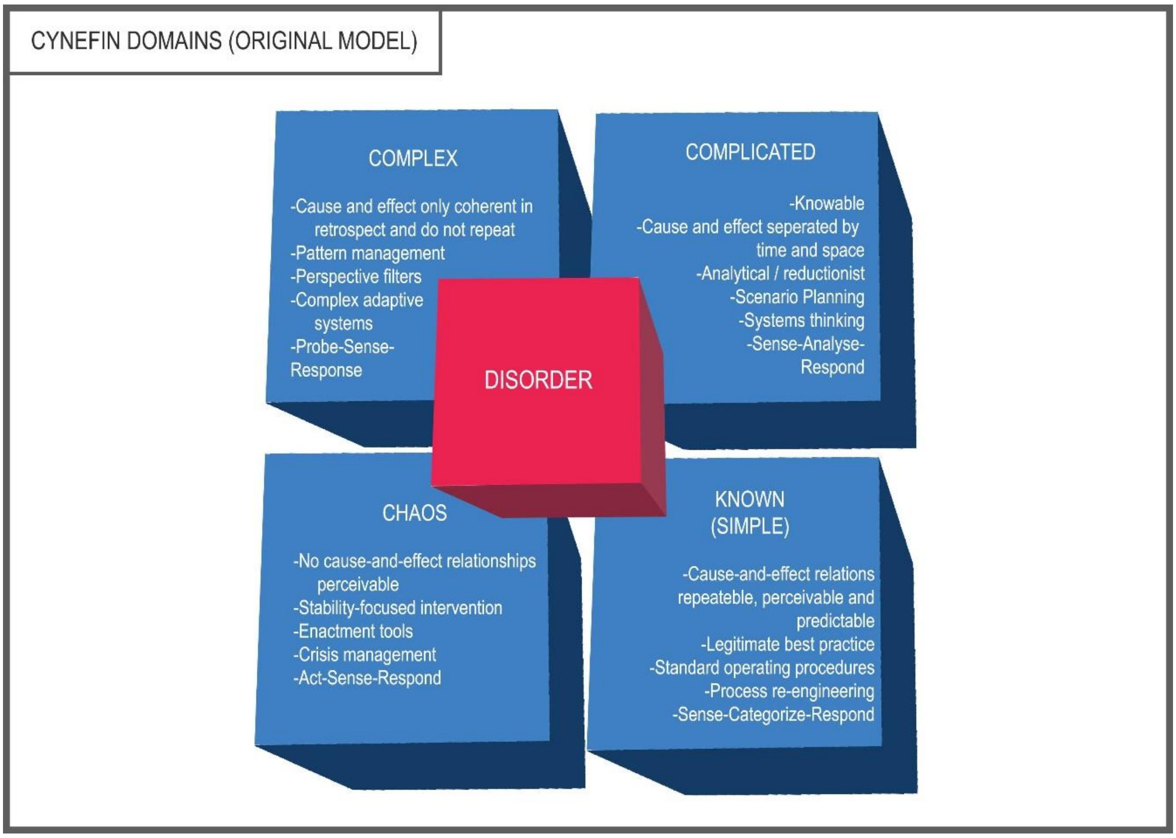

Figure 2.7 Cynefin Domains (original model)

(after Kurtz and Snowden, 2003).

Referring to **Figure 2.7**, the Cynefin framework describes four domains. Users can make use of the framework to break out of old ways of thinking, and formulate new constructs to make sense out of a wide range of unexpected or unspecified problems. Its main use is in a group context. The different domains describe a dynamic situation where the attributes in the various quadrants dynamically describe situations. There is not necessarily convergence to one or another quadrant. The value of the framework is “not so much in logical arguments or empirical verifications as in its effect on the sense-making and decision-making capabilities of those who use it” (Kurtz and Snowden, 2003, p.468).

In the development of the Cynefin framework, a basic distinction was made between *unordered* and *ordered*. The unordered was placed on the left-hand side and divided into two domains, *complex* and *chaos*. The ordered domain was placed on the right-hand side and divided into a *knowable* or *complex* domain and a *known* or *simple* domain. Amongst all four domains is the domain of disorder where situations that do not fit any other domain, are placed. The five domains are depicted in **Figure 2.7**, which is the original Cynefin framework.

However, more and more people started to use complexity thinking, and there is a growing popularity of the application of the Cynefin framework (Snowden, 2013d). Snowden remarked that he found that it was no longer enough just to say whether the world is complex, complicated, simple or chaotic. Over the last few years, Snowden developed a series of new domain models for each of the original Cynefin domains. The revised form is very similar to the original model, but each domain was expanded and now consists of 3x3 matrices designed to create something more familiar for managers. Each domain’s matrix comprises two scalable axes, thereby depicting a total of nine “states” or situational attributes or characteristics. Each state is given a metaphorical or descriptive name and written in each “box”. Instead of depicting the model as it originally was, in a square-type arrangement, Snowden placed the domains in a linear model. In addition, he turned each matrix through 45 degrees. This model in shown in colour in **Figure 2.8**. (An image was taken from a slide by Snowden; from the website of Cognitive Edge, Snowden [2013d] depicts the latest version of the presentation of the Cynefin framework.)

A detailed explanation of the Cynefin Model is beyond the scope of this study. However, explanations are given of the model in **Appendix A**. There are also some very important perspectives, especially regarding the methodology that is of interest in this study.

The framework starts on the left-hand side with the chaotic domain on the left-hand side of the diagram and then proceeds from left to right from the complex, through to the complicated and the simple domains.

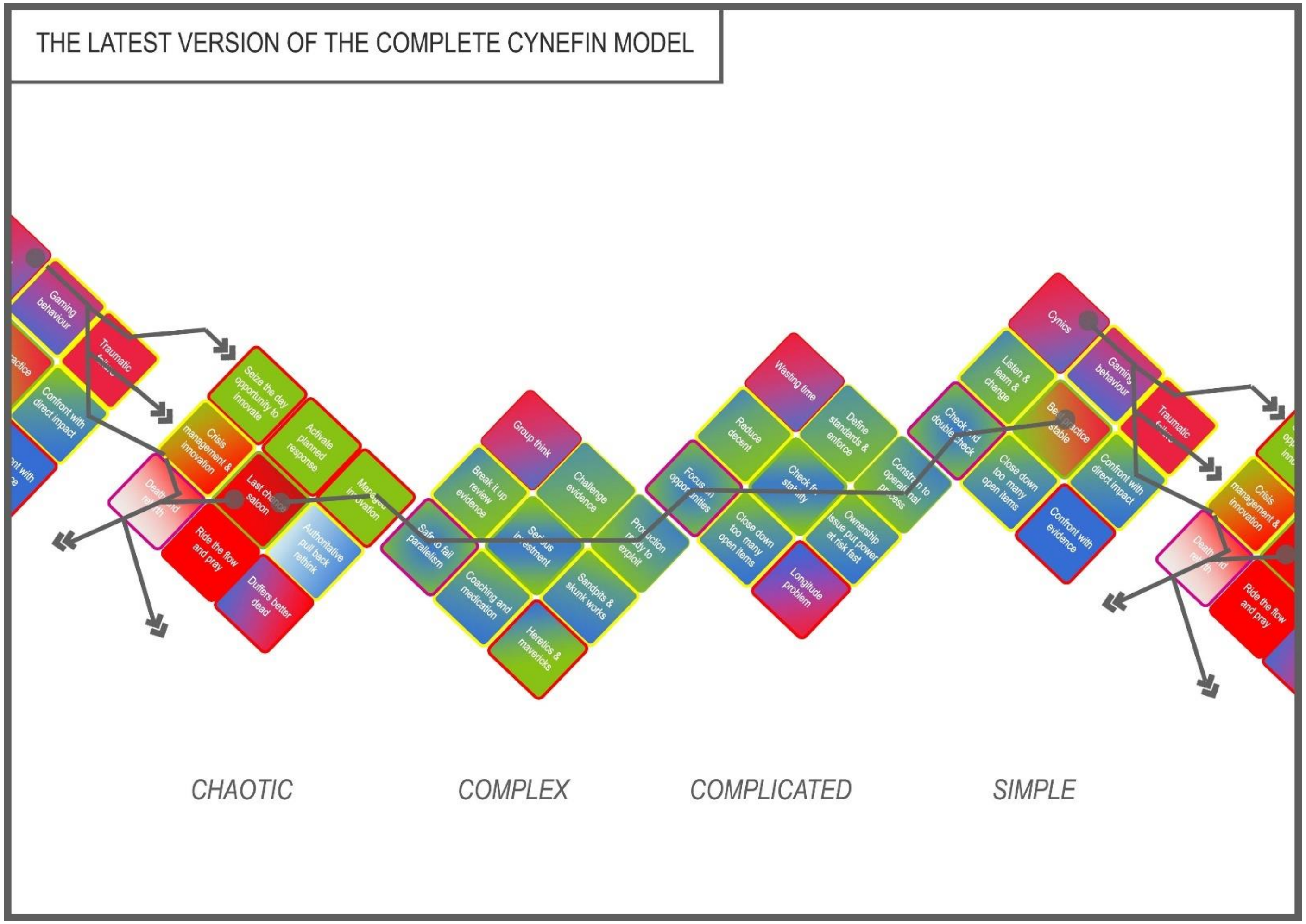

Figure 2.8 The latest version of the complete Cynefin Model

(Snowden, 2013d).

The new version of the model is considerably more elaborate that the earlier model. An important addition is the colour coding as shown in **Figure 2.8**. The red colour denotes “warning”, blue denotes “management action”, and green to say “use it, there could be something good in it” (Snowden, 2013a and 2013d).

A diagonal line (white line in **Figure 2.8**) goes from the bottom left to the upper right; or in the 45-degree version, from left to right. This line is called the “coherence line”. The idea is that in group workshop sessions participation of people can cause thoughts and opinions to run in many directions, but in facilitating, one should be on the coherence line at all times and if it isn’t the case, steps should be taken to return to it. The important principle employed by Snowden is that two axes with scaled attributes are defined for the matrix. An ideal path (the diagonal line of coherence) is defined. Movement between the “boxes” or different states or conditions is moderated by the attributes defined on the axes. This model is dynamic and, depending on the situation, the weights of the attributes can change at any time and therefore the situational state moves to other boxes within the domain or even into other domains. This movement from one state to another (or said to move from one box to another) can be seen against its relative position to the coherence line – which is the preferred place to be. Snowden explains this moderation to be analogous to a number of people sitting around a table and each holding a magnet of different strength, controlling the movements of a steel ball on the table. The influence of each magnet is different. The influences of the magnets are determined by the proximity of each magnet to the ball. These factors control where the ball would be rolling.

2.4.9 Comments on the Cynefin Model

a) Comments on basic assumptions

Referring to the above three basic assumptions, the following comments are given:

The assumptions are not explicitly mentioned again in any of Snowden’s expositions of his models. However, the first assumption is indirectly challenged by the description of the domains, in that causes and effects are not recognisable or are completely absent. The second and third assumptions are indirectly challenged by the fact that people would preferably make choices to suit their own agendas, and this is best demonstrated in the model in the complex domain where people would follow group thinking (way of the least resistance) and further by the box of “Heretics” and “Mavericks” where a small group of people know or believe they are right and intentionally drive concepts and capabilities that they intend to use. The revised model therefore adequately challenges these assumptions and allow sufficiently for the assumptions to be seen as correct, or to discard the assumptions. The dynamics of the model is therefore sufficiently flexible to allow for most situations and need not be *right* or *wrong*. It adapts to the prevailing situation at any point in time.

b) Further comments on the Cynefin Model

i) The Cynefin Model finds application where problem-solving and decision making is required. (The Cynefin Model has both knowledge-creation and problem-solving aspects.)

ii) The most valuable part of the Cynefin Model lies in complex and chaotic domains (Graves, 2012).

iii) The Cynefin Model provides the method and tools "to create the capability that can adapt and then constantly exapt to meet changing and shifting while maintaining coherence." It provides the scaffolding for others to create their own ideas. The purpose of scaffolding is to support a structure while it is built, but then to remove it, or incorporate it into the structure itself (Snowden, 2013b).

iv) Snowden developed a method (software driven, "Sensemaker®"), employing large numbers of people ("sensor networks") to gather information through micro-narratives. Participants signify their own stories and therefore it does not need further verification. This method replaces traditional surveys. A large volume of narratives is gathered on, say a weekly basis, and almost instantaneously turned into useful information. Fitness graphs are then generated to reflect the information in a graphic way (Snowden, 2009).

The Cynefin framework provides useful insights into knowledge creation in a group context through a sense-making process. These concepts will be helpful in the development of the proposed logic base. Civil engineering is an applied science, but it ultimately serves people. The environment (physical, social, economic, financial, political, cultural) determines what and how things are done. This immediately suggests that the work in civil engineering (not excluding other engineering disciplines and other applied sciences) is of a complex and complicated nature. The application of the Cynefin Model is therefore very relevant in this study. (The drafting of complex concept maps can best be done in a group context.)

2.4.10 Comments on the Nonaka and Takeuchi model (SECI Model)

(and on the Cynefin framework and the synergy between the models)

The Nonaka and Tacheuchi (also referred to as the SECI Model) was discussed in the earlier sections (refer to section 2.4.4). The importance of the model lies in the knowledge conversion processes and the interplay between tacit and explicit knowledge.

The SECI Model describes the processes of knowledge conversion:

a) From tacit knowledge to tacit knowledge;
b) From explicit to explicit;
c) From tacit to explicit;
d) From explicit to tacit.

Although each of the conversion modes is capable of generating knowledge, it is rather the continuous interaction among the four modes that create knowledge. As soon as socialisation takes place, for instance, people share their experiences and perspectives (as is also the case with the Cynefin framework). Nonaka (1994, p.20) states that "Concepts formed by teams can be combined with existing data and external knowledge in search of more concrete and shareable specifications." By the same token, when any qualitative research, case-study research, action research, descriptive research and exploratory research are done, concepts would trigger shifts between modes of knowledge conversion (Nonaka, 1994, p.20). The value of the SECI Model is also to act as a basis for connecting experience to either tacit of explicit knowledge. As described in sections above, prior knowledge transforms data into information, and information into knowledge. The contents of a logic base should provide the facility to record the basic knowledge concerning a subject. Basic knowledge for this study means a fundamental or minimum knowledge needed about a subject to enable building on further knowledge. This basic knowledge is, in fact, a foundation for making essential knowledge explicit for the population of a knowledge base. This implies that there should be a connecting framework of prior knowledge to facilitate subsequent knowledge creation. An ontology of the subject domain serves as a basis for building the body of knowledge.

This is illustrated when an experienced structural engineer, working with structural steel, says that he learned by experience that the "turn-of-the-nut-method" is a very reliable method to ensure that structural bolts are properly fastened. Most structural engineers will have knowledge of exactly what this term means; however, most non-structural engineers may not recognise this term. If one now considers a logic base, it is essential to have a brief description of the principles of bolt torqueing (making the information explicit) for those who do not know the term yet. Also, by recording the basic operating principles of this method, a trigger is provided to the user of the logic base to critically re-think the basis of this torqueing method. This, together with tacit knowledge of the user, can trigger new thoughts which could lead to the creation of new knowledge. The process of transfer of tacit knowledge to explicit knowledge is also described in **Figure 2.2**, wherein the metaphor is used to resolve contradictions through analogy. Tacit concepts can be transferred to explicit concepts through consistent logic. Through the above basics of a subject and fundamental principles, a firm basis is formed for the connection of experience to logic and the creation of knowledge. (An example is where the “turn-of-the-nut-method” is applied, construction workers started to put marks on the bolts and the adjacent steel to show that the nuts have been correctly turned. These marks served as torque indicators. Development of torque indicators subsequently took place whereby special plastic washers were developed that changed colour when the required torque is applied. These devices are referred to as Direct Tension Indicators or “DTIs”.)

When one considers the Cynefin framework, the various quadrants or domain matrices provide a dynamic framework to make sense of complexities. Sense-making domains are presented as the “known”, “knowable”, “complex”, “chaos” and “disorder” domains. The author contends that the more tacit knowledge one has about a subject, the more “known” or “knowable” a problem or unfamiliar situation will become. However, this does not mean that certain matters or aspects of the problem or situation would not still be in the “disorder”, “chaos”, “complex” or “knowable” domains. It just means that the person with substantial tacit knowledge may understand quicker and more of the characteristics of the subject matter, than a person with less tacit knowledge. Sense-making further defines the level or status of knowledge about the particular topic. It serves to identify where shortcomings or gaps are present in the knowledge. Some knowledge, for instance, can be seen to be in the “chaotic” domain which could tell that there are shortcomings in the knowledge which may or may not be resolvable. The core of sense-making is to enable the definition of some form of logic of various attributes. The logic is aimed at developing (even if it is only for a portion of, or only in some of the attributes in question) some form of pattern, repeatability or predictability. In the chaos domain, one sees a dynamic situation appearing where the actions taken are described as “act-sense-respond” and in the chaos domain as “probe-sense-respond”. As new ideas are formed, the Cynefin frameworks provide a line of coherence to guide thinking or responses to proceed to a domain of greater order.

Sense-making is highly dependent on the “state of the world” and one’s perceptions. Perceptions can be rooted in one’s tacit knowledge environment where prior knowledge and experiences shaped the way one understands and interpret things. The contention is therefore that there exists a synergy between the SEIC Model and the Cynefin framework, in that the knowledge conversion processes depicted in the SEIC Model directly influences the domain within which complexities in data, information and knowledge elements are resolved to provide focused information and knowledge. The Cynefin framework aims at resolving contradictions or constraints that pre-exist in one's tacit domain. It is, therefore, important to note that not all the knowledge residing in one's tacit domain is necessarily complete or even correct. Experience is just a body of knowledge that pertains to specific circumstances and contributes to the solving of a particular problem. The matter could be much more complicated when more variables are present, and therefore further iterations of sense making are required to build upon prior knowledge.

Furthermore, in the Cynefin framework, the relaxation of constraints results in context changes and movement from one knowledge domain to another. This is described by Kurtz and Snowden (2003, p.462).

Looking therefore at the synergy between the SECI Model and the Cynefin framework, the conclusion is that both the SECI Model and the Cynefin framework describe knowledge-conversion processes from the tacit to the explicit domains. The Cynefin framework serves as a tool to establish what the status of the knowledge is, i.e., in which domain the knowledge lies and establish where contradictions and constraints are present in relationships amongst elements. It also forms the seeds for new ideas and serves the purpose of knowledge creation (progressing along the line of coherence). This provides a basis for going forward to search for new knowledge. The Cynefin framework can also be seen as a dynamic, continued process. As constraints or contradictions are resolved, new ones appear and the investigations or dynamics continue until a point is reached where a decision is taken to stop the iterative process. The Cynefin framework integrates with concept diagrams where ideas or concepts are mapped and relationships studied. (Concepts change, and dynamically, through the resolution of problems and constraints, migrate to the line of coherence. This process is discussed in Chapters 4 and 5 of this study. There is also considerable synergy between the SECI model, the Cynefin framework, TRIZ and the Theory of Constraints (TOC) and is discussed in subsequent sections.)

Summarising, the following diagram, **Figure 2.9** is constructed, synthesising the thoughts up to this point.

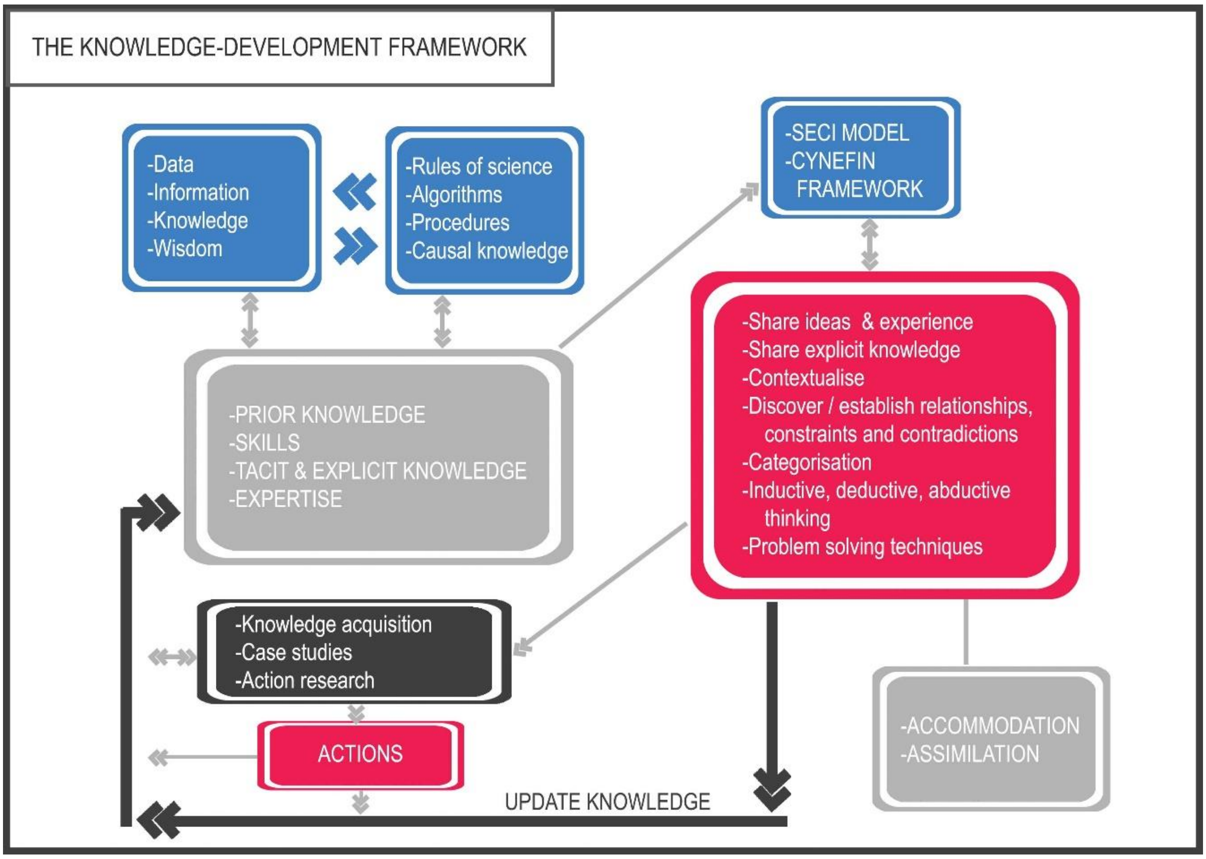

Figure 2.9 The knowledge-development framework

The **Figure 2.9** depicts the synergy of knowledge components. “Actions” are based on knowledge. (In earlier definitions of knowledge where knowledge is defined as “the capacity to act”.) In **Figure 2.9**, “Actions” determine the outcomes of prior knowledge and knowledge acquisition by way of several means, including case studies and action research. Prior knowledge, skills and expertise could be tacit, explicit or a combination of these and are found in rules, algorithms, procedures and causal knowledge. Apart from these data, information, knowledge and wisdom are attributes which support the prior knowledge. Actions performed and knowledge acquired informs knowledge creation as depicted by the elements on the right-hand side of **Figure 2.9**. This model endeavours to summarise and depict the interplay in the knowledge environment.

The processes of knowledge conversion define the way knowledge is transferred to individuals. These processes are described in the preceding sections.

These processes answers sub-sub-research question a) (iv).

2.5 APPROACHES AND PROCESSES

2.5.1 Organisations – how knowledge is handled

Zack (1999, p.1) expresses an opinion that, while the popular press calls for effectively managing knowledge, almost no research has been done regarding "*how* to do it".

"It (knowledge) originates and is applied in the mind of the knower" (Davenport and Prusak, 2000, p.6).

In organisations, knowledge gets embedded not only in documents and repositories but also in organisational routines, business processes and practices.

Tobin (2006, p.27, Table 2.7) gives a useful consolidated list of knowledge-management practices in a large organisation. (Part of knowledge-creation processes.)

The following table was adapted from Tobin (2006):

Table 2.2 Consolidated list of knowledge management practices

After-action review/retrospect	Exit interviews	Learning centres/meeting rooms
	Expert networks	Libraries
Benchmarking	Expert forums	Measurement systems
Brainstorming	Innovation workshops	Mentoring
Business intelligence	Internal networks of knowledge workers	Office layout
Centre of excellence	Internal surveys	Peer assists
Coaching (on-the-job training)	Knowledge audit	Process modelling
Communities of practice	Knowledge conference	Scenario planning
Competitive intelligence	Knowledge education/training (off the job)	Stories and storytelling
Discussion forums	education/training (of the job)	Oral, written, drama, combined
Embedding knowledge into processes	Knowledge fair/exchange	Suggestion schemes
Environmental scanning	Knowledge workshops	Surveys (internal and external)
Establishing new knowledge roles	Learn before, during and after	Standards

Specifications	Learning by doing	Codes of Practice
Learning from incidents	Work instructions	Gap analysis
Guidelines	Incident reports	Standard operating procedures
	Legal reviews	

Many of the elements in the table are interrelated, interconnected and interdependent. Through the actions listed in the above table, corporations collect multitudes of raw data and information that, when given context, can become useful knowledge, but much can be lost due to poor organisation and disconnected storage methods. The vast flow of information must, however, be conducted and connected and given strategic content, and be integrated with (normal) business processes for it to become useful (Ramhorst, 2001). Each of the above knowledge management practices takes place in a different context.

For example, incident reporting can contain issues that would find its way into standards specifications and standard operating procedures. The same information may be presented in different contexts in overlapping situations.

These practices may contain elements that can represent conflict constraints or paradoxes. The drive to resolve these can lead to the creation of new knowledge. This is dealt with in subsequent sections. (Refer to problem-solving techniques.)

Knowledge management integrates knowledge, minimises knowledge loss and fills knowledge gaps on a continuous basis or throughout the duration of a project, if a project approach is followed. However, knowledge management through social networks is by far the preferred way of obtaining knowledge for most engineers. Contacting people in a social network is easier done than consulting an inanimate database or filing cabinet (Cross and Israelit, 2000). Coordinating information flow for decision making for project success is necessary (Knowledge management can be considered as both an object and a process.) (Zack, 1999).

When considering the way that individuals and organisations go about the management of knowledge, it is important to know how knowledge is reused. It is contended that the analysis of how knowledge is acquired and reused will lead one to an understanding of the context and content of knowledge, which would, in turn, lead to suggestions of structuring knowledge with the view of developing the logic base.

In this respect, reference is made to Lin, Chi and Hsieh (2012, pp.349-360) where a novel way of Information Retrieval (IR) was researched and reported on. It was found that general-purpose search engines do not deliver satisfactory results in domain-specific documents. Their approach is to partition a long document or a document with multi-topics into smaller passages as a base unit for search engines to retrieve target information more precisely and efficiently. When considering the list of knowledge-management practices in **Table 2.2**, opportunities exist to consolidate and streamline information and then to apply the passage partitioning as suggested by Lin, Chi and Hsieh (2012, pp.249-360).

The preceding section provides in part the answer to sub-sub-research question b) i) and ii). The final part of the sub-sub-research question is provided in the section on knowledge representation later in this chapter.

2.5.2 The reuse of knowledge

As described in sections above, knowledge is primarily developed within an individual in various ways. This knowledge resides in the tacit dimension and can only become useful to others when the knowledge becomes external to the person and enters the explicit domain and therefore is made independent of the person. The purpose is, therefore, to make knowledge explicit and to put it in a storable way for reuse by others (Neve, 2003; Snowden, 2004). Knowledge reuse is considered to be as important as the creation of knowledge. The reuse is also dependent on how the created knowledge is subsequently managed. Storage of the knowledge in all its numerous forms and how to recover it are of prime concern. (Refer to Section 2.6 where knowledge acquisition is discussed.) The development of a logic base is considered to be a step in the direction of establishing a basis for knowledge reuse.

Knowledge reuse was not originally defined as separate from knowledge creation. Harsh (2009, p.1) makes the statement that “It is beyond doubt that Nonaka’s (1994) theory of organisational knowledge creation is the most important theory in knowledge management. However, the concept of explicit reusable knowledge and its consequences are absent in the theory.” The deductions are made that it was implied by the Nonaka and Takeuchi model, that all created knowledge could in fact be reusable. However, the contexts thereof play a pivotal role. Harsh (2009) suggested that knowledge reuse could be seen as a part of knowledge creation but as a separate aspect thereof. Harsh (2009, p.2) states that “during the (one knowledge form to another form) knowledge transformation process, part of the knowledge is also reusable knowledge. Knowledge reusability is possible for both explicit and tacit knowledge. If we consider such knowledge as independent knowledge like other knowledge, then a separate axis is required to present the knowledge reusability because it fulfils the condition of orthogonally.” Harsh (2009) developed a model, based upon the original Nonaka and Takeuchi model whereby a third axis is put on the diagram, referred to as the *upper spiral* and can be seen in **Figure 2.10**. As illustrated in the diagram, one of the axes represents time. The diagram shows that with time, the interaction between tacit and explicit knowledge increases, thereby creating knowledge. As knowledge creation goes through the various phases of socialisation, externalisation, combination and internalisation, reusability increases and describes a solid cone in the third dimension above the two-dimensional plane as depicted in the original Nonaka and Takeuchi model. The volume of the solid cone increases due to the increase in overall knowledge and reusability. The more reusable knowledge is, the faster the process of knowledge conversion will be.

The above is depicted graphically in **Figure 2.10**.

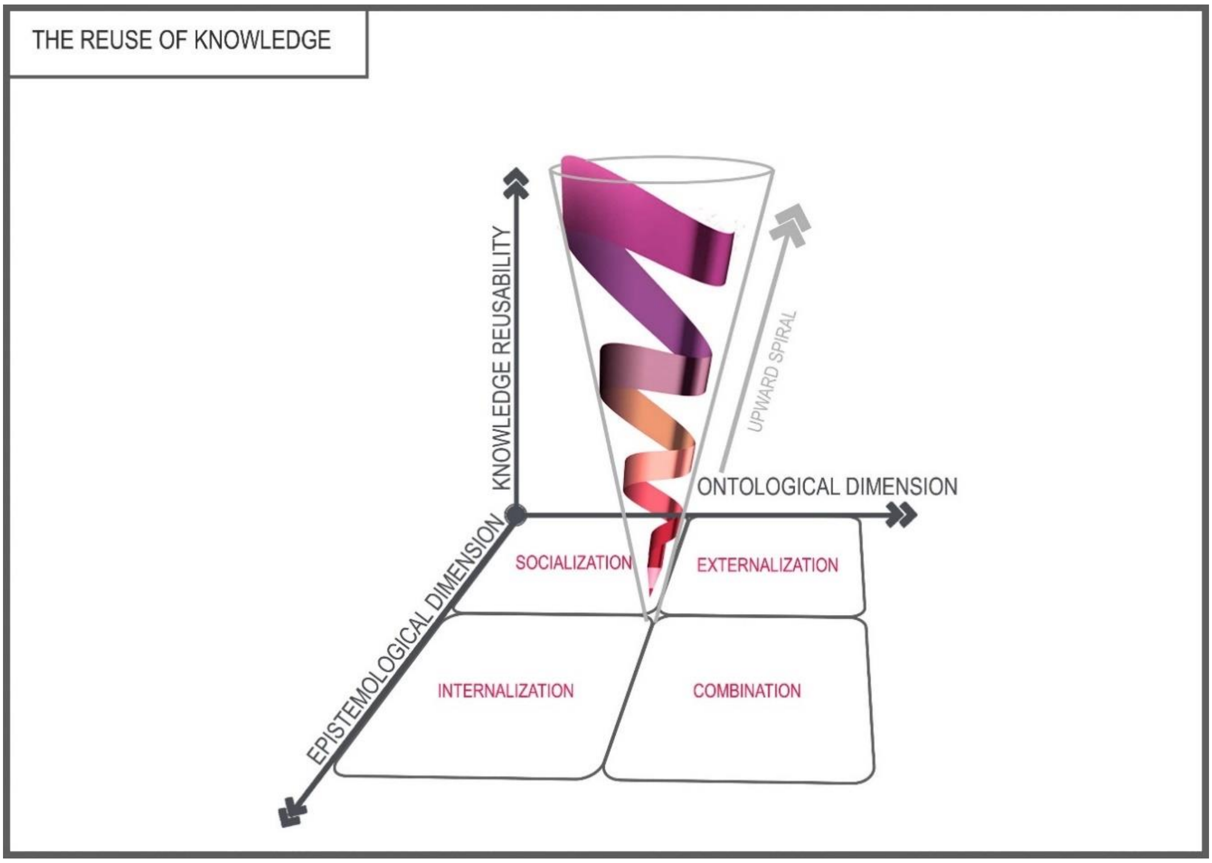

Figure 2.10 The reuse of knowledge (adapted after Harsh, 2009)

Harsh (2009, p.3), in referring to the Nonaka and Takeuchi model, argues that as knowledge reusability increases, knowledge increases (from one form to another).
Knowledge reuse is also dependent on the purpose and the situation of the end-user. Markus (2001) identifies four distinct types of knowledge-reuse situations. These are:

a) Shared work producers that produce knowledge that they can later use.

b) Shared work practitioners who reuse each other's knowledge contributions.

c) Expertise-seeking novices.

d) Secondary knowledge miners.

Each person that reuses knowledge has different requirements for knowledge repositories. The methods of how repositories are created will determine if these repositories would meet the needs of the different types of reusers.

Because of the peculiar nature of context, situations and circumstances, the reuse of knowledge is a particularly big challenge. Bennet and Bennet (2008, p.13) conclude that "for the sustainability in our communities we must be able to find or have available robust sources of information following through (i) facilitating the continuous flow of information needed for improvement and (ii) developing a process to assimilate, integrate and apply the knowledge we need."

Koenig (2002) notes that there are three stages in knowledge management. These are:

- **Stage 1**: Organisations realised that their stock in trade was information and knowledge. Information Technology (IT) and particularly the internet play a big role. "The hallmark phrase of stage 1 was first, *best practices*, to be replaced by the more politic lessons learned" (Koenig, 2002, p.2).

- **Stage 2**: Human and cultural dimensions were added. Learning organisations (Senge, 2000) and knowledge-creating companies (Nonaka, 1994) were important developments. "The hallmark phrase of stage 2 was *communities of practice*" (Koenig, 2002, p.2).

- **Stage 3**: The importance of content comes to the front. This refers to the importance of retrievability and therefore of the arrangement, description and structure of the content. Taxonomies emerge as major topics. The hallmark phrases for the third stage are "*content management* (or enterprise content management) and *taxonomies*" (Koenig, 2002, p.3).

The statements made by Koenig (2002) in Stage 2, was that "knowledge management is no good if they don't use it". In the third stage, the statement is, "it is no good if they try and use it and can't find it". The trends in the third stage are that information specialists such as librarians and taxonomists (and ontologists) should spearhead developments in knowledge management.

Another model, the so-called Mitre Model (Maybury, 2003), is also described in the literature. This model is essentially a management model that describes how the Mitre Corporation structured its knowledge management in the corporation. It discusses two dimensions, the first being the activities that are crucial for knowledge creation and innovation. These refer to activities such as knowledge exchange, capture, reuse and internalisation. The second dimension represents elements that will influence knowledge creation activities such as corporate knowledge management strategies and metrics, policies, content-process technology and culture. What is interesting about this model, is that people-to-people interaction forms the basis of knowledge creation (socialisation). This is achieved by the establishment of speciality groups. Knowledge is then captured, which forms knowledge assets (externalisation) capable of reuse. Since this model is focused on the implementation of knowledge management in an organisation and does not consider fundamentals on knowledge creation and reuse, it is not considered any further in this research.

The conclusions from the above are:

a) That knowledge reuse can be considered as a separate and specific element of knowledge management.
b) That content and context management is of increasing importance.
c) Taxonomies (and ontologies) will have to be developed according to the needs of the reusers.
d) Apart from the “technical” aspects of knowledge management, organisational aspects will continue to play an important role in knowledge reuse.

In the development of the proposed logic base, the role of knowledge reuse is of prime importance. The development of content and taxonomies (and ontologies as will be seen in subsequent sections) is highly relevant. (As can also be seen from research questions in the previous chapter.)

These will be dealt with in greater detail in subsequent chapters.

The analysis and investigation that follows are aimed at the creation of engineering knowledge and at discovering the main drivers for a logic base.

2.5.3 Knowledge management and problem-solving

Several authors, such as Leonard and Sensiper 1998, Nonaka, 1994, Gray and Chan, 2000 indicate that knowledge creation and problem-solving are closely related. Leonard and Sensiper (1998, p.114) said that “The most common application of tacit knowing is to problem-solving […] A second application of tacit knowing is to framing problems." Itabashi-Campbell, Perelli and Wayne (2011) did a study on engineering problem-solving from an epistemological perspective. They stated that, to their knowledge, their study was the first to model the dynamics of knowledge creation in an engineering problem-solving context. Solving of a particular problem does not necessarily involve knowledge creation, as there could be existing solutions to problems, but the context may differ. However, when an existing solution is not at hand and a specific solution must be created to solve a problem, knowledge can then be said to have been created. Engineers are continuously faced with the need to identify and solve problems and constraints. This drive to find solutions stimulates knowledge creation. "One of the ways learning and knowledge creation may be prompted is by problem-solving" (Itabashi-Campbell, Perelli and Wayne, 2011, p.1). The goal of Itabashi-Campbell, Perelli and Wayne's study (2011, p.1) was to "generate a grounded theory about the way engineering problem-solving results in organisational learning and knowledge creation."

Gray and Chan (2000, p.3) published on the subject of "Integrating knowledge management practice through a problem-solving framework", and stated that "problem-solving therefore improves the stock of knowledge held by individuals in an organization, allowing the organization as a whole to adapt better to its environment."

Problem-solving and decision making are seen to be supportive of knowledge creation (Gray, 2001). Gray (2001) concludes as follows from his research: "This research demonstrates the relevance of problem-solving and decision-making theory in assessing the *purpose* of organizational knowledge management activities. The problem-solving process is the vehicle for connecting knowledge and performance; knowledge gains economic value when it is used to solve problems, explore opportunities and make decisions that improve performance."

Gray (2001) used the terms "problem solving" and "decision making" interchangeably as the basic concepts are regarded as roughly the same. For this research the same approach will be followed.

Knowledge is required to enable the solving of problems or to make decisions. The drive to obtain or to create knowledge (i.e., new knowledge and pre-existing knowledge) is stimulated by the need to solve a particular problem or to make a specific decision. Solving a problem involves the synthesis and application of particular knowledge on the subject which leads to the end resolution. This synthesis embodies experience which, in turn, updates knowledge. This is shown schematically in **Figure 2.11**. The figure shows that the increase in knowledge makes it possible to solve more problems or more complex problems that, in turn, increases knowledge, which in turn increases the ability to solve more problems. This can be seen as a never-ending process.

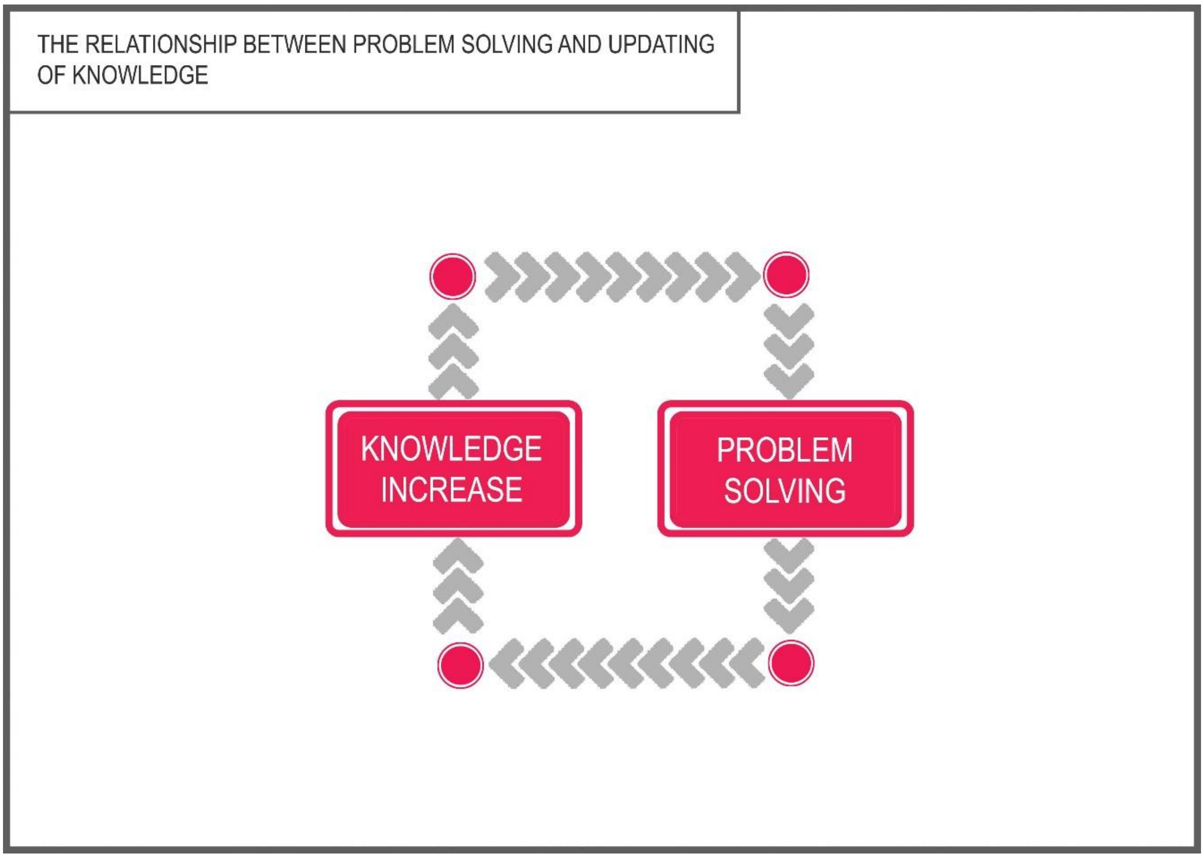

Figure 2.11 Problem-solving and updating of knowledge

In his research, Gray (2001, p.17) uncovered systematic connections between knowledge-management practices and decision theory. The research also underscores the importance of knowledge as a resource for organisational decision making and problem-solving processes.

Knowledge acquisition methods and problem-solving play important roles in knowledge creation and are discussed in greater detail in the sections below.

Knowledge-acquisition methods and problem-solving play important roles in knowledge creation and are discussed in greater detail in the sections below.

2.6 AN OVERVIEW OF KNOWLEDGE-ACQUISITION METHODS

Knowledge acquisition is one of the foundation stones for knowledge reuse and also for knowledge creation/problem-solving. The knowledge acquired by using the methods described below, seeds knowledge creation.

2.6.1 Case-based reasoning

a) Definition

Case-based reasoning has generated much interest since 1993 (Aamodt and Plaza, 1994). The basic process in case-based reasoning is that, when a new case is to be resolved, or a problem is to be solved, the knowledge from previous cases is retrieved and selectively reused to apply to the new case. This process assists with the identification of problems. Solutions are then suggested, tested and revised for application to the new case. After finding an appropriate solution, the solution is stored in a collection of cases where it updates the database for future use. Each time a problem is solved, the experience is retained, therefore adding to learning. The case-based reasoner is heavily dependent on the structure and content of its collected cases. The case memory has to be appropriately organised and indexed for effective retrieval and reuse. The case memory has to be suitably integrated into general domain knowledge.

b) Some examples of case-based reasoning

An auto mechanic who fixes an engine by recalling that another car exhibited similar symptoms is using case-based reasoning. A lawyer who advocates a particular outcome in a trial based on legal precedents or case history is using case-based reasoning. So, too, an engineer copying working elements of nature (practising biomimicry) is treating nature as a database of solutions to problems. Case-based reasoning is a prominent kind of analogy making.

2.6.2 Evidence-based management

Evidence-based management (and learning) means translating principles based on best (or most plausible) evidence into organisational practices (Rousseau, 2006). Evidence-based management is often used in the medical profession as a clinical-management tool. The outcome of a certain treatment under certain defined conditions defines knowledge that can be used for treating another patient under similar conditions.

This approach is highly relevant to this study since the outcomes of designs and specifications can be observed and tested for effectiveness. The designer can then learn from the outcomes to constructively add knowledge about the performance and compliance to the original design intent. (This approach reminds one of the Cynefin approaches in the management of matters in the complex domain where the approach to decision making is to sense-analyse-respond; and even in the chaotic domain where the approach is to act-sense-respond; and of conducting safe-to-fail experiments to test the system response.)

2.6.3 Experiential learning

A topic closely related to evidence-based learning is experiential learning. David Kolb (1999) made significant contributions by stating that learning is a multi-dimensional process.

Kolb, Boyatzis and Mainemelis (1999, p.2) define experiential learning as “the process whereby knowledge is created through the transformation of experience.”

The learning theory developed by Kolb, Boyatzis and Mainemelis (1999, p.194) is also referred to as a learning cycle and comprises “two dialectically related modes of grasping experience – Concrete experience (CE) and Abstract Conceptualisation (AC) and two dialectically related modes of transforming experience – Reflective Observation (RO) and Active Experimentation (AE).” This is graphically depicted in the **Figure 2.12**.

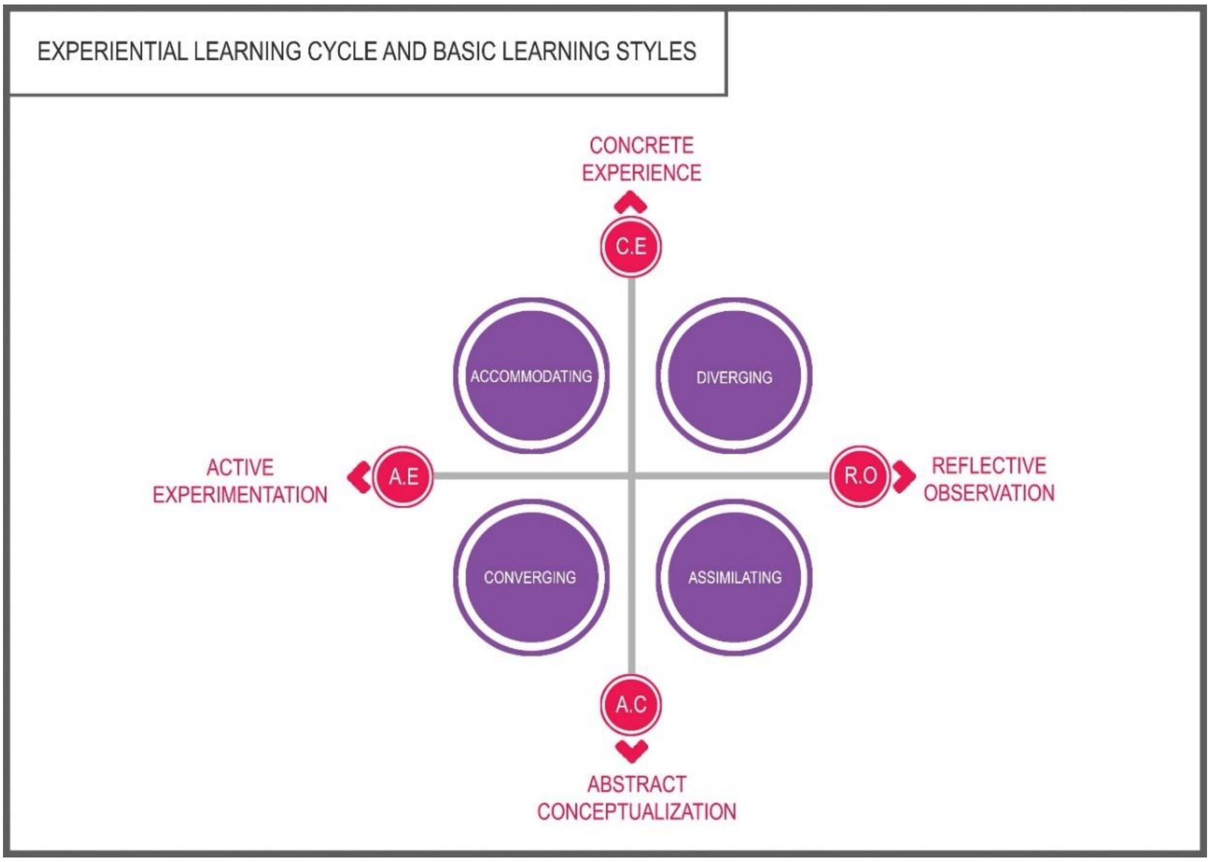

Figure 2.12 Experiential learning cycle and basic learning styles

The above describes an idealised learning cycle or spiral where the learner "touches all bases". Immediate and concrete experiences are the bases for observations and reflection. These reflections are assimilated into abstract concepts from where new inferences for action can be drawn. These inferences can be actively tested and serve as guides in creating new experiences. Experiential learning is a process of constructing knowledge that involves a creative tension among the four learning modes that is responsive to contextual demands" (Kolb, Boyatzis and Mainemelis, 1999, p.194). Again, this process is of a similar nature to that of evidence-based management.

Referring to **Figure 2.12**, each learning mode (CE, RO, AC, and AE) represents personal learning styles. For example, some people learn best when they are presented with concrete experiences whereby they prefer to deal with reality and tangible, felt qualities. Some people learn best by reflection. They observe what is happening and look what others do. Some people prefer to learn by thinking about things and to analyse. Doers are people that get right into something – active experimentation. Research by Kolb, Boyatzis and Mainemelis (1999) identified four statistically prevalent learning styles. These are indicated in **Figure 2.12** as divergent, assimilating, converging and accommodating. Persons with a divergent style have learning dominance in both Concrete Experience (CE) and Reflective Observation (RO) modes. These people create ideas and perform well in brainstorming sessions. They like working in groups and are imaginative and emotional and have wide interests. People with an assimilating style have dominance of both reflective observation and abstract conceptualisation. They are less interested in people and focus more on ideas and abstract concepts. They prefer analytical models. Persons with a converging style have dominance in both the abstract conceptualisation and the active experimentation modes. They find practical applications of ideas and theories. They are good at solving problems. They prefer technical matter to social and interpersonal matters. People with an accommodating style have dominance of both the active experimentation and concrete experience modes. They learn best by doing. They are hands-on people and rely on others for information rather than doing their own technical analysis.

The above processes are akin to evidence-based management and also to the approach given in the Cynefin framework. The level of complexity adds an important dimension to the models. One can, for instance, argue that observations of outcomes may not suggest clear cause-and-effect relationships and other tactics need to be found to resolve decisions regarding the processes to follow. This is depicted in the Cynefin Model.

The various learning styles are of importance in this research because learning is fundamental to the knowledge-creation process. The various learning techniques as well as the application of the Cynefin framework support the most essential elements of identification, definition and understanding of the contributing elements and context of situations or problems that need to be resolved. This forms part of the design of the proposed logic base.

2.6.4 Reflective learning

Boyd and Fales (1983, p.100) define reflective learning as “the process of internally examining and exploring an issue of concern, triggered by experience, which creates and clarifies meaning regarding self, and which results in a changed conceptual perception.”

Scanlon and Chernomas (1997, p.1139) state that “Germane to the development of professional expertise is the use of reflection so that the practitioner can get in touch with the tacit knowledge inherent in practice.” Reflection is an everyday action but it can be developed for specific professional purposes. Reflection is always good and develops thinking practitioners. “In order to encourage reflection, keeping of journals became the ‘de rigueur’ in nursing education programmes” (Scanlon and Chernomas, 1997, p.1140).

Scanlon (1997) describes a theoretical model of reflection; this is summarised in **Figure 2.13.**

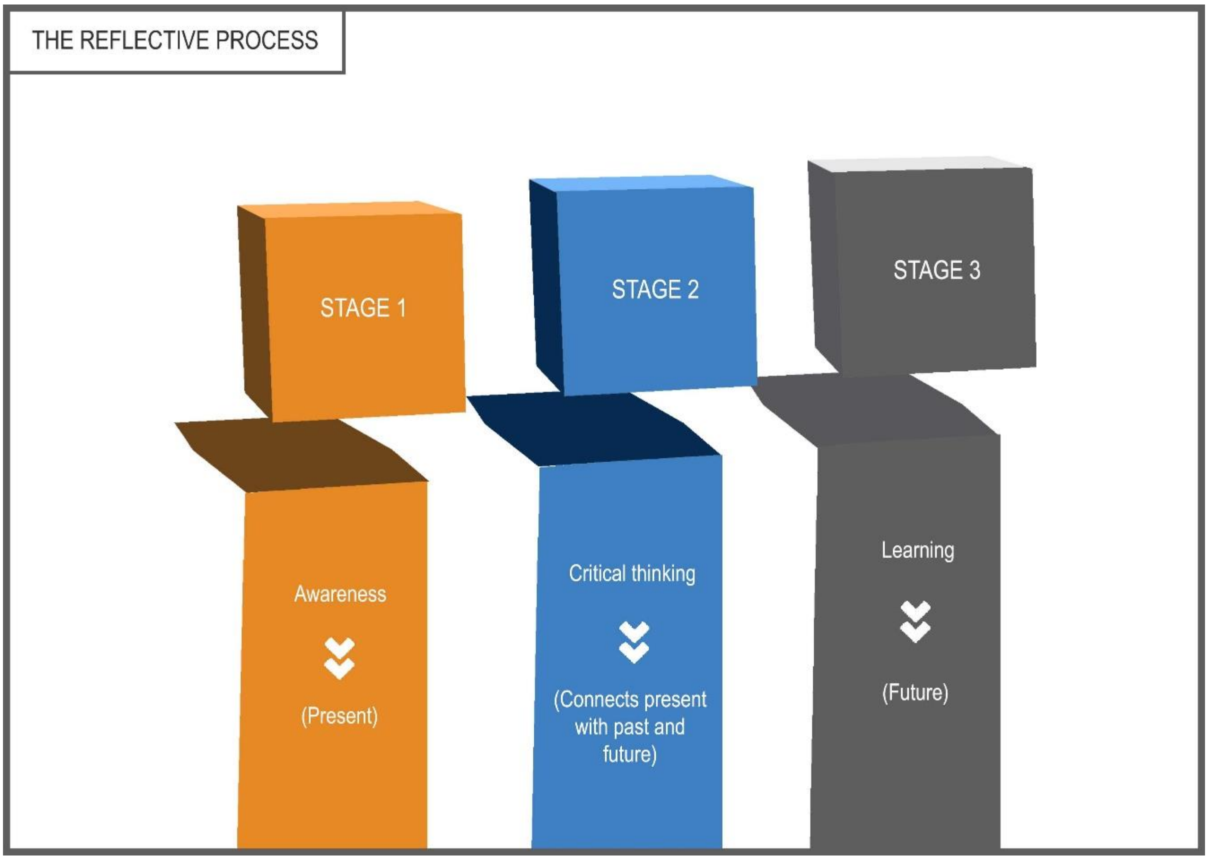

Figure 2.13 The reflective process (stages added)

The model postulates that a person may be aware of a particular event, but unless a critical analysis takes place which reviews and links the experience to either the past or the future, reflection has not occurred. Awareness is an essential starting point and comes into being when a person experiences a discomfort of feelings or thoughts. The discomfort arises when a person realises a lack of knowledge or understanding about the situation and stimulates further exploration. At the second stage, existing knowledge comes to bear to think critically about the situation. Synthesis and evaluation take place, and the opportunity exists for generating new insights that lead to the third stage where new perspectives are formed, and learning takes place.

In the field of nurses' education, Loo and Thorp (2002) describe the use of journaling to guide critical reflection in the learning process. They emphasise that "journals are not simply a 'diary' or 'log' but an articulated narrative that follows from the reflective and critical thinking of one's learning experiences or specific learning events" (Loo and Thorpe, p.135). (The narratives contained in journals lend itself to automatic capturing and analysis if one follows the methodology that Snowden employs for gathering information through the use of software.)

Essentially, nurse educators strive to encourage students to think about past experiences, current situations and expected outcomes of their actions so that they can explain what they do in the clinical setting and why they do things. (As a critique, one can postulate that this approach strongly suggests that cause-and-effect relationship are in fact clearly identifiable.)

Kember *et al.* (1999) did research on the determination of the level of reflective thinking from students' written journals. Kember formulated the definitions below to form the basis for evaluating the quality and depth of reflective thinking. These definitions are most useful for providing a better understanding of reflective thinking and could be useful when taking these concepts further in the development of a logic base.

Non-reflective actions are firstly described to distinguish it from reflective actions.

e) Non-reflective actions

- Habitual actions: These are activities that are performed frequently and became automatic. A typical example of this is riding a bicycle.
- Thoughtful action: These are activities that make use of existing knowledge without attempting to appraise that knowledge. Pre-existing knowledge is therefore used and "remains within pre-existing meaning schemes and perspectives" (Kember *et al.*, 1999, p.20).
- Introspection: This has to do with feelings and can be very personal. However, it does not encompass us deciding how or why these feelings develop. It remains at the level of just recognising or having an awareness of feelings.

f) Reflective action

Reflective actions or learning is defined above (Boyd and Fales, 1983, p.1). Also, three categories of content are described:

- Content reflection: This defines what we perceive, think, feel and act upon.
- Process reflection: This is how and the efficacy of performing content reflection.
- Premise reflection: This involves the transformation of our meaning framework.

It is stated that man's actions are governed by a set of beliefs and values which have been assimilated from a particular environment. "Premise reflection then requires a critical review of presuppositions from conscious and unconscious prior learnings and their consequences" (Kember *et al.*, 1999, p.23).

The above definitions support the theory of Nonaka and Takeuchi's model of knowledge conversion (SECI Model) and, in particular, the process of internalisation of knowledge. Reflective learning or actions can be seen as an important contributor to the process of internalisation.

A more elaborate reflective learning cycle shown in **Figure 2.14** serves as a summary.

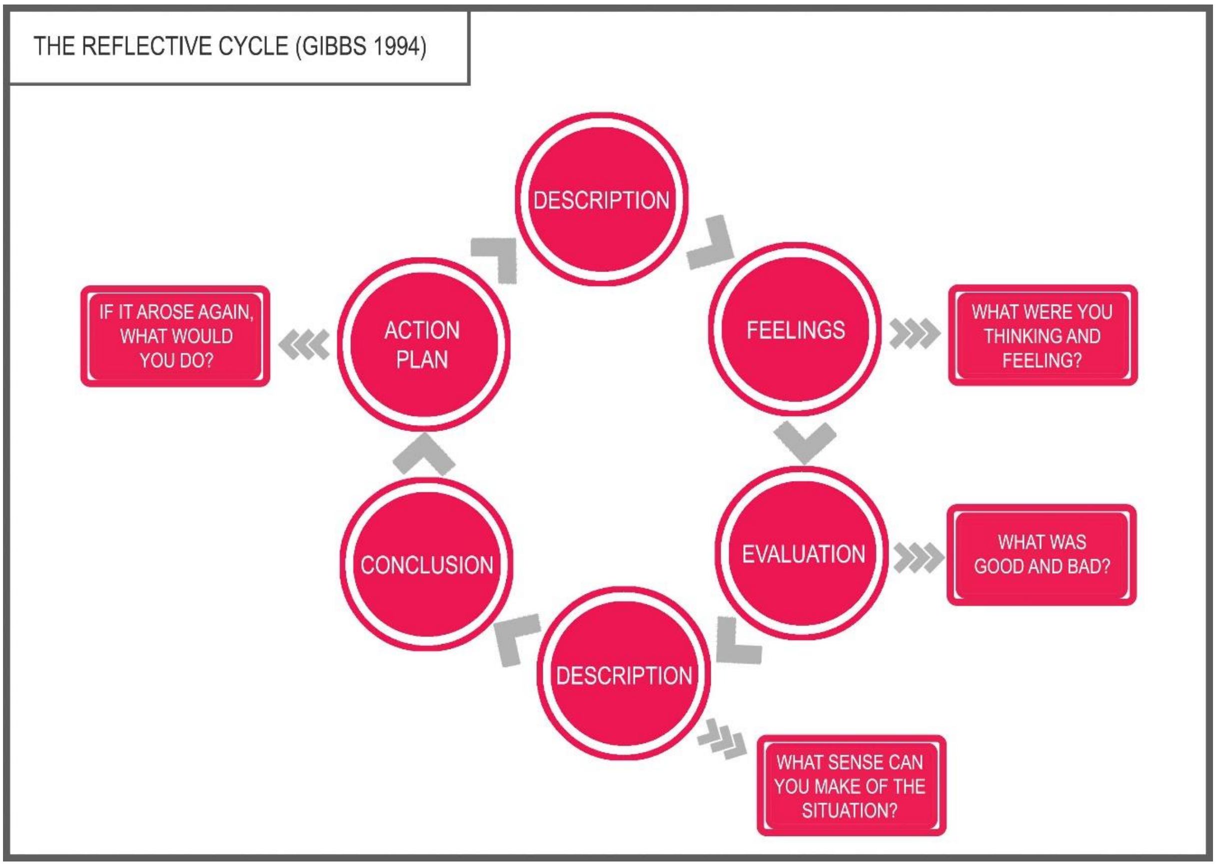

Figure 2.14 The reflective cycle; Figure after Gibbs (1988, p.15)

Hutchinson and Allen (1997) developed the Reflection Integration Model to enhance reflective learning among education students. Their model is based upon experiential learning theory and comprises four components: pre-experience, experience, reflection and integration. The model is applicable to any experience and can be the essential ingredient for "turning experiences into meaningful learning" (Hutchinson and Allen, 1997, p.228). McCaugherty (1991) and Schön (1987) developed valuable principles regarding the handling of problematic situations by professionals. This also refers to problem-solving applications. When a problematic situation requires a response from a professional, it often happens that the case is unique and falls outside the categories of existing theory and technique. The practitioner cannot treat the problem by solving it through rules in his or her store of professional knowledge since “the case is not in the book”. A kind of improvisation, inventing and testing in the situation is required whereby own devised strategies are involved (Schön, 1987, p.5). Schön noted an increasing divide between societal expectations and the ability of professionals to adequately respond to needs. He remarks that “the most important areas of professional practice now lie beyond the conventional boundaries of professional competence” (Schön, 1987, p.7). Solutions to problems mostly not lie in the rigorous analysis, deterministic areas for which theories exist or where research could lead. We have to frame problematic situations in a broader constellation of “disciplinary backgrounds, organisational roles, past histories, interests and political/economical perspectives” (Schön, 1987, p.4). It begs the question whether professional education can ever yield a curriculum that would adequately prepare professionals to address the “complex, unstable, uncertain and conflictual worlds of practice” (Schön, 1987, p.12).

In discussions with some professionals that exhibit exceptional performance, Schön (1987, p.4) remarks that such professionals are “not said to have more professional knowledge than others but more ‘wisdom’, ‘talent’, ‘intuition’ or ‘artistry’. The application of research and science do not address the full spectrum of knowledge needed to ensure exceptional performance. […] There is an art of problem framing, an art of implementation, and an art of improvisation – all necessary to mediate the use in the practice of applied science and technique.” Schön emphasises the role of coaching and of doing, and practical experience in the learning process. Schön, (1987, pp.13-19) refers to work by Polanyi and the role of tacit knowledge. Schön coined the term “*knowing-in-action”* to the sorts of know-how we reveal in our intelligent action, like riding a bicycle and private operations like instant analysis of a balance sheet. We reveal it by our spontaneous, skillful execution of the performance and we are characteristically unable to make it verbally explicit (Schön, 1987, pp.25-26). While performing a procedure or task, one intuitively expects certain outcomes. If during performance, it appears that the desired or expected outcome will not be achieved, one can stop and think, or one can reflect afterwards on the matter and figure out what the cause was of the unexpected outcome. Alternatively, while performing the task one can “reflect-in-action”, thereby reshaping what one is doing to endeavour to achieve the desired or expected outcome. One might refer to it as trial and error, but the trials are not randomly related to one another; instead, they are used to improve or reshape actions. This is best described as a process of reflection-in-action.

The process is diagrammatically presented in **Figure 2.15.**

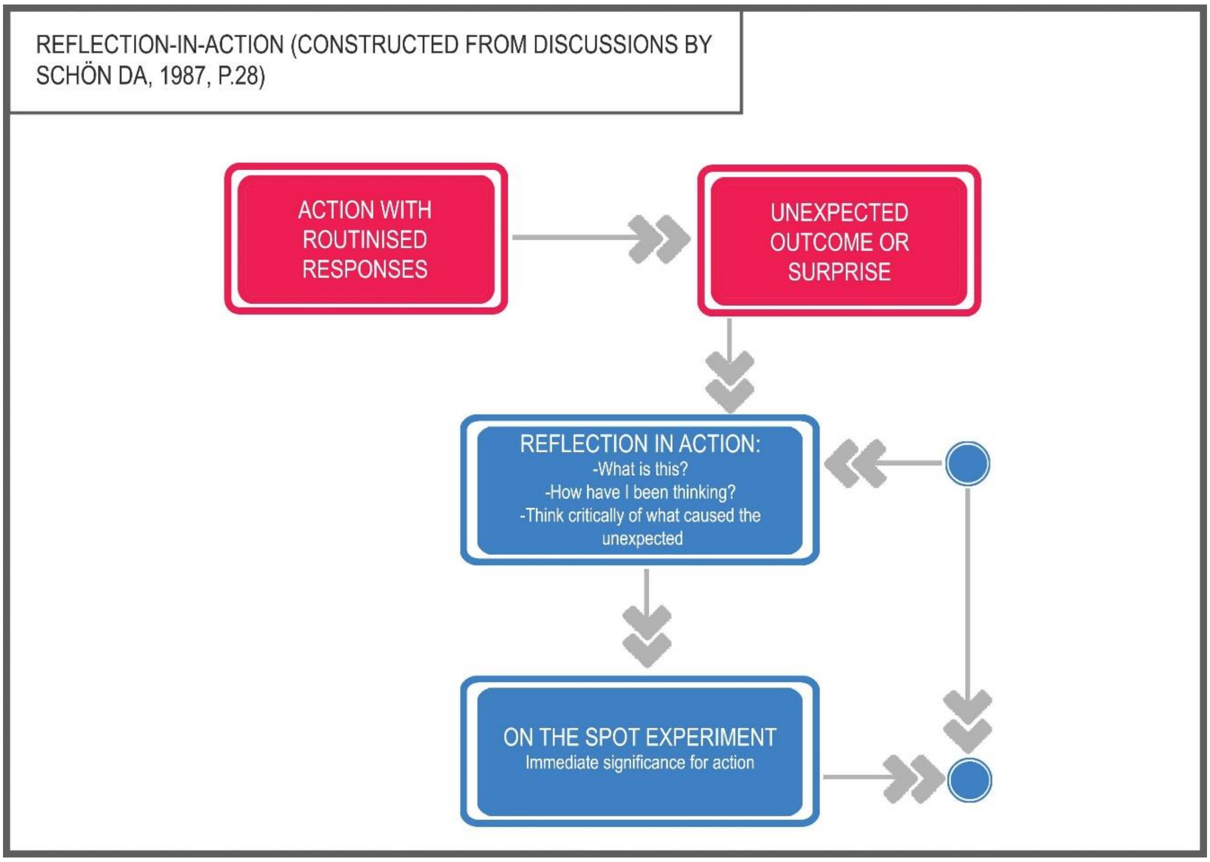

Figure 2.15 Reflection-in-action

(Constructed from discussions by Schön, 1987, p.28.)

Whether reflection takes place as indicated above or whether it is done by journaling, or done with the assistance of a coach, the principle remains the same – that of learning in a practical way; how to apply knowledge or how to sharpen skills.

The above discourse also supports aspects depicted by the Cynefin framework where cause-and-effect relationships are not obvious or cannot be identified. Reflective learning provides a basis for dealing with uncertainty or disorder.

2.6.5 Critical thinking

The field of critical thinking has a pedagogical origin and is mainly applied to improve education. The goal or outcome of education is to develop “careful, rigorous thinkers” (Kuhn, 1999, p.16). Furthermore, the subject is of interest in this study because of the close association with learning (and reflective learning) and its perceived similarity and applications in the requirement of creation and application of a logic base. The relevance is further exemplified by Kuhn’s statement: “A question we might be asking at this point, then, is whether progress is being made in establishing a knowledge base to support its realization" (referring to critical thinkers; Kuhn, 1999, p.16).

Critical thinking (Norris, 1985) is defined as rationally deciding what to do or to believe. Kurfiss (1988, p.2) defines critical thinking as "a rational response to questions that cannot be answered definitively and for which all the information may not be available. It is here as an investigation whose purpose is to explore a situation, phenomenon, question, or problem to arrive at a hypothesis or conclusion about it, that integrates all available information and that can, therefore, be convincingly justified."

As a method to test students' ability to think critically, the Watson-Glaser test (Watson and Glaser, 2009) was designed to measure a student's ability to recognise assumptions, to evaluate arguments and to appraise inferences. Research showed that critical thinking is sensitive to context. A person's knowledge and assumptions can strongly affect their ability to make correct inferences and hence, to assimilate or accommodate knowledge. One of the highlights from research on critical thinking is that, to think critically, one must have prior knowledge. It cannot take place in a vacuum. Critical thinking requires persons to apply what they know about the subject and they must apply their common sense and experience.

When experiential or reflective learning takes place, the learner will take the knowledge to a tacit knowledge level. The perspective of the Cynefin framework, and more specifically, the most recent development of utilising narratives to make knowledge explicit and to collect the knowledge automatically in a knowledge base, seem to be most promising. Further research in this regard should be done in domain-specific applications.

2.6.6 Knowledge spill-over

Knowledge spill-over is defined as the exchange of ideas among individuals (Carlino, 2001). Knowledge spill-overs can be internal (within the same firm and external-crossing firm boundaries).

As described by Thornton and Thompson (2001) during the process of manufacturing weaponry (during World War II), new knowledge was acquired through the development of new technology. The same technology used in the production of weaponry was also useful in other fields. In the case of the development of space technology, significant advances were made in, for example, the development of lightweight materials. This technology turned out to be most useful in other fields and is now used in the manufacturing of motor cars. Spill-over, therefore, occurs when knowledge is developed for a specific purpose in a discipline, but the same knowledge is also useful for other disciplines.

Knowledge spill-over has the advantage of enriching knowledge in other fields or disciplines. A wider context and application of knowledge can be observed that enhances and expands the knowledge base. It can also serve to challenge existing assumptions and inferences.

This is important in the development of a knowledge base since the content of the knowledge base should display a wide applicability and the logic should apply as widely as possible. This is achievable through engaging other fields and even actively searching or suggesting knowledge spill-overs. The interoperability of systems and the sharing of knowledge is of fundamental importance.

Snowden (2012 and 2013b) uses the term “exaptation” – the process whereby “features acquire functions for which they were not originally adapted or selected” (OED, 2010). An interesting example of exaptation was when a person wrapped his car in a large plastic bag to protect it from flood water. The large plastic bag was previously used for the packaging of new furniture. Subsequently, it became a new business in flood-prone areas to offer large plastic bags for the protection of motor cars (Snowden, 2012 and Snowden, 2013b and 2013d). Knowledge spill-over incorporates the principle of exaptation.

2.6.7 Summary and inferences on knowledge creation

The above methods of knowledge creation, knowledge reuse and knowledge acquisition exhibit common elements:

a) Tacit knowledge
b) Awareness
c) Sense-making
d) Reflective action
e) Content-process premise
f) Critical thinking
g) Cause-effect relationships
h) Experiments
i) Exaptation (knowledge spill-over)

The above methods seek to discover hidden perspectives and responses in a holistic way to understand context and situations, thereby endeavouring to define contributing elements to problems or phenomena that need to be resolved. The above methods and techniques can be considered to be the forerunning part or even an integral part of problem-solving. In this way the discovery of knowledge is supported.

The theories of knowledge and knowledge acquisition techniques can be integrated or contextualised to enable the drafting of concept maps. This process is described in later sections and more specifically, in **Appendix H**.

2.7 PROBLEM-SOLVING TECHNIQUES

In sections above the role of problem-solving in knowledge management was discussed. There is indeed a plethora of problem-solving methods (Silverstein, Samuel and DeCarlo, 2012). In sections below, some more common methods are investigated for their applicability in the development of a logic base. In this research, it is not the intention to do an exhaustive study and synthesis of all the problem-solving techniques, but rather to give brief summaries of some techniques that would be sufficient to support the logic base.

Research in human problem-solving had a long and venerable history and played a central role in the creation of cognitive science. Early studies on puzzle solutions and novel tasks led to insights into presentation, performance and learning which now underpin cognitive science (Langley *et al*., 2005).

The terms “problem solving” and “creative thinking” are found in the literature. From the research on problem-solving, reflective thinking is a term commonly associated with problem-solving and that it also pertains to generic problem-solving techniques. These terms are often used interchangeably.

According to Sickafus (2006), humans are not logical thinkers. By understanding the natural ways of human thinking, one can learn more about the resources for problem-solving. The question is how problem-solving is executed mentally. The resources used to do problem-solving are the two hemispheres of the brain. Both hemispheres are active at the same time and perform tasks such as reasoning, remembering, communication and problem-solving separately and share the results. The one hemisphere is usually good at logic and the other at intuition. Sickafus (2006, p.2) also contends that technologists are more influenced by the left hemisphere and artisans by the right hemisphere. Mention is also made that thinkers use both conscious and unconscious processes in problem-solving. Man is aware of the conscious, but one cannot know the subconscious (tacit knowledge). However, by introspection, one can make useful deductions about subconscious thinking. (This reminds one of the difference between explicit and tacit knowledge, where one cannot necessarily know the tacit knowledge component.)

When solving problems in the mental processes, content and structure are more important than order. Sickafus (2006, p.3) holds that "Structure and language are the tools of logical communication. Image and metaphor are the tools of creative thinking." Sickafus continues by saying that "A flowchart is not needed for creative thinking, it is too organized and works against unregulated random thinking. A simple model of consciously seeding the subconscious can be used instead." This model is described in **Figure 2.16.**

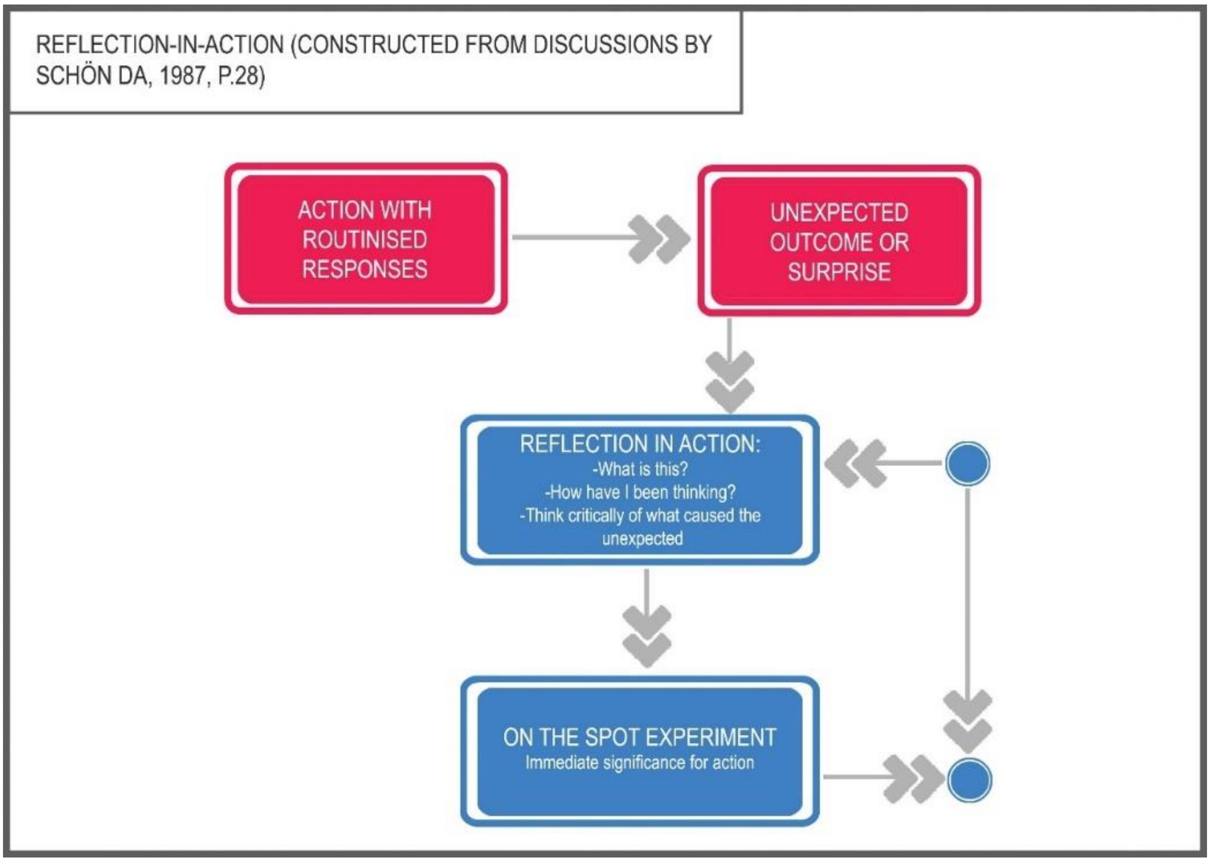

Figure 2.16 Simple model – seeding of the subconscious

(Sickafus, 2006).

In this model, it is shown that by using a metaphor to *seed* the *subconscious*, intuitive concepts can emerge that aid in problem-solving. Sickafus (2006, p.4) describes two types of intuitive thinking, viz., instant recall of past experiences that are, in fact, known problems and the recall of past experiences exhibiting similarities to the problem at hand. Innovation requires the unusual and non-obvious assembly of parts with considerable insight. (Refer to the TRIZ inventive problem-solving where the way inventors thought – derived from patent research – was translated into inventive principles. Guidance is given, but it still required considerable insight into innovation.)

An interesting concept is described by Sickafus (2006, p.4) in that he describes a problem situation as arising from a “collection of objects, attributes, functions, unwanted effects, causes and extraneous information.” (This can be called the *input information*.) This represents a rather complex situation. When one wishes to solve a problem, the most obvious first steps are to sort, reduce and simplify the input information to arrive at a well-defined problem. Sickafus (2006, p.4) holds that two heuristics aid this process, namely, simplify, generalise and to “construct the well-defined problem into a graphic metaphor based on sharp focus at the interaction of two objects (a single point of contact).” (Similar to TRIZ concept.) Metaphorically, two causal attributes of an unwanted effect are selected or determined. As an example of the above thinking process, an example is given by Sickafus (2006, p.5), whereby a candle-making company needed to improve their product to regain their market share. “Insufficient light” was identified as a root cause of the poor performance of their candles. Two objects were determined, namely “candle” and “flame”. The interaction or single point of contact is the “molten fuel” and the “flame”, which can be seen as two metaphors. An analysis of these leads to the other causal objects, “temperature” and “rate of combustion” that contribute to the light intensity. This can then be further analysed to find solutions to obtain a higher temperature and a faster rate of combustion to increase the light intensity. (Similar to the substance-field concepts of Altshuler. See: Gadd, 2011.)

From the above example, it can be seen how sorting is done and objects identified, and causal relationship used to create metaphors to stimulate thinking. Intuition is used to establish the causal relationships. This “intuitive” thinking is seen as tacit knowledge that is made explicit. The causal relationships between objects are either tacitly known or determined or deducted heuristically.

Problem-solving can be explained using an information processing theory. Humans are seen as information processors – in particular, metaphorically as digital computers, at least when he is solving problems. Newell’s focus is to describe how man processes task-oriented symbolic information. Newell and Simon (1972, p.9) says that he doesn’t want to speculate on the physiological locality of processing systems, such as in the central nerve system. “Because of the gap that still exists between physiological and behavioural science, nothing would be served by such speculation — it is all internal to the organism.”

This comment contrasts with that of Sickafus (2006) who explains the roles of the left- and right-hand hemispheres of the brain. However, for this research, the standpoint of Newell is supported and it suffices to be aware of the peculiar functions that co-exist in the human thinking processes which all add to the thinking domain present in humans.

Newell and Simon (1972, p.6) direct their discourse specifically to the field of artificial intelligence. Newell states that "a theory of the psychology of problem-solving requires not only good task analysis but also an inventory of possible problem-solving mechanisms from which one can surmise what actual mechanisms are being used by humans. Thus, one must work with task environments in which artificial intelligence has provided the requisite array of plausible mechanisms."

For this research, the actual processing of the information or knowledge (as focused upon by Newell) and how this is done is not considered appropriate. The main aim is to focus on the abstraction of knowledge and establishing a logic base rather than the subsequent treatment of the knowledge that resides in the knowledge base (from Newell and Simon's work, 1972).

In the plethora of problem-solving techniques which can be found in the literature, many overlap and there are a many commonalities in the various techniques. A summary of some of the problem-solving techniques is given in **Appendix B.** It is not the intention to provide a comprehensive summary, description and exposition of all the listed techniques. The techniques that are regarded as specifically relevant to this study are discussed in more detail below.

2.7.1 Trigger-word technique

Sarkar and Chakrabarti (2008) describe a case of how designers that were faced with design problems were positively influenced by the presentation of trigger ideas that are potentially useful for problem-solving. The trigger ideas invoked thought processes in the designers that influenced their solutions to the problems.

Gick and Holyoak (1980, p.308) describe experiments whereby analogies are used from two distant domains to help solve ill-defined problems. An example is quoted whereby a military problem had to be solved. After analysis, a solution was found to this military problem and analogies were triggered to generate analogous solutions to a medical problem.

2.7.2 Checklist technique

Cambridge Dictionaries Online (viewed 2011) describe checklists as follows: "A list of things you must think about, or that you must remember to do."

There are numerous forms of checklists that help to focus on critical issues, processes or standards. Some of the different forms of checklists are given by Levy (2010):

a) Criterion checklists

b) Task checklists
c) Troubleshooting checklists
d) Coordination checklists
e) Discipline checklists
f) Procedural checklists
g) Communication checklists
h) Project checklists

Checklists can also be seen as a set or group of statements defining the desired status or outcome of specified parameters at any point in time or stage in a process. A checklist requires confirmation of the state you want. By filling in a checklist, actions or corrective measures are implied, i.e., if the desired end state as depicted in the list does not exist, it suggests a process or actions that need to take place to arrive at the desired end state. This also implies a problem-solving process to identify the causes of the absence of the complete end state. A fault-finding procedure is commonly associated with the actions followed in the completion of a checklist. A checklist does not usually define details of the process as such, although it could also be the case. A checklist can be regarded as a particular case of problem-solving, since outcomes are contemplated that imply that actions already took place, that led to a result that can be recorded in a checklist. This checklist can be seen to represent a set of solutions. Checklists are of significance in this research since the solutions as recorded in the list may reflect experience. The actions that need to be taken to arrive at an item on the checklist are of importance and can be used in the development of logic that will be recorded in the proposed logic base.

2.7.3 Morphological analysis

Morphological methods are described by Zwicky (1949, p.121) as “essentially nothing more than an orderly way of looking at things. Our aim is to achieve a schematic perspective over all of the possible solutions of a given large-scale problem. […] Because of unavoidable limitations on time and means a choice must obviously be made, and preference must be given to some specific solutions. With the general perspective achieved, this choice will, however, be more rational and organic than it would be if engaged haphazardly in work on this and that solution of a given problem” (Zwicky, 1949, p.121).

Ritchey (2002) reported on the “General Morphological Analysis” in a problem-structuring and problem-solving technique which was designed for multi-dimensional and non-quantifiable problems. It serves as a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes (Ritchey, 2002, p.3). It is particularly suited to instances where causal modelling and simulation do not function well.

Zwicky (1949) developed this approach to address seemingly non-reducible complexity. Using the technique of cross-consistency assessment (CCA), the system, however, does allow for reduction (by not allowing for reduction of the number of *variables* involved), but by reducing the number of *sets* of possible configurations (Ritchey, 2002).

Parameters or attributes are entered into a multi-dimensional matrix and the relationships – however trivial or seemingly irrelevant – are studied. The effects of these relationships in finding solutions are determined by inspection, selection, logic or judgement. All the illogical, irrelevant or too trivial relationships can be discarded and the focus can then be on the relationships that would best contribute to the problem solutions.

This technique is valuable and applicable in the development of a logic base. It forces the user to consider the maximum number of relationships between attributes or parameters. In so doing, one can be more confident that all the possibilities have been discovered. This method could also contribute to the expansion of experience, since relationships that would not normally be ignored or not recognised could be discovered, thereby enriching the experience. (The technique is also used in the theory of inventive problem-solving or TRIZ as described in subsequent sections.)

2.7.4 Attribute-seeking technique

In this method, a listing is done of all possible attributes of an object or system. Each attribute is then considered in the problem-solving process. Govindaraju and Mital (2008) discuss how attributes of new products are identified to meet functional and manufacturing criteria. They also highlight how this method combines very well with brainstorming techniques as well as morphological techniques. Attributes are required as inputs to morphological analysis (Govindaraju and Mital, 2008).

In essence, this technique forms part of the foregoing techniques and its relevance to this research is similar to the other techniques, such as TRIZ that is discussed in later sections.

2.7.5 Brainstorming technique

The explanation for the word “brainstorming” is given by the OED online, (2010) (viewed 2011) as: “The action or process of making a concerted attempt to solve a problem, usually by group discussion of spontaneously arising ideas.”

In the literature, there are numerous brainstorming techniques and they serve as powerful tools for solving problems.

Six important brainstorming principles are described by Rossiter and Lilien (1994). Some of these are:

a) Brainstorming instructions are essential and should emphasize, paradoxically, number and not quality of ideas;
b) A specific, difficult target should be set for the number of ideas; and
c) Individuals, and not groups, should generate the initial ideas.

Groups should then be used to amalgamate and refine the ideas. Individuals should provide the final ratings to select the best ideas, which will increase the commitment to the ideas selected. The time required for successful brainstorming should be kept remarkably short. By following these principles, brainstorming will more dependently produce high-quality creative results. Group effectiveness seems to be challenged and, except for boosting the morale of participants, it may not be more effective than individuals working independently. An exciting development is that of electronic brainstorming. This method uses either electronic meeting systems where participants can anonymously enter ideas, direct browser-based e-mails or peer-to-peer software. These techniques can also be employed to identify key concepts that could be taken up in a knowledge base.

2.7.6 Synectics

A succinct description of synectics is given by Seligmann, Sidorkin and Jacobs (2007). They state that the term originates is from the Greek words "*syn*" and "*ektos*", meaning that it is a fusion of diverse ideas. Diverse ideas that are created by synectics are more formalised and rigorous forms of idea generation than those of brainstorming. It is primarily a group activity. Furthermore, it uses analogies and metaphor in the model to think creatively. By so doing, familiar things are looked at in unfamiliar ways to stimulate thinking and problem-solving.

There are three forms of metaphor: "direct analogy, personal analogy and compressed conflict" (Seligmann, Sidorkin and Jacobs, 2007, p.4). Direct analogy examines similarities between two ideas" – for example, such as comparing the cardiovascular system to a highway. Trucks travelling on the highway may represent the blood cells transported in the vascular system. In the case of personal analogy, participants are encouraged to "feel" or "live" into the direct analogy and to imagine what it feels to be. In the case of the above example, the participants are encouraged to imagine how it feels to be a blood cell being transported in the artery like the truck on a highway and to experience the frustrations of blockages, for example.

Compressed conflict refers to “conceptual understanding of natural paradoxes”. Interrelationships between ideas may produce conflict or paradoxes, which stimulate thinking and creativity. (The resolution of conflicts and paradoxes are core to TRIZ and to the Theory of Constraints that is dealt with later in this study.) In the case of the example above, blockages due to blood clots in the artery can be deadly if it goes to the heart or brain, but paradoxically, it can be a lifesaver since it prevents bleeding. A blockage on the highway can also be seen as a good or a bad thing. (It can be expanded on by adding that a blockage on a highway may slow down traffic, rendering lower operating speeds and therefore enhancing road safety in general – speeding is accepted as a high-risk factor in causing vehicular accidents.)

Seligmann, Sidorkin and Jacobs (2007) describe a procedure for creating something new in six phases:

a) “Phase 1: Description of the present condition
b) Phase II: Direct analogy (examines similarities between two ideas)
c) Phase III: Personal analogy (encourages empathize with subject – what does it feel like? – this triggers new perspectives and ideas)
d) Phase IV: Compressed conflict (examines paradoxes – e.g., something can be beneficial, but at the same time also detrimental – it provides insight from different angles of thought)
e) Phase V: Direct analogy (based on the compressed conflict from phase IV) and
f) Phase VI: Re-examination of the original task.”

(Note – comments in parentheses as well as bullets were added by this researcher.)

It is important that students do not return to the original problem until the final phase. In the description of the methodology of synectics, a list of trigger questions is given to apply when looking at familiar things in an unfamiliar way.

The list of ways to look at things is as follows: “Subtract, add, transfer, empathize, animate, superimpose, change, scale, substitute, fragment, isolate, distort, disguise, contradict, parody, prevaricate, analogize, hybridize, metamorphose, symbolize, mythologize, fantasize, repeat, and combine” (Yoe, 2013, p.157).

This technique is considered necessary in this research since it examines things or situations in a way to turn the familiar into the unfamiliar. This adds different dimensions to knowledge and is useful in the creation of new knowledge.

2.7.7 Analysis and synthesis

"The terms 'analysis' and 'synthesis' come from (classical) Greek and mean literally 'to loosen up' (meaning to break a substantial whole down into elements or components) and 'to put together' (meaning to combine separate elements or components to form a coherent whole)" (Ritchey, 1991, p.1).

Two approaches for gaining knowledge about a thing or system can be followed:

a) Proceed with its construction, attributes or parts, and from there seek to determine the laws of mutual interaction of its parts as well as the possible response to external stimuli or effects.
b) Begin with what the thing or system accomplishes and then try and account for this.

Under (a) above, the effects from given causes are inferred (synthesis).

In (b) above, the causes of given effects are investigated (analysis).

In the development of a logic base, whereby experience is recorded in a logic base, it is of great importance to do a synthesis and analysis of the matter at hand. The processes of analysis and synthesis are of primary importance in the methodology of operation of a logic base.

2.7.8 Root-Cause Analysis (RCA)

A root cause is defined as follows:

"One of multiple factors (events, conditions or organizational factors) that contributed to or created the proximate cause and subsequent undesired outcome and, if eliminated, or modified would have prevented the undesired outcome, typically multiple root causes contributed to an undesired outcome" (NASA, 2003). Root-Cause Analysis refers to a structured evaluation process to identify the root causes. It is a method to establish what, how and why a detrimental event happened. Root-Cause Analysis seeks to identify system faults that could have played a role or could have caused a particular problem or mishap. The intention then is to take appropriate action to eliminate a similar problem from recurring (Rooney and Van den Heuvel, 2004).

Root causes are used to develop procedures, solutions or measures to ensure that the event does not re-occur Rooney and Van den Heuvel (2004). Root causes are the most basic reason why an event occurred.

Numerous procedures were developed for conducting Root-Cause Analysis. However, this will not be studied further at this stage. The concepts of how RCA is employed in the development of a logic base will first be investigated. It is anticipated that specific procedures will have to be established to suit the knowledge base. This will be dealt with in later chapters.

The relevance of RCA in this research is that for any problem that has occurred and for which the experience will be taken up in the knowledge base, a RCA analysis will have to be conducted or the outcomes clearly stated. RCA is expected to form an essential part of the proposed logic base as it builds experience and knowledge which otherwise may not be available.

2.7.9 Failure-Modes, Effects and Criticality Analysis (FMECA)

"FMECA (Failure-Modes, Effects and Criticality Analysis) is an engineering analysis and a core activity performed by reliability engineers to review the effects of probable failure-modes of components and assemblies of the system on system performance" (Luthra, 1991, p.235). (Reference is also made to Silverstein, Samuel and DeCarlo (2012, pp.285-292), who refer to "Design failure mode and effect analysis".)

In essence, a procedure is followed whereby each component of a system or each functional aspect is evaluated for its effects on other related components and the system as a whole. The evaluation involves considering all possible potential failure modes, the effects of failure(s) under different circumstances and the risks (and consequences/effects) associated with the failure modes. The risks associated with various issues are ranked regarding the importance, and corrective actions are identified to address the most pressing concerns. Risks are also ranked according to the risk priority numbers according to the equation:

RPN = Severity X occurrence X detection

The *risk priority number* (RPN) is equal to the severity of each effect of failure multiplied by the likelihood of occurrence of each cause of failure multiplied by the likelihood of prior detection for each cause of failure (Huang, Shi and Mak, 2000).

The above analysis is also referred to as a FMEA (Failure Mode and Effect Analysis).

A criticality analysis can also be carried out. A criticality analysis can be quantitative and qualitative. Criticality is assessed by the following equation:

Mode criticality = Item unreliability X mode ratio of unreliability X probability of loss
Item criticality = sum of mode criticalities

Where the item's unreliability is determined by assessing the reliability/unreliability of each item at a given operating time. The mode ratio of unreliability is the portion of the item unreliability that can be attributed to each failure mode that may occur. The probability of loss is the severity that will result from each failure mode that may occur. The criticality of each item is obtained by summing the criticalities for each failure mode that has been identified for the item.

The following necessary information is obtained:

- Items
- Functions
- Failures
- Consequences and severity of failures
- Effects of failure
- Causes of failure
- Current controls
- Recommended actions
- Plus other relevant items

In the process of evaluations, the typical questions are as follows:

- What?
- On what?
- With what?
- When?
- Where?
- How much? (in extent)
- How many?
- How long? (period)
- How much? (cost)

Sage and Rouse (2009, pp.1240, 1292).

The above are considered as operators. On each component/element/topic/activity or system, the above questions are asked, and the effects or results on other related components and systems are evaluated and systematically recorded.

Performance criteria are applied to measure the evaluation against. All combinations of component or system variables are evaluated. The intention of the assessment is also to identify the components and conditions that may lead to systems failure or non-conformance to the set criteria. This approach has much in common with axiomatic design and morphological techniques, whereby the basic functions of a system are expounded and analysed. It also has a close linkage to Root-Cause Analysis (RCA). The advantage of FMECA is that sub-systems and performance of the entire system are evaluated against set criteria. Functional Requirements (FRs) as found in axiomatic design are similar to the criteria used in the evaluation process in FMECA. In the case of morphological analysis, the matrix-method of evaluation of relationships between parameters is analogous to the effects analysis in FMECA. FMECA is seen to imply a pre-event analysis that would discover root causes of potential failure. Root-Cause Analysis (RCA) is mostly directed towards post-event investigations.

When a logic base is developed, it is important to identify and record which items or component in a system or a system itself are considered for evaluation. FMECA can also lead one to the examination of relationships between items and the effects it has on the system performance. A logic base is meant to have a pre-emptive function, i.e., to enable the prevention of problems.

2.7.10 Functional Analysis Systems Technique (FAST)

FAST (often the acronym F.A.S.T. is used) was developed for application in value analysis or value engineering. Although authors seem to differ in opinion, Lawrence Miles has been the inventor of functional analysis during the Second World War (Grönqvist, Male and Kelly, 2006). FAST was further developed by Charles W. Blythway in 1964 and presented it at a conference of the Society of American Value Engineers in 1965.

FAST is an effective management tool and can be used in any situation that can be described functionally. Bartolomei and Miller (2001, p.1) describe FAST as a “rigorous method for understanding complex systems by converting the ‘activities’ performed in a system to ‘functions’ performed by the system for its customers.” FAST is a system without dimensions. Functions are displayed in a logical sequence, making use of a “Why-How?” and “When?” framework. Prioritisation is done of the functions and the dependency of the functions is tested. It will not tell anything about the specification of how well a function should be performed, or by when or by whom and what the cost thereof will be. These can, however, be added, depending on the objectives of the analysis. The FAST-technique involves a diagrammatic representation of functions. The functions are best determined by a group of suitably selected individuals. There is no one specific “correct” FAST-technique. The consensus among the participants determines the outcome of a FAST-diagram.

The technique is best represented diagrammatically. When one moves from a higher to a lower order function, the question is asked: “How?” When moving from the lower order functions to the higher order functions, the question “Why?” is asked. Functions are described in a noun-verb format. Only action verbs should be used, such as “do”, “make”, “move”, “draw,” etc. The noun is the operant on which the operation takes place (Kardos, 1993).

A critical path is also defined for the functions. The functions on the critical path are those that are necessary for achieving the objectives or higher order function or output. Major and minor critical paths are possible. Functions on the major critical path relate to the basic functions, while the roles on the minor critical path are supportive to the major functions. Any function located on the critical path is connected with a major logic path and the functions that are not on the critical path are connected with minor logic paths.

The basic concepts necessary, in **Figure 2.17**.

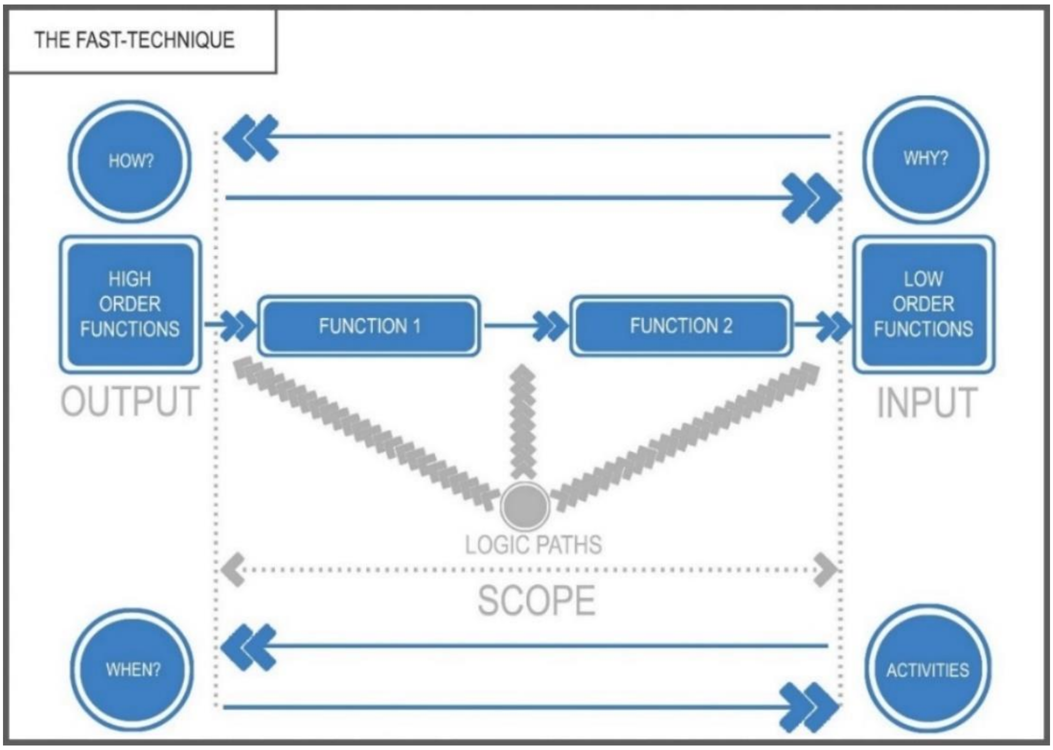

Figure 2.17 The FAST-technique

With reference to the above diagram, there can be any number of functions when going from left to right. The linkage of the functions when proceeding from left to right, is by way of the questions: *How,* w*hy*, or *what* is the input and output? The functions can be activities, actions processes or operations.

The question, “When?” can also be incorporated on a vertical dimension.

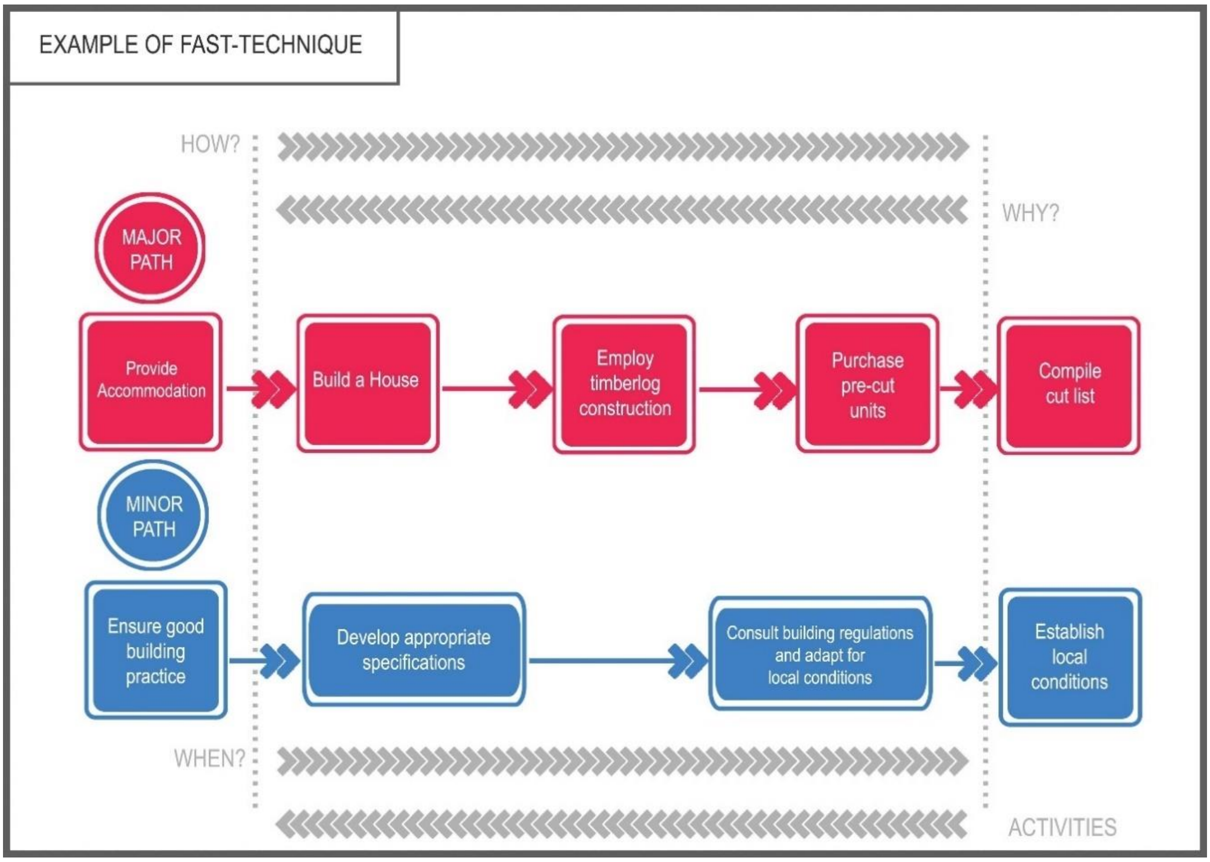

Figure 2.18 Example of FAST-technique

Figure 2.18 illustrates the representation of the logic of the FAST-diagram in a How?-Why? framework. The actions in the blocks sequentially show the development or creation of knowledge relating to each predecessor.

The above technique is considered to serve as one of the building blocks of the proposed logic base.

2.7.11 The Hierarchy of Objectives Technique (H.O.T.)

This graphical technique was adapted from value engineering techniques, and more specifically the diagrammatical procedure called the Functional Analysis Systems Technique (FAST) as described above. A technique referred to as the *Hierarchy of Objectives Technique* was employed by Hugo (1991) and said to be “the most important tool for capturing constructability knowledge” (Hugo, 1991, p.11). Youker (1998, p.2) describes it as “a tool that helps analyse and communicate the project objectives.” The hierarchy of objectives approach organises objectives into three broad levels (Youker, 1998, p.2), namely:

a) Policy objectives: These are at top management level, also called goals, that policy makers deal with.

b) Strategic objectives: These are at middle management level and represent specific goals that are formulated to support the policy.

c) Operational objectives: These are working level objectives which directly relate to the project, also referred to as input objectives and focuses on what is needed to make a project to function. These objectives also relate to project inputs.

The policy objectives are the highest order objectives and are the starting point in the analysis. When moving vertically down in the hierarchy, the question, "How ?" is asked to formulate the next order objective. This means that the strategic objectives are in answer to the question of how effect is given to a particular policy in a particular situation. By asking the question "How?", one can move further down the hierarchy to the operational level. When moving up in the hierarchy from the operational level, one can ask the question, "Why?" The answer to the question will be the strategic objective at the higher level.

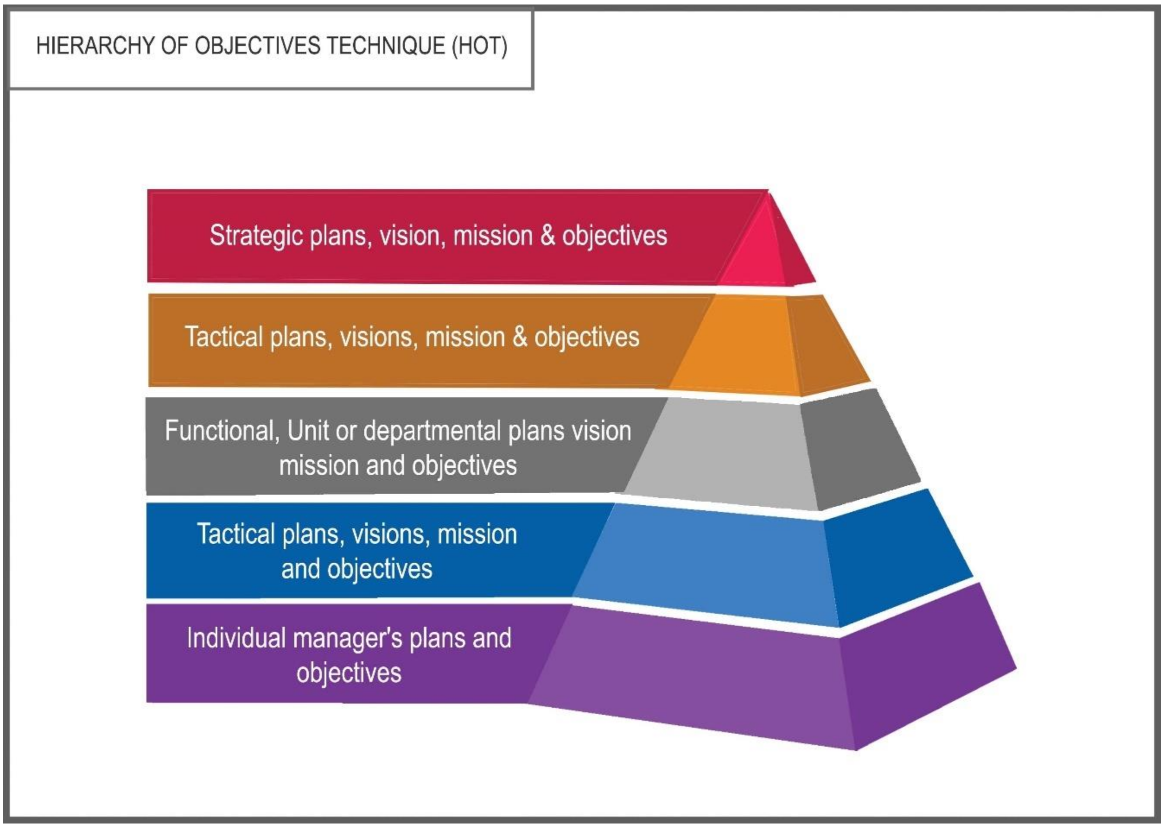

Figure 2.19 Hierarchy of Objectives Technique (H.O.T.)

This vertical "How?-Why?" logic is also found in the FAST-diagrams described in the preceding section. The "How?-Why?" logic in the FAST-diagram is shown horizontally when moving from one statement to the next. Youker (1998) also describes a horizontal logic which shows what outcomes the project has to achieve at each level. These are thought of as "If-then" relationships, for example, one can say that, *if* it rains in time, *then* there will be a good crop. In Youker's discussion, there are therefore both horizontal as well as vertical logic. The vertical dimension differentiates the organisational goals as depicted in **Figure 2.19.**

A description of another application of the Hierarchy of Objectives Technique (H.O.T.) is given by Hugo (1991, pp.11-12). This method was developed to provide a "logic process for hierarchically structuring constructability objectives in decision tree on outline format." The "How?-Why?" diagram starts on the left-hand side with the highest order objective or concern. When one moves towards the right, the next level follows by addressing the question, "How?" The answer will provide a problem, constraint or complaint. The next level in the horizontal hierarchy will again result from answering the question, "How?" This will lead to the formulation of ideas or tactics to solve the problems or complaints. The next level will be solutions to the problems or complaints. These solutions can go down to any number of further levels and can also direct one to specific actions, documents, resources, precedence networks, standards, specifications, appurtenant publications, photographic material, videos, contact information, etc. – which are all in support of the solutions that are offered. All the information can reside in a database (which constitutes a knowledge base). It is important to note that the essence of this technique is to start off with a specific objective on the left-hand side of the diagram, and by following the diagram and asking the question, "How?" when moving from left to right, the reader's thoughts are guided towards a specific solution or field of solutions and valuable information. One can even find H.O.T.-diagrams within H.O.T.-diagrams – so-called nested H.O.T.-diagrams. The logic of the diagram when moving from the right to the left always remain the same, i.e. when moving from the right to the left, the question, "Why?" is answered from one level to the next. When comparing the H.O.T. diagram as Hugo applied it with that of Youker, one would notice that Youker has both horizontal and vertical hierarchies. The objectives or concerns, as indicated at the highest level in Hugo's diagram, are not in a hierarchical format. When the situation warrants such a hierarchical approach, Hugo's diagram can be modified to include such logic. The "If-then" logic is also not present in Hugo's diagram. It may however be a useful addition when one considers the taxonomies of various knowledge domains.

A compendium of H.O.T. outlines was foreseen, containing the outlines compiled by Hugo (1991). This compendium of H.O.T. outlines serves as a knowledge base for a constructability enhancement programme in South Africa. H.O.T. outlines were produced in Texas, USA for their State Highway Department. The Texas outlines were, where necessary, adjusted for the South African situation.

(Constructability is defined as the ease or expediency with which a facility can be constructed [Hugo, 1991, p.1].)

The HOT-diagram serves as a logic-development tool to find solutions to constraints or problems. By solving the problems or constraints, higher order objectives or policies may be satisfied. The question is, what are the higher-order objectives to start off with, in the H.O.T.-diagram?

The H.O.T. outline diagram is graphically illustrated in **Figure 2.20**

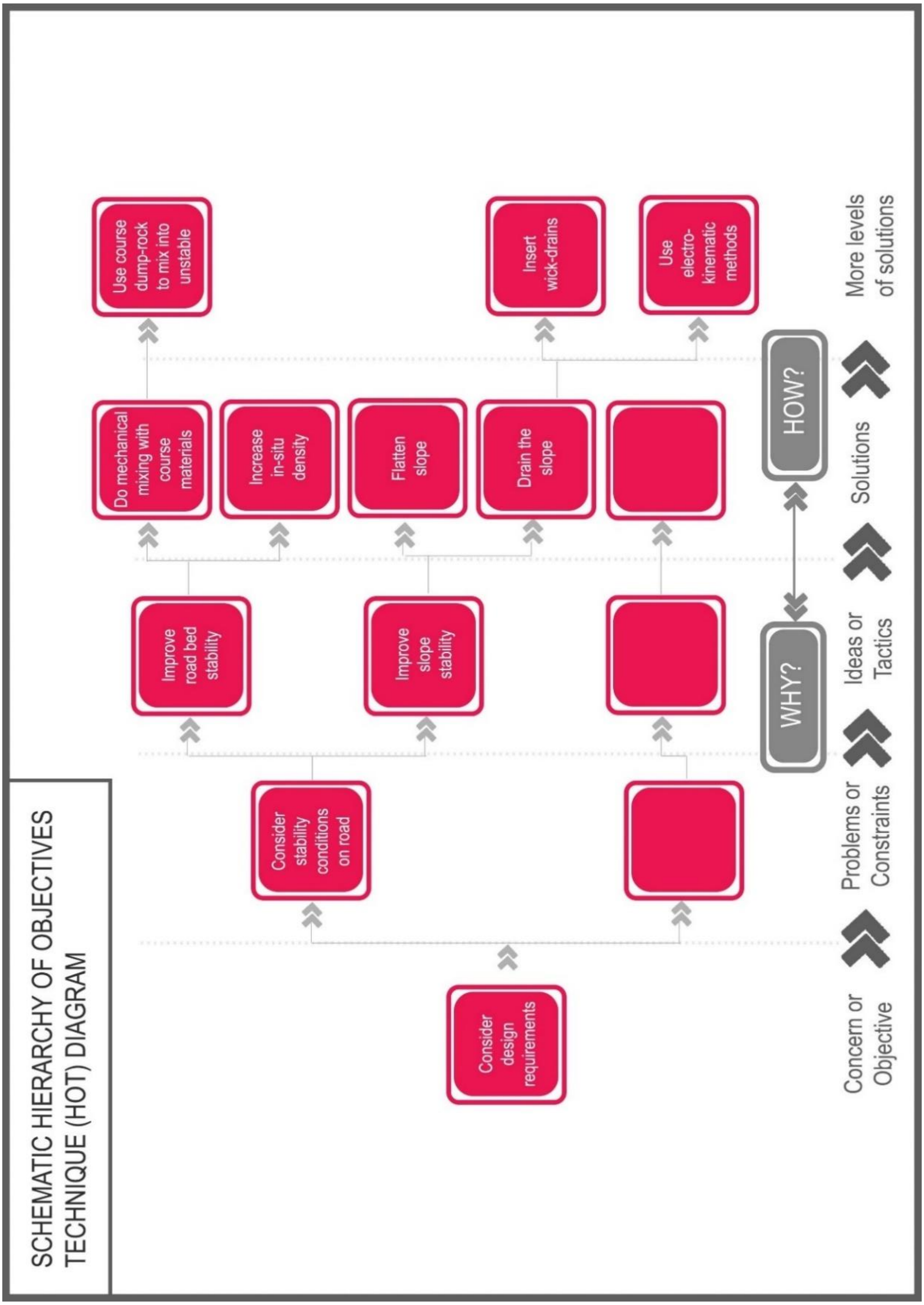

Figure 2.20 Schematic Hierarchy of Objectives Technique (H.O.T.) diagram

Further developments were done on the H.O.T. diagram. (Sometimes referred to as the HOT-technique. These acronyms are used interchangeably.) A system was devised by Verbeek (1992, pp.25-38) to identify "constructability candidates". These candidates were identified through consideration of:

- Topics or activities
- Project phases
- Influencing factors

First of all, a topic or activity is selected from a list. This topic is then paired with a selected project phase and with a selected influencing factor chosen from a list. The combination of the three aspects is then interrogated by using questions typically used in the Failure-Mode Effect and Criticality-Analysis technique. The following example is given concerning earthworks during road construction. The following aspects are chosen:

- Topic/activity: "Volumetric considerations."
- Project phase: "Construction."
- Influencing factor: "Resources."

The above combination of aspects is termed constructability candidates. In the above example, the aspects are "volumetric considerations and resources during construction". The question is, *if* and *how* do these impact constructability? To evaluate the impact, a conformance analysis is carried out. The compliance analysis involves asking a series of questions to interrogate the candidate to determine if it has a significant impact on constructability. The questions are such as: "What?", "On what?", "With what?", "When?", "Where?", "How much?" and "How long?" for each combination. As an example, one can ask the question, "How long?" and identify problems directly related to "volumetric considerations and resources" such as:

- Productivity: The problem is poor productivity will prolong the project duration
- Delays/schedules: The problem is delays are obvious issues that would extend project duration.
- Unnecessary activity: The problem is that such activities would prolong the project duration and could influence the project cost.

Each of the above problems has a significant impact on constructability and hence each of the above aspects would qualify as a valid candidate for further analysis and application of the H.O.T.-technique. These problems are termed "constructability non-performance" since these problems, if not addressed satisfactory, will be detrimental to the objective of enhancing constructability.

When taking the analysis to the next hierarchical level, one can, for example, ask, "How can productivity be improved for handling a greater volume of earth?" The next level will contain certain ideas or tactics related to the previous question, such as "increasing the size of truck used in earth moving."

The next level will define a possible solution, namely to hire larger trucks.

The next level may contain the contact details of plant hire companies that could be approached to hire the vehicles from.

The above would reside in a knowledge base. The logic of the system leads the reader through some logic and eventually to specific information such as contact numbers of companies that could be approached to assist with the solution.

The above is referred to as a "knowledge-base system" (KBS) (Verbeek, 1992, p.26). The system is graphically illustrated in the **Figure 2.21**.

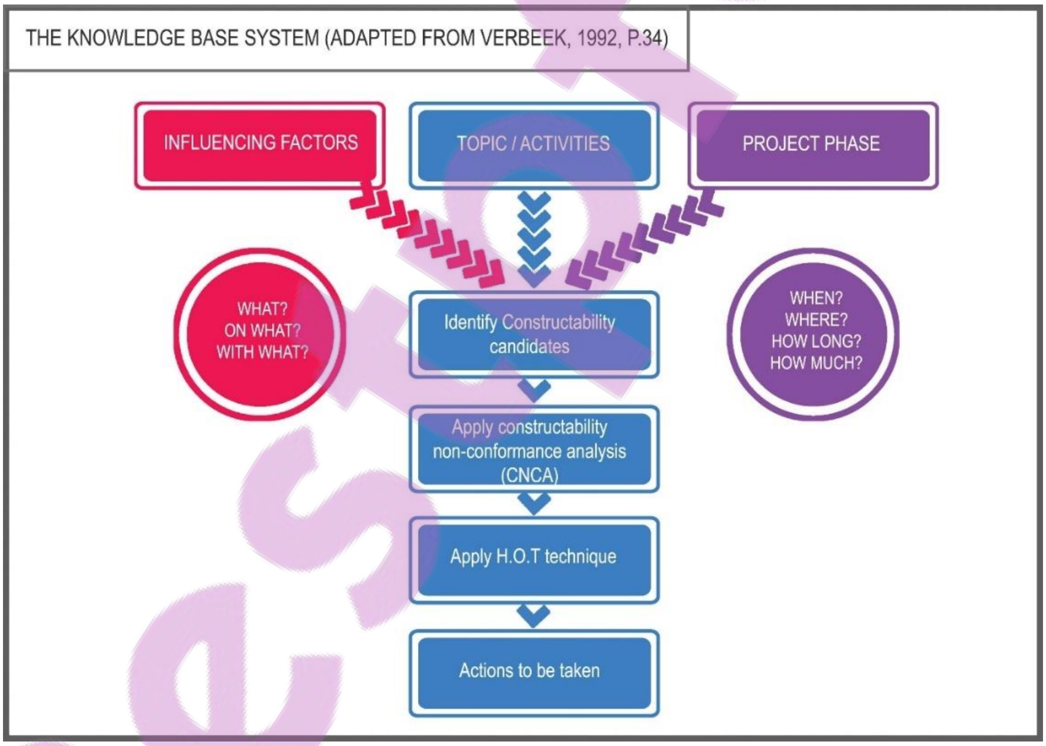

Figure 2.21 The knowledge base system

(adapted from Verbeek, 1992, p.34)

The above technique is highly relevant to this research. The objective of this research is to develop a logic base. The FAST-technique and the HOT.-technique describe logic diagrams or hierarchies that can be included in the logic base.

The FAST- and HOT-techniques have much in common with some of the methods that were identified above.

Table 2.3 Brief summary of techniques and synergies with FAST- and HOT-techniques

METHOD	**REASON FOR COMMONALITY WITH *FAST* OR *HOT***
Checklist	On the righthand side of the diagram, a checklist can be developed as a solution.
Brainstorming	Ideas/tactics/objectives and functions are identified for analysis.
Attribute seeking	Attributes define the object for further analysis.
Root Cause Analysis (RCA)	A systematic process is followed to identify retrospectively problems and solutions.
Failure Mode Effects and Criticality Analysis (FMECA)	Elements/components are identified that can be analysed for finding solutions and prevention of failure.

2.7.12 TRIZ-technique

TRIZ is a Russian acronym for “The Theory of Inventive Problem Solving”. It was developed in the former U.S.S.R. by Altshuller and his colleagues, between 1946 and 1985. Altshuller studied over one million successful patents and identified common parameters or typical characteristics present in the development of patents. It was found that patents were registered in response to perceived problems or constraints experienced in the use of a great variety of objects or systems. These solutions were then patented. TRIZ is essentially a problem-solving technique that is based upon logic and knowledge (Mann, 2002, pp.86-90). The TRIZ process is depicted in **Figure 2.22** Mann (2007b, p.31).

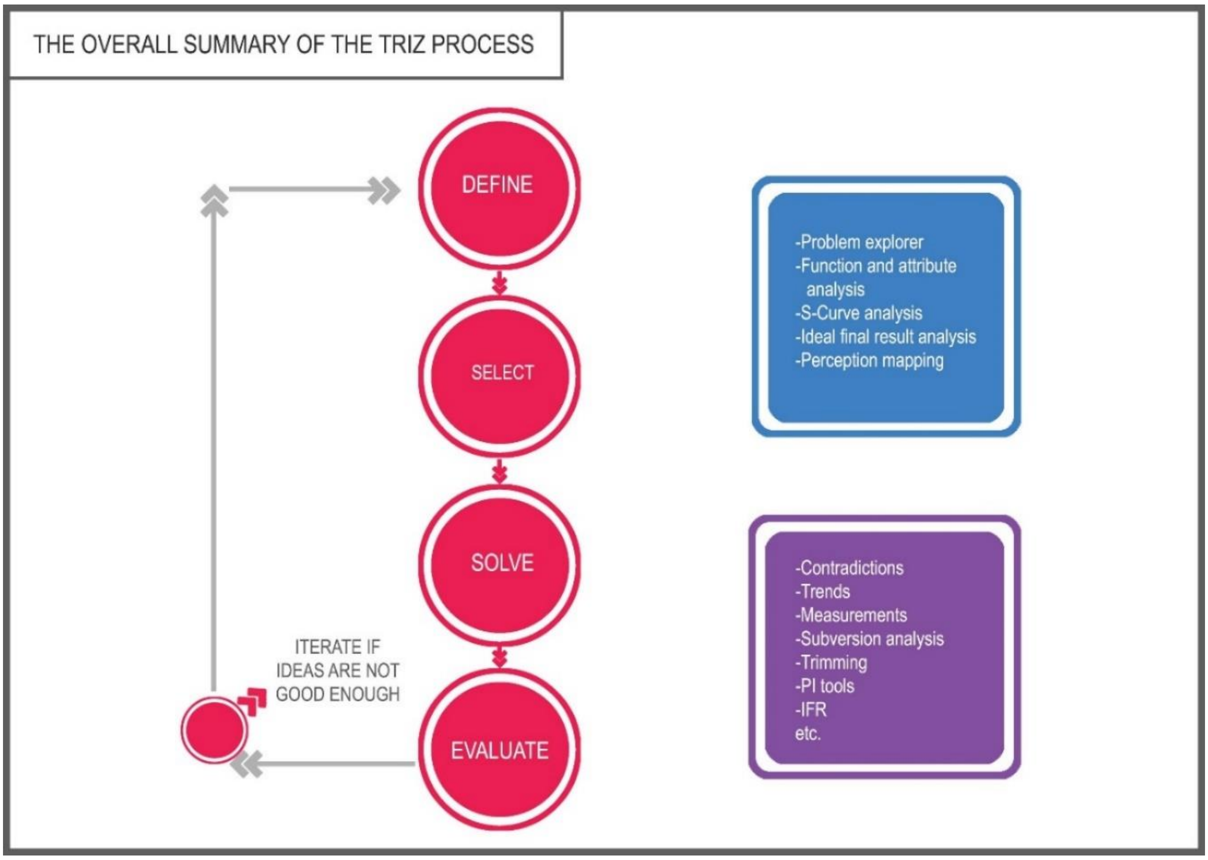

Figure 2.22 The overall summary of the TRIZ process (Mann, 2007b)

It is said that due to its structure and algorithmic approach, it is reliable, repeatable and predictable. TRIZ also contains functional-analysis techniques, substance-field techniques, methods to identify trends and "lines of evolution" (Gadd, 2011). Yonghai and Jianhau (2009, p.529) describe TRIZ as "an international science of creativity that relies on the studies of patterns of problems and solutions, not on the spontaneous and intuitive creativity of individuals or groups." More than one million patents worldwide have been analysed to date to discover the patterns that predict breakthrough solutions to problems. The contention is that most problems were already solved in the past and the challenge now is to find that solution and to adapt it to a specific issue at hand. Once one has discovered the patterns that led to the solutions one can apply these patterns to any new problem. Three initial findings are reported:

Firstly, that problems and solutions are repeated across industries and sciences.

Secondly, the classification of contradictions in each problem predicts the creative solution to that problem. Thirdly, that patterns of technical evolution are repeated across industry and sciences.

"Much of the practice of TRIZ consists of learning these repeating patterns of problems solutions, patterns of technical evolution and methods of using scientific effects, and then applying the general TRIZ patterns to the specific situation that confronts the developer" Yonghai and Jianhau (2009, p.529).

A fundamental concept in TRIZ is the elimination of contradictions, (e.g. coffee must be hot but cold enough not to burn a person, or software should be complex, [to have many features] but should be simple and easy to learn). TRIZ employs a separation principle to solve or eliminate contradictions. The separation principles include four methods, namely:

a) Separation in space (separation of two conflicting parts in different spaces that reduce difficulty of problems).
b) Separation in time.
c) Phase transformation (separation on condition).
d) System transformation (separation of parts form the whole).

Altshuller and his team initially extracted from over 200 000 patents, 39 standard technical characteristics or parameters that cause conflict. The research into patents was subsequently expanded and by 1990 over 2 million patents had been investigated (Hirst, 2007) and the list of 39 standard technical characteristics has been extended to 50 parameters (Mann, 2009, p.8). Altshuller also extracted 40 inventive principles (TRIZ. 40 TRIZ Principles). These inventive principles are suggestions that will help the engineer to find a highly inventive solution to a problem. (Mann, 2009) developed 42 corollaries or combined/special principles from the 40 inventive principles. The list of 40 inventive principles, the corollaries, and the 50 standard technical characteristics or parameters are shown in **Appendix D**, **Tables D1**, **D2** and **D3**.

It is interesting to note that Yang and Zhang (2000, p.242) did a comparison between TRIZ and axiomatic design. They found several common areas existing between the two methods. However, "axiomatic design pays much attention to functional, physical and process hierarchies in the design of a system." TRIZ abstracts the design problem as either a contradiction or the required functional realisation. "Then corresponding knowledge base tools are applied once the problem is analysed and modelled. Axiomatic design lacks the vast knowledge base to support the application of its theory, so the creative process of conceptualizing and devising a solution is not very clear" (Yang and Zhang, 2000, p.242).

A study was done by Zhao and Huang (2009) regarding enterprise knowledge management, and more specifically how the TRIZ method, can be utilised to enhance knowledge management. The model comprises six parts: "knowledge base, knowledge-management system (KBS), knowledge operating process, knowledge management strategic environment, knowledge visualization environment and TRIZ tool (knowledge activation, reorganization and integration." Through the interplay of these parts, an enterprise can manage knowledge effectively. The model can help technical innovation and also the integration of enterprise knowledge (Zhao and Huang, 2009, p.4).

Successful innovation happens when factors such as conflicts, trade-offs and contradictions are "eliminated". In this research, the concept of "constraint" is added to the list. It is not always a case of elimination, but to challenge the above factors to such an extent that a step-change jump in the direction of "Ideal Final Result" takes place (Mann, 2007b, p.131). In using the contradiction-problem-solving methodology, 50 parameters are compared to one another in a so-called "contradiction matrix", and contradictions between parameters, applicable to the problem or issue at hand are identified. For each contradiction, four and up to seven most frequently applied inventive principles are named. When a specific inventive principle or principles are selected, one could now work with these principles to guide one's thoughts, knowing that through the results of all the patent research one can confidently peruse these principles to arrive at one or more solutions.

The TRIZ Contradiction Matrix can be seen in Mann (2009, 2007a and 2007b).

The TRIZ process is depicted in **Figure 2.23.**

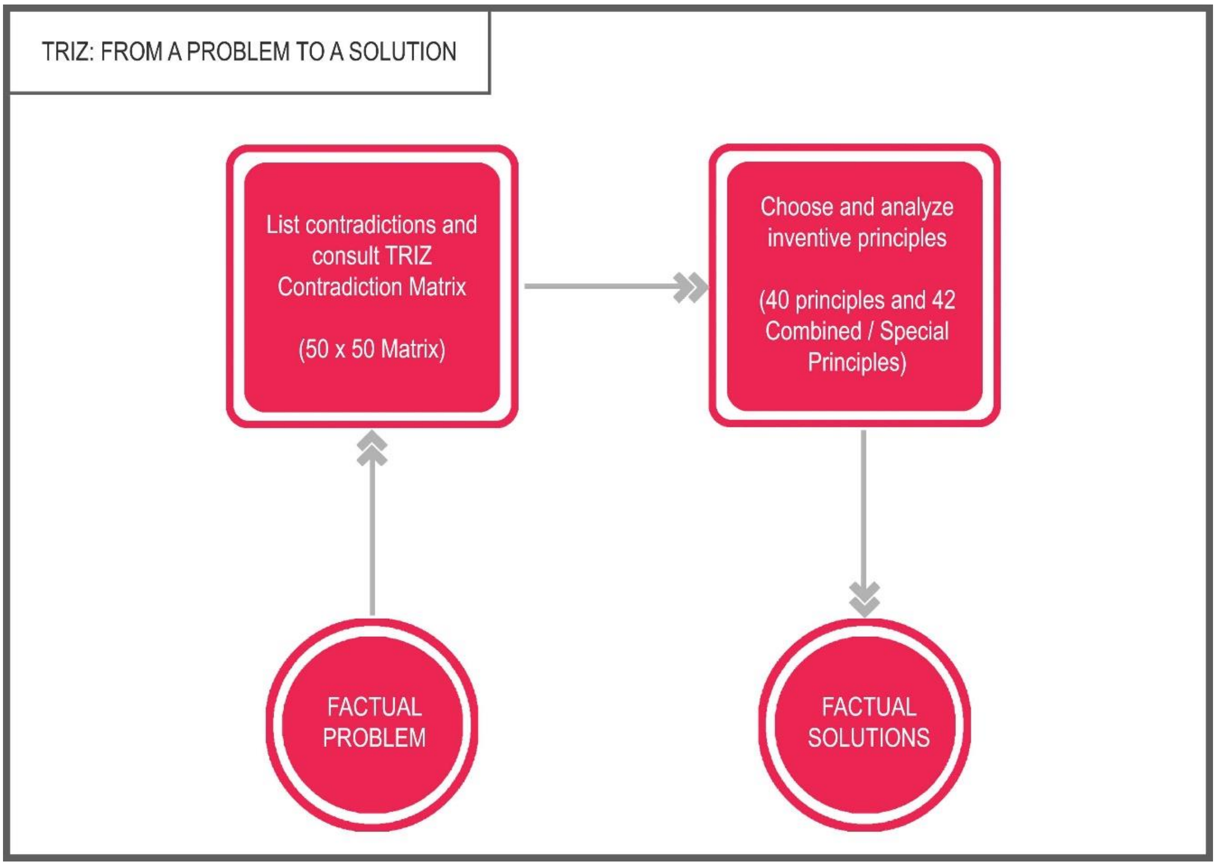

Figure 2.23 TRIZ: From a problem to a solution

The technique starts off with a problem statement. It is of great importance to uncover the real problem or the root problem. One then proceeds to identify the physical contradictions. The following example illustrates the thinking. When one considers the speed of a motor vehicle and the amount of energy required to attain a certain speed, one would realise that the greater the speed, the more energy would be required. One may decide that in the light of the current high energy costs and unwanted greenhouse effects resulting from emissions from fuel, a contradiction arises. The contradiction is that one may desire a high speed BUT not use more energy. One wants to ideally have increased speed AND less energy use. One then transposes the physical contradiction to a technical contradiction (the "but" issues – speed increased, BUT energy increases). One can then identify the generic contradiction from the TRIZ contradiction matrix (Mann, 2009). On the left-hand side (rows) of the matrix are the parameters that are getting better or improve, e.g., the speed increases and one can argue that speed improves). At the top (columns) the contradiction matrix shows the parameters that are getting worse, e.g. energy consumption. Going down the column and meeting the corresponding row, a common cell can be identified. This meeting cell in the matrix between the selected row and column then provides a number of typical generic inventive principles for that particular set of contradictory parameters. ("Speed", no 14 on left hand side, and "Energy

Used by Moving Object", no 16.) These generic inventive principles can then lead to the solution of the particular problem at hand. In the above example, inventive principles 35, 28, 19 and 12 are found to be most applicable (these 40 inventive principles are shown on the right hand side of the matrix). These principles in the cell are placed in the hierarchy of *mostly used* to *less frequently used*. (No. 35 is *parameter changes*, No. 28 is *mechanics substitution*, No. 19 is *periodic action*, and No. 12 is *equipotentiality*.) One's thoughts are directed to these generic solutions and one can then think of innovative ways to satisfy or address these suggested solutions.

The process is therefore as follows:

i) Identify the specific factual problem.
ii) Find the contradictions.
iii) Look up the generic inventive principles.
iv) Find the practical, factual solution.

When considering the above suggestion of "parameter changes", it can be thought of to reduce friction. This can, for example, be done by reducing the number of moving parts. The rotary engine or turbine engines are examples. Electric drives, the rotary engine or nuclear-powered drives are potential solutions to the "mechanics substitution" idea. A flywheel-driven arrangement can meet the principle of "periodic action". This has found its way into applications in buses and trains. "Equipotentiality" can be attained by reducing the gradients of railway lines to equalise the potential energy – an accepted design principle on all rail lines and freeways.

Contradiction matrices were now also developed for business applications and further matrices are under development for other sectors (Mann, 2007b.; Zhang, 2010). So far inventive principles have been developed (the 40 principles customised) for architecture, business, construction, food industry, microelectronics, social and for software. (TRIZ's original principles were developed from an engineering perspective.)

A research team is still continuously developing the system from analysis of patents world-wide and through associated studies of contractions. Natural phenomena are also investigated to endeavour explanation of the resolution of contradictions that appeared in nature and how nature had solved the numerous contradictions (Mann, 2002, 2007a and 2007b).

TRIZ partially uses semantic search tools to identify and abstract concepts and to identify contradictions between the concepts found in patent descriptions.

The problem-solving toolkit developed in TRIZ is, in fact, a comprehensive subject as can be seen below, from a summary of the tools and the dates when the tools were primarily developed (Gadd, 2011, pp.376). A short history of development is shown below with the period of first development in the technical field shown in parentheses. Developments are still ongoing.

- 40 Principles (1946-1971).
- ARIZ – Algorithm of Inventive Problem-Solving. This is a systematic problem-solving methodology that can be applied to any problem (1959-1985).
- Separation principles (1973-1985).
- Substance-field analysis and function analysis (1973-1985).
- 76 Standard Solutions (based upon Substance-Field analysis) (1975-1985).
- Natural effects (Scientific effects) (1970-1980).
- Patterns of evolution (1975-1980).

A comprehensive description and analysis of all the above TRIZ elements are beyond the scope of this study. However, it is an important tool and must be integrated fully into problem-solving techniques and in the logic base.

The principles applied in TRIZ's problem-solving represents, a type of logic base. This conclusion is made on the basis that TRIZ seeks to analyse a particular situation and then applies a technique referred to by TRIZ as the contradiction matrix to find, through the consideration of contradictions, guidelines or standard solutions to specific problems. In this research, the development of a logic base focuses on the systematic classification of knowledge and on the analysis of the attributes of the knowledge to enable replication and therefore to enhance knowledge. The TRIZ system investigates contradictions, primarily derived from S-Field relationships between parameters. In the logic base, the pairing of concepts or attributes takes place. This pairing leads to some effects on the system, or on other or new concepts that need to be evaluated. The assessment of the effects or concepts can be done against a set of criteria. Such as goals or objectives. The logic base, therefore, focuses on a wider spectrum of issues to enable knowledge enhancement in engineering. The logic base is designed in Chapter 5 incorporating problem-solving techniques, including TRIZ.

2.7.13 The Theory of Constraints (TOC)

This technique (also referred to as a management science; McMullen, 1998) was developed by Eliyahu Goldratt in 1948. He published a book entitled "The goal: a process of ongoing improvement" (Goldratt, 1997), where he introduced his novel way of assessing processes with the view of improving throughput. He also added the TVA (Throughput Value-added System) management system (McMullen, 1998).

The TOC offers a methodology to draw “current reality trees” which represents a thinking process to identify a core problem, which may be thought of as the invisible constraint responsible for many of the system’s current problems. It identifies core competencies and strengths and is used to simplify understanding of why change is necessary for a given environment. The tool helps to see order amidst chaos. Current reality trees are made up of entities consisting of statements or expressions that are linked to show causes and effects. From these relationships, core causes may be identified. The origin of TOC is in the manufacturing environment. However, the applications of TOC became applicable to management science in general. It is beyond the scope of this study to provide a comprehensive exposition of TOC.

Some aspects of this technique will be further dealt with in **Chapter 5.**

2.8 ENGINEERING DESIGN

2.8.1 General remarks

Engineering design is the most important output of civil engineering. The process of design is where problem-solving methods are applied and the solutions to problems transferred to constructible elements. Design can be construed as a particular kind of problem-solving and therefore of knowledge-creation process. Bajaria (2000, p.2) remarked that “we are most interested in the systematic use of existing knowledge.” However, we are also most interested in creating new knowledge. Both are equally important. “The fundamental belief is that we can never claim to have sufficient knowledge. We need to replenish our knowledge on a continuous base. Many unsolved problems evidence this need.” Bajaria (2000, p.2) stated that, “there exists an unjustified belief that knowledge management includes both the creation of knowledge as well as the systemization of existing knowledge. However, KM (Knowledge Management) solely deals with knowns. With KC (Knowledge Creation) we are investigating unknowns. Success depends upon the successful pairing of knowledge management and knowledge creation.” (Note: parenthesis added.) In this sense, a new design centres on something that did not exist before. When a design is done, existing knowledge is synthesised and new knowledge is created when solving problems. These problems often arise from conflicts between Functional Requirements (FRs).

The process of engineering design always starts with the definition of what one wants to achieve and deliver. The goal is to produce a design that best satisfies needs.

A design process provides valuable insights into a process that is dependent upon experience and so-called *know-how*. It is the culmination of thought processes and serves as an appropriate subject to analyse, for the discovery of the underlying tacit knowledge and also to establish how it is made explicit during the design process. A design is delivered as an outcome of a process and made explicit and tangible by the production of plans and specifications and by way of construction. The performance of the constructed item can be evaluated and the quality of the design can be assessed against its original intention or performance goals. Should a final product fail to meet the appropriate design intent, one can establish the causes and learn from it. Design processes apply knowledge and incorporate elements, among other things, of case-based reasoning, evidence-based learning, experiential learning, reflective learning, critical thinking and knowledge spill-over. During the design process, information and knowledge are applied to create something new to meet Functional Requirements (FRs).

In the field of engineering, design is probably the single most important and used method in knowledge conversion. The obvious example is the conversion of tacit knowledge into explicit knowledge when a client's needs (which start off in the tacit dimension) are translated into designs and then also into specifications. During a design process, socialisation and externalisation take place. This happens when the designers consult each other, when project teams meet to discuss the designs and when designers interact with clients, sponsors and with external parties. (Such external parties are, for example, suppliers, service providers and regulatory authorities.)

Designing also involves creative processes as stated by Suh (1990, p.26): "Analogies, extrapolation, interpolate, reduce complex arrays of facts, data points, and information to a limited number of critical sets of variables and combines facts to create new solutions."

In a draft research paper by Salter and Gann (2003), the authors noted that designers who are involved in complex, non-routine design processes rely heavily on face-to-face conversations. This interaction is, in essence, a socialisation process such as tacit-to-tacit and tacit to explicit knowledge conversion.

If one reverses the process ("reverse engineering") and looks back into the causes of a failed product (for example by using Root-Cause Analysis), one should be able to discover where things went wrong in the first instance. This learning process stimulates internalisation where explicit knowledge is converted to tacit knowledge (processes of updating of existing knowledge take place).

A logic base relating to design can be constructed by having regard to the input parameters of a design and to define a construct or process that would lead and guide the user of the logic base towards reducing the possibility of mistakes or errors in judgment during the design process.

2.8.2 Axiomatic design

In this section extensive reference is made to the books written by Suh (1990; 2001) on the subject of "axiomatic design". (Suh is the originator of axiomatic design.)

Suh outlines basic approaches to design, namely, an algorithmic and an axiomatic approach. The algorithmic approach endeavours to identify and prescribe the design process that would lead to a design that satisfies the design goals. Axiomatic design begins with the premise, "that there are generalizable principles that govern the underlying behaviour of the system being investigated" (Suh,2001, p.9). The axiomatic approach is based on the abstraction of good design decisions and processes. Axioms are general principles or self-evident truths that cannot be derived or proven true, but for which there are no counter-examples or exceptions. "Axioms generate new abstract concepts such as force, energy and entropy that are the results of Newton's laws and thermodynamic laws. […] The axiomatic approach to design and manufacturing was born out of the need to develop the disciplinary base for these fields, and to teach engineering students generalized fundamental knowledge.[…] The basic assumption of an axiomatic approach to design is that there exists a fundamental set of principles that determines good design practice" (Suh, 2001, p.9).

In the development of the axioms, Suh and his team identified common elements in several successful projects. These common elements were then condensed and used in formulating axioms. The purpose of the axioms is also to limit the number of variables that need to be considered and analysed to enable the generation of efficient and effective design solutions. Axioms can also be seen to be rules that should be followed to optimise designs.

"Axioms are hypothesized from a large number of observations by noting the common phenomena shared by all cases; they cannot be proven or derived, but they can be invalidated by counter-examples or exceptions" (Suh, 2001, p.12).

Suh, (2001, p.16) states the following axioms:

“**Axiom 1**: The Independence axiom

Maintain the independence of Functional Requirements” (FRs). This means that all FRs and their associated Design Parameters (DPs) remain independently attached. If one adjusts a DP to satisfy a FR, you do this without affecting other FRs. Designs that do not satisfy the independence axiom are called coupled. Designs that do satisfy the independence axiom are called uncoupled or decoupled. Decoupled designs are the most desired (Silverstein, Samuel and DeCarlo, 2012, pp.223-230).

“**Axiom 2**: The Information axiom

Minimize the information content of the design” (Suh 2001, p.12). This is based on the information axiom stating that “the best design is the one with the least information content – while also satisfying the independence axiom. Information content is defined in terms of probability: the more likely the design is to reduce the influence of variation from process parameter changes, different customer-usage conditions, and repeated use, the better it meets the information axiom.[…] A design meeting the information axiom is called a robust design” (Silverstein, Samuel and DeCarlo, 2012, p.224).

In support of axioms, Suh (2001, pp.12, 14) also defines theorems, corollaries, Functional Requirements (FRs) Design Parameters (DPs), constraints and process variables.
The principles of axiomatic design provide useful tools for the development of a logic base. Axioms essentially reduce the number of variables and therefore simplify the construction of a knowledge base. In the process of knowledge development, the vastness of knowledge can, therefore, be simplified through the identification of common elements. Appropriate axioms can be defined in the field of knowledge creation to enhance the simplicity and efficacy thereof. The formulation of axioms strongly agrees with the approach followed by TRIZ (Mann, 2009, p.240).

This researcher contends that generalised principles that govern the behaviour of a system can be identified. Such principles will be invaluable in the construction of a logic base.

Synthesising the above discussions, a simplified model is compiled, depicting the relationships between knowledge acquisition and design (refer to **Figure 2.24**).This model is derived by using an analogous approach such as that developed by Snowden for the processes in the Cynefin framework. The two main axes chosen are the knowledge that one has about a situation or what a certain design requires. It also reflects the level of tacit knowledge that the person (or even group of designers) has. The orthogonal axis indicates the complexity of the problem or situation. The axes are each calibrated by the amount of knowledge and with the degree of complexity as shown on the diagram. There is no correct or incorrect path that should be followed. Everything depends on the situation or problem and how it unfolds during the development of the design. However, it indicates that, if a little knowledge is available, a design may start with research and analysis. If the situation is highly complex, for instance, one will become aware of more and more variables. When trying to reach consensus about the status and on the number or variables, or when the number of variables (and unknowns) increases, the entire design process slows down and can even come to a halt. Whereas, if the situation becomes more complicated, a stage may be reached when one uses knowledge and experience to make rational choices and assumptions to gain momentum again and to move towards a positive result (approximately path A in **Figure 2.24**). Another possible route is when a relatively experienced and knowledgeable person or group starts by using their previous experience and knowledge about the situation, make the necessary rational choices and assumptions and move to the successful outcome. Another path could be when a highly experienced person might start a design based only on intuition (resembling tacit knowledge). Reflection takes place and the design can be taken to a successful conclusion.

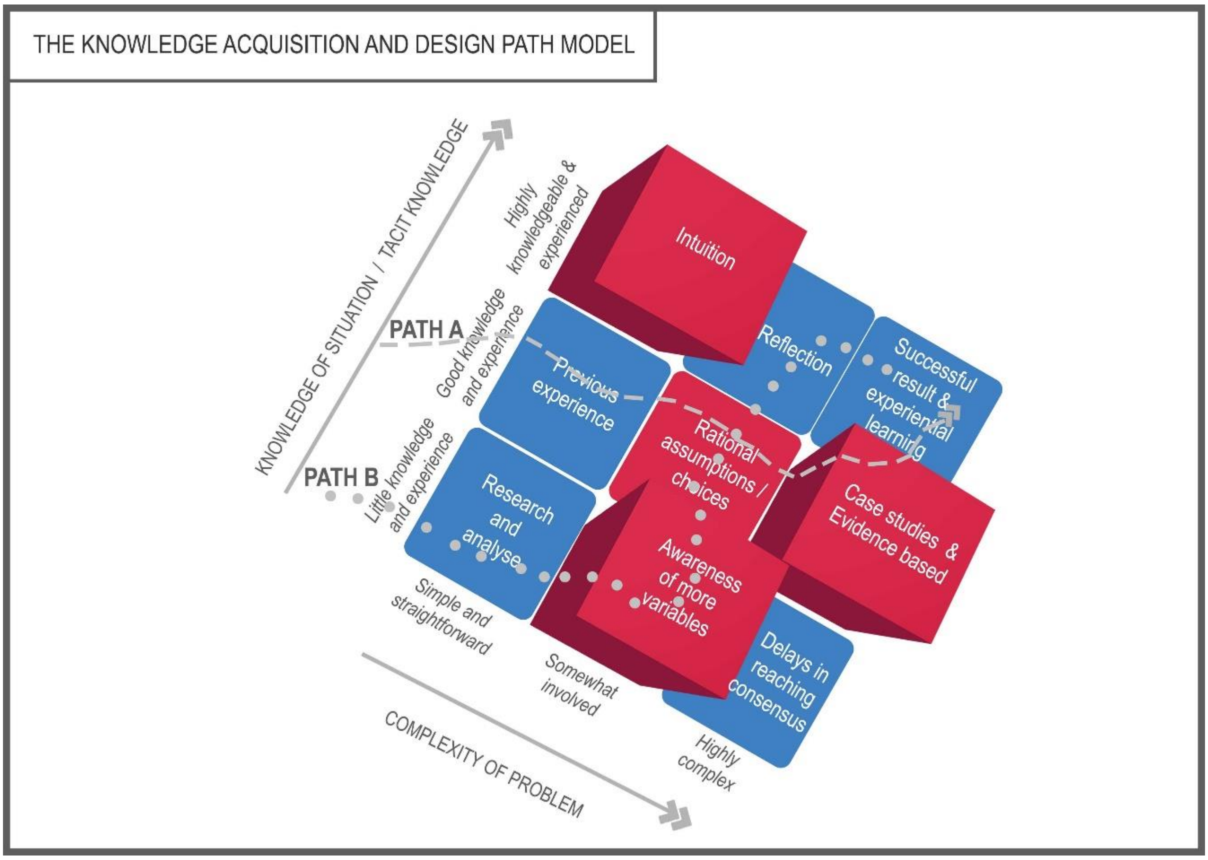

Figure 2.24 The knowledge acquisition and design path model

2.8.3 Summary and concluding remarks

In the above sections, aspects regarding knowledge creation were studied. The most important point for this study is the process of knowledge acquisition and knowledge creation. An overview is given of knowledge acquisition methods. The following methods were covered:

a) Case-based reasoning
b) Evidence-based management
c) Experiential learning
d) Reflective learning
e) Critical thinking
f) Knowledge spill-over
g) Sense making – Cynefin framework

From the above treatise, one can integrate knowledge acquisition and problem-solving methods. Knowledge acquisition is considered to be a forerunner and as such an integral part of problem-solving. A further deduction is made that knowledge reuse stems from existing knowledge, and therefore also from knowledge acquisition that comes from or incorporates problem-solving. This is, in fact, mentioned in the literature of knowledge acquisition and is considered highly appropriate for the purpose of this research and development of a logic base. Engineering design was covered, more specifically that of axiomatic design. This was brought into the context with problem-solving techniques. The most important aspects are the systematic design process and the definition of axioms, theorems and corollaries. Problem-solving techniques were then studied. A selection was made of some techniques that were considered to best support the development of a logic base. The methods are:

- The trigger-word technique
- Checklists
- Morphological analysis
- Attribute-seeking technique
- Gordon Technique (also referred to as Synectics)
- Brainstorming
- Analysis and synthesis
- Root-Cause Analysis (RCA)
- Failure-Modes, Effect and Criticality Analysis (FMECA)
- Functional Systems Analysis Technique
- Hierarchy of Objectives Technique
- Theory of Inventive Problem Solving (TRIZ)

- Theory of Constraints (TOC)
- Engineering design

In each part the relevance of the particular topic to this research was highlighted.
In summary, aspects that can be highlighted from the various problem-solving techniques are:

- Identification and definition of elements and context.
- Causes and effects are uncovered.
- Relationships are investigated (common to morphological analysis, attribute seeking, RCA, FMECA, TRIZ and TOC).
- Prompting is done to expand discovery.
- Classification is made of themes.
- Anticipative thinking techniques are applied.
- Analogies are used.
- Analysis and solving of contradictions take place.
- Hierarchical divisions are made.
- Constraints are uncovered.

In addressing or resolving problems, the study of relationships play a dominant role in many of the techniques. The resolution of conflicts or contradictions and constraints are secondary, common elements in all the problem-solving techniques and play major roles in many of the knowledge-acquisition techniques, especially in the Cynefin framework, which is also a decision- or problem-solving framework. The identification and definition of elements and context play an over-arching role in all problem-solving and knowledge acquisition methods.

When one considers these highlights, attributes for the logic base can be identified. These attributes are shown in the Table 2.4:

Table 2.4 Attributes of the proposed logic base

TOPIC	CHARACTERISTICS	PROPOSED ATTRIBUTES OF LOGIC BASE
• Knowledge	• Definition of knowledge. • Knowledge hierarchy. • Types of knowledge, knowledge conversion – four processes of	• Must lead to effective actions. • Must take situations and uncertainties into account.

TOPIC	CHARACTERISTICS	PROPOSED ATTRIBUTES OF LOGIC BASE
	knowledge conversion plus 3rd. dimensions of knowledge reuse. • Prior understanding, mental models. • Analogies, metaphors, redundancy. • Methods of knowledge creation. • Reuse of knowledge – content, ontologies and taxonomies.	• Tacit and explicit knowledge must be recognised. • Make use of knowledge-conversion methods. • Contain analogies, mental models and metaphor. • Must contain redundancies. • Must integrate with organisational strategies, policies, content, technology and culture.
• Case-based reasoning	• Reference to previous experience and knowledge.	• Specific experiences must be recordable.
• Evidence-based management	• Knowledge is gained by observing evidence in support of or in response to actions.	• Evidence-based updating of knowledge must be possible.
• Experiential learning	• Act, reflect, conceptualise and apply.	• This procedure should be embedded in the logic base.
• Reflective learning	• Past experiences are used.	• Exploring issues (logically) and updating knowledge.
• Critical thinking	• Knowledge, context and assumptions are important.	• Context must be provided for knowledge presented.
• Knowledge • spill-over	• Knowledge from different fields can be employed to solve problems.	• Expansion of knowledge to cover a wider field is essential. This includes knowledge-sharing capabilities.

TOPIC	CHARACTERISTICS	PROPOSED ATTRIBUTES OF LOGIC BASE
• Trigger-word technique	• Analogies of distant domains are used to suggest solutions.	• Triggers must be identified.
• Checklists	• The outcomes that must be considered.	• Where appropriate, checklist must be generated as actionable items.
• Morphological analysis	• Matrix of multi-dimensional attributes that are investigated.	• All attributes must be identified to establish relationships and to extract logic.
• Attribute-seeking technique	• Attributes are identified and listed for consideration.	• A process to identify attributes must be part of the logic base.
• Synectics	• Different types of metaphors and analogies are used.	• Reference must be made to analogies – put in context.
• Brainstorming	• Mainly a group activity.	• This can act as a method to input parameters in the logic base.
• Analysis and synthesis	• Causes and effects are used.	• All causes and effects of actions must be analysable.
• Root-Cause Analysis (RCA)	• Analysis of possible causes of failure (mainly used after the event).	• The root-cause discovery procedure must form part of the logic base.
• FMECA	• Systematic component analysis of potential failures – preventative.	• This method must be embedded.
• FAST & HOT	• Systematic analysis of objectives using: How? Why? and When?	• This method must be embedded.
• TRIZ	• Knowledge base of patterns of problems and solutions, using contradictions.	• This is in fact defined as a logic base. This can be used

TOPIC	CHARACTERISTICS	PROPOSED ATTRIBUTES OF LOGIC BASE
		as a powerful supporting tool.
• TOC	• Current reality trees and cause-and-effect relationships evaluated.	• The evaluation of cause-and-effects is a most important part of problem-solving and therefore of knowledge conversion from tacit to explicit knowledge.
• Engineering design	• FRs (Functional Requirements) and DPs (Design Parameters), axioms, theorems and corollaries are defined.	• Appropriate similar FRs, DPs axioms, theorems and corollaries must be defined and satisfied in the logic base.

The above problem-solving techniques are considered sufficient for the purpose of the design of the logic base. The main purpose was to consider a selected number of techniques to analyse and to find the commonalities among the techniques. This does not mean that other problem-solving techniques cannot be used in the logic base.

2.8.4 Synthesis of problem-solving techniques

Considering the foregoing, one can argue that problem-solving techniques can be sub-divided into the following categories:

a) Generation/discovery of new thoughts (Trigger-word technique, brainstorming, synectics morphological analysis)

b) Synthesis and analysis (Attributes are identified and analysed)

c) Methodical parametric studies (RCA, FMECA, FAST, HOT, TRIZ & TOC)

2.9 THE STRUCTURING AND ARCHITECTURE OF KNOWLEDGE

2.9.1 Taxonomy

a) Introduction to taxonomies

In knowledge management, there is a need to categorise knowledge. In section 2.3.2 the categorisation of concepts was discussed and the need to do categorisation of knowledge was mentioned (also referred to as the classification in this study). One of the obvious sources of knowledge is written matter such as magazine articles, journals, company documents and other information that are classified to enable easy retrieval. This implies that one has to *structure* knowledge. All document-management systems and filing systems classify information by structuring it. An example is the arrangement of folders on computers which most people do on a daily basis. For example, the creation of main folders and sub-folders or sub-sub-folders is nothing else than the creation of taxonomies. People create main folders and sub-folders according to some form of logic – probably intuitively and sometimes haphazardly with no apparent logic. It is highly improbable that two persons would create the same taxonomy for their own filing system. People would also call things by different names. This is because there are no fixed rules and it is up to each person to decide for himself or herself what the taxonomies should look like. Very little, if any, planning goes into the process and there are little of no cross-linking and referencing. In certain businesses it may be expected by the organisation for each user to employ a prescribed taxonomy with standardised nomenclature. This is done for ease of retrieval by any user or groups of users. Sharing of folders on a server and between individuals then becomes much easier. When filing is systematically done in a standardised format, searching and recovery of documents become easier. If documents were filed in "wrong" folders, recovery becomes quite difficult. Fortunately, various search facilities are available and when keywords are used, or some other characteristics of the "missing" document are entered into the search engine, the software will mostly recover the "missing" document. When the number of users increase and vast volumes of documentation and other information are shared by vast numbers of users around the world, taxonomies become necessary to simplify the search for information. As an example, if one takes the World Wide Web (www), where millions or even billions of users search for information, share information and communicate, one can understand the need to systematise the taxonomies and apply powerful search engines to recover information. It is, therefore, necessary to research this topic, because in the development of the logic base, knowledge will be shared by many users and it is equally important that one understands what a taxonomy is, what its characteristics are and how it is applied. The sections below deal with taxonomy.

In the world of computer software and artificial intelligence (AI), a related term “ontology” is mostly used. The characteristics of taxonomies and ontologies are very similar, but there are important differences, especially in the computing world. In the sections below, consideration is firstly given to taxonomies, and after that to ontologies.

b) Definitions

Taxonomy:

To get an understanding of the term, the following exposition is given:

Taxonomy is described in the OED (2010) as:

“1. Classification, esp. in relation to its general laws or principles; that department of science, or of a particular science subject, which consists of or relates to classification; esp. the systematic classification of living organisms.”

“1927 Amer. Mercury May 84/2 one of the oldest branches of science, taxonomy or systematics – the study of the relationships and kinds of living animals.”

“1972 Sci. Amer. Jan 116/3 His taxonomy of bridge structures before the age of steel and concrete.”

Taxonomy is described by Issa and Mutis (2015) as a class hierarchy and indispensable component for organising concepts contained in a body of knowledge. Taxonomy is the science of classification. Originally taxonomy was used to classify organisms, but “in a more general setting, it refers to the classification of things or concepts, as well as schemes underlying such classification. Also, taxonomy normally has some hierarchical relationships embedded in its classifications” (Sun, Wang and Yu, 2011). However, in a knowledge management application, taxonomies are considered narrower than ontologies since ontologies apply to a larger variety of relation types. It is also possible to indicate the relationships between the terms contained in the scheme (Sun, Wang and Yu, 2011).

c) Characteristics of taxonomies

There are three basic characteristics of a taxonomy for knowledge management (Lambe, 2007, p5):

i) A taxonomy is a form of classification scheme;

ii) Taxonomies are semantic; that is, they provide a controlled vocabulary to describe their knowledge and information assets, and express the relationships between terms in the taxonomy;

iii) A taxonomy is a kind of knowledge map. A taxonomy should give its user an immediate grasp of the overall structure of the knowledge domain covered. The taxonomy should be comprehensive, predictable and easy to navigate.

Gašević, Djuric and Devedžić (2009) describe a taxonomy as a “hierarchical categorization or classification of entities within a domain. It is also a clustering of entities based upon common ontological characteristics. The classification/clustering is organized according to a predetermined system. A good taxonomy should separate its corresponding entities into mutually exclusive, unambiguous groups and subgroups that, taken together, include all possibilities.” Taxonomies are widely used in the fields of, inter alia, biological sciences, medical sciences, education, numeric studies, software, engineering and in knowledge management. For example, the “Wand Engineering Taxonomy” (2017) is commercially available and covers the following:

- Engineering design process
- Engineering documents
- Engineering drawings
- Engineering materials
- Engineering standards and codes organisations

In dealing with taxonomies, the essential characteristics are that they represent systematic classifications according to some rules. When applying a systematic classification, it is necessary to determine an overall logic or pattern of inherent attributes of the entity or subject at hand and then to do classifications. The logic built into the rules of a classification system gives valuable insights into the attributes and its characteristics to consider. New learnings about certain attributes and characteristics can be recorded in the taxonomies. Since basic attributes are reflected in taxonomies, one can deduce certain attributes of lower order elements relative to the higher order elements, since lower elements contain or inherited attributes of higher order elements. (This is particularly evident in the biological field where the high-order attribute, “vertebrate”, is an attribute of all the lower classes.) The use of primary attributes represents relationships, presents opportunities for knowledge preservation, transfer of knowledge and even for developing new knowledge.

By way of an example, one can consider Bloom’s taxonomy (Forehand, 2010). This taxonomy contains three domains of “emerging perspectives on learning, teaching and technology”

(Forehand, 2010, p.3). Bloom's taxonomy is a multi-tiered model of classifying thinking according to six cognitive levels of complexity. In the cognitive domain, he classifies thinking into six levels of complexity (lowest to the highest), namely: "Remembering, understanding, applying, analysing, evaluating and creating." The classification provides valuable insights into the science of thinking.

Summarising the meaning of taxonomy from the dictionaries, the following explanations can be given:

- A taxonomy is a classification system.
- It is structurally organised.
- It is hierarchical.
- It comprises the assemblage of things.
- It comprises connected objects or groups.
- There are relationships between or among taxons (individual objects of a taxonomy).
- Taxons are interdependent.
- The taxons form a complex unity, i.e., part of a whole.
- There is a particular purpose for the taxonomy (to constitute a part of a whole).

From what the other authors explained about taxonomies, the following can be added:

- A taxonomy must be done according to a hierarchy.
- A nomenclature used in the taxonomy must be unambiguous.
- Clustering is done according to common ontological characteristics.
- The organisation of the classification is done according to a predetermined system.
- The logic or patterns of attributes will determine the classification.
- There must be logic in the rules of the classification system.
- One must be able to deduce attributes of lower order taxons from properties of the higher order taxons.
- Taxonomies can be multi-tiered.

When one considers the contribution of taxonomy to knowledge management, an immediate obvious advantage is that information can be logically stored and recovered. However, there is more to it. By breaking down a whole into parts, more is learned about the system than just a single item. An example is on engineering construction projects where one may identify taxons (objects of a taxonomy) such as, "concrete structures". If the concrete structures have taxons for "pre-stress tendons", one can deduce that there are concrete structures with major spans or loads that have the need to employ pre-stress tendons. The scope of the construction work is therefore contained in the taxonomy provided. However, the taxons do not contain much more than objects or elements. One has to study the files that are connected to specific folders to get more details of what information is given. The information files associated with or attached to taxons can contain as much knowledge as one needs. The information files could contain videos of how to do certain tasks or can contain training material, etc.

When one considers linking, for example, the information in the document that is stored in the folder to the taxon – it becomes a rather different set of information. This led to the definition of the term "ontology" that is specifically used in computer science and that carries attributes in a standardised format, readable by computers. This is explained in the section below.

2.9.2 Ontology

a) Introduction

In the quest to record and share knowledge, databases and knowledge bases are created, stored and manipulated by computing systems. Models possessing various properties are used and integrated into network systems with appropriate computer language protocols to enable sharing of knowledge over the widest possible spectrum of users in different domains. The sharing of information by various systems defines the interoperability among the systems.

In this research, dealing with the quest of knowledge creation and the design of a logic base, the application in computing is of fundamental importance. The logic base stands centrally in the way that users interact with knowledge bases and share knowledge. To facilitate the sharing of knowledge, computer technology is the only plausible way. In the case of this study, it is foreseen that the logic base would function and interact with existing knowledge bases and with new knowledge bases that will develop over time. The need for knowledge sharing stems from the field of Artificial Intelligence (AI). Since natural language cannot easily be made recognisable by computers, it was necessary to develop and standardise vocabulary pertaining to a particular knowledge domain. The term 'ontology' emerged as a means of formally standardising, systematising, classifying and specifying concepts about knowledge in a certain domain (Gašević, Djuric and Devedžić, 2009).

b) Definitions and explanation of ontology

The section below provides a variety of definitions of ontology. These definitions are given to provide a broad coverage of the meanings.

OED 2010 (online) explains the word as follows:

Etymology: The word “ontology” comes from the “post-classical” Latin *ontologia* and is a combination of the words ‘onto’ and ‘logia’ and is described as the science or study of being (that which exists), in ancient Greek.

1. *Philos*. a) The science or study of being; that branch of metaphysics concerned with the nature or essence of being or existence.

   b) As a count noun: a theory or conception relating to the nature of being. Also in extended use.

2. *Logic*. Chiefly with reference to the work of Stanislaw Leśniewski (1886-1939): a system similar in scope to modern predicate logic, which attempts to interpret quantifiers without assuming that anything exists beyond the written expressions.

(Roussey *et al.*, 2011, p.9) remarked that “Artificial Intelligent researchers have initially borrowed the word “ontology” from Philosophy, then the word spread in many scientific domain and ontologies are now used in several developments.”

The most widely used definition of the Artificial Intelligence (AI) and computing, in general, is (merging of definitions of various authors):

“Ontology is a formal, explicit specification of a shared conceptualization” (Borst, 1997; Gruber, 1993).

Gašević, Djuric and Devedžić (2009, p.68) state that “Ontologies represent concepts, their properties, the values of the properties, events and their causes and effects, processes and time. Also, ontologies always include some kind of hierarchy, and most ontologies represent and support generalisations, inheritance, aggregation (part-of) and instantiation relationships among their concepts.”

Borst (1997) explains that “Ontologies are formal descriptions of shared knowledge in a domain. An ontology can be used as a specification of an information system because it specifies the knowledge that is required for the tasks information systems have to perform. Sharing and reuse of ontologies across different domains and applications can, therefore, improve information system design.”

Gašević, Djuric and Devedžić (2009, p.45) describe ontology as: “More precisely, it is the study of categories of things that exist or may exist in some domain.” (Refer also to OED [2010] description of ontology – “being or exists”.) “A domain ontology explains the types of things in that domain. Informally, the ontology of a certain domain is about its terminology (domain vocabulary), all essential concepts in the domain, their classification, their taxonomy, their relations (including all important hierarchies and constraints) and domain axioms." Ontology is the fundamental part of knowledge and that all other knowledge should rely on it and refer to it. Ontology is defined in this instance from the perspective of computing and knowledge presentation.

Guarino (1995, p.5) says of ontology, that it can be seen as the study of the organisation and the nature of the world independently of the form of our knowledge about it.

Hendler (2001) argues that ontology is a set of knowledge terms, including vocabulary, the semantic connections and some simple rules of inference and logic for some particular topic.

Swartout and Tate (1999) offer a useful definition for understanding the essentials of ontology: Ontology is the basic structure or armature (some authors call it scaffolding) around which a knowledge base can be built.

Issa and Mutis (2015, p.222) defines ontology as a "technical term denoting an artefact that is designed for a purpose, which is to enable the modelling of knowledge about some domain, real or imagined." In the 1980s "the Artificial Intelligence community began to use the term ontology to refer to both theory of a modelled world and a component of knowledge systems" (Issa and Mutis, 2015, p.222). Issa and Mutis (2015) mentioned that, as the term ontology received wider acceptance as a technical term in computer science, definitions were merged as a "formal, explicit specification of a shared conceptualization." Also, Issa remarked that, "Ontology and taxonomy are not the same. However, the scope of the ontology is determined by the scope of its taxonomy" (Issa and Mutis, 2015, p.231).

Gašević, Djuric and Devedžić (2009, p.52) describe a taxonomy as follows: "A taxonomy (or concept hierarchy) is a hierarchical categorization or classification of entities within a domain. It is also a clustering of entities based upon common ontological characteristics. The classification/clustering is organized according to a predetermined system." Further, that "Every ontology provides a taxonomy in a machine-readable and machine-processable form. However, an ontology is more than its corresponding taxonomy – it is a full specification of a domain. The vocabulary and the taxonomy of an ontology together provide a conceptual framework for discussion, analysis, or information retrieval in a domain."

c) What should the characteristics be of an ontology?

Borst (1997, p.5) remarks that, "For knowledge sharing and reuse across different applications they must capture the intended meaning of concepts and statements in a domain. Sharing and reuse imply two additional requirements:

Ontologies must aim at a maximum level of genericity and thus bring out commonalities within extensive bodies of detailed and specialised knowledge. They must be able to explicate tacit and meta-level knowledge, as significant parts of domain expertise are highly implicit and have a background nature."

Gruber (1993) describes that "knowledge-based systems are based on heterogeneous hardware platforms and programming languages. This negatively affects interoperability. Knowledge-based systems pose special requirements for interoperability. And for knowledge level communications, three conventions are needed:

- Representation language format
- Agent communication protocol
- Specification of the content of shared knowledge

The first two levels stated above are independent of the content of the knowledge being exchanged or communicated. For establishing agreements about knowledge, such as shared assumptions and models of the world, ontologies can play a software specification role."

d) Reasons for developing ontologies

The need and application for ontologies are clearly demonstrated because ontologies have become common on the World Wide Web (Noy and McGuinness, 2001). In facilitating ontology applications, the advantages of taxonomy as a knowledge-organising scheme include making searches "more robust by relating words matching instead of simple keywords matching; more intelligent browsing interfaces by following the hierarchical structure and by exploring broader/narrower terms; promoting reuse of knowledge and facilitating data interoperability through formally organizing domain knowledge" (Sun, Wang and Yu, 2011) and (Issa and Mutis, 2015, p.223).

Noy and McGuinness (2001, p.1) provide the following reasons for developing an ontology: (format changed):

- "To share a common understanding of the structure of information among people or software agents. (It, therefore, has to be machine readable.)

- To enable reuse of domain knowledge;
- To make domain assumptions explicit;
- To separate domain knowledge from the operational knowledge;
- To analyse domain knowledge."

Further to the analysis of domain knowledge, Noy and McGuinness (2001, p.2) state that "Often an ontology of a domain is not a goal in itself. Developing an ontology is akin to defining a set of data and their structure for other programmes to use." Problem-solving methods, domain-independent applications, and software agents use ontologies and knowledge bases built from ontologies as data. "An ontology together with as set of individual instances of classes constitutes a knowledge base. In reality, there is a fine line where the ontology ends and the knowledge base begins. Classes are the focus of most ontologies" (Noy and McGuinness, 2001, p.2). (Issa and Mutis, 2015, p.v) explain that "Ontologies formalize and present the information that is valuable to the end-users. Ontologies formalize concepts of conforming to a common vocabulary or a set of rules. They allow participants to map the domain concepts to a computable format and to base their business information on the formalization of concepts as a reference."

Gruber (1993, p.2) states that "Pragmatically, a common ontology defines the vocabulary with which queries and assertions are exchanged among agents."

Noy and McGuinness (2001, p.2) remark that classes are the focus of most ontologies. Classes describe concepts in the domain. In his guide, Noy and McGuinness (2001, p.2) note that "for purposes of the guide an ontology is a formal explicit description of concepts in a domain of discourse (classes are sometimes called concepts), properties of each concept describing various features and attributes of the concept (slots – sometimes called roles or properties) and restrictions on slots (facets – sometimes called role restrictions)."

Gómez-Pérez and Benjamins (1999, p.119) said that "PSMs (problem-solving methods) and ontologies can be seen as complementary reusable components to construct knowledge systems from reusable components. Ontologies are concerned with static domain knowledge and PSMs with dynamic reasoning knowledge." Benjamins and Pérez (2000, p.1) remarked that "Ontologies and problem-solving methods are promising candidates for reuse in Knowledge Engineering. Ontologies define domain knowledge at a generic level, while problem-solving methods specify generic reasoning knowledge. Both type of components can be viewed as complementary entities that can be used to configure new knowledge systems from existing reusable components." The integration of ontologies and problem-solving methods is regarded by Benjamins and Pérez (2000, p.1) as possible solutions to problems with interaction that hampered knowledge reuse.in the eighties. In this study the logic base is designed to fulfill this integration function.

Having regard to the reasons for developing ontologies, it is also important to note that different people see or understand ontologies differently. This poses particular reconciliation difficulties when multiple competing ontologies are developed, and very time-consuming, consensus-reaching efforts are made. There are also barriers to the representation of expressiveness and reasoning (Issa and Mutis, 2015). Staab states that, “As a consequence, domain ontologies will always be constrained to a limited domain and a limited group of people. Otherwise, agreement will not be feasible […]. That is clearly one lesson learned from the failure of specifying enterprise-wide data models in the eighties” (Staab and Studer, 2009, p.viii).

d) Ontology types

In the context of knowledge development systems ontologies were classified into domains of information ontologies, linguistic/terminological ontologies, method ontologies, task ontologies and top-level ontologies that cover the different aspects that are relevant when modelling knowledge-based systems. At the beginning of the 2000’s ontologies changed and developed drastically as the realisation grew that conceptual, yet execution models of application domains provided significant added value to knowledge management and e-commerce. The advent of the semantic web provides the conceptual underpinning for making the semantics of metadata machine interpretable (Roussey *et al.*, 2011; Staab and Studer 2009). In this regard, the WWW Consortium (W3C) developed the RDF (Resource Description Framework) language for encoding knowledge on Web pages to make it understandable to electronic agents searching for information. RDF was extended by the Defence Advanced Research Project Agency (DARPA) in conjunction with W3C to make DARPA more expressive and to facilitate agent interaction. Subsequently, DAML (agent mark-up language) was developed. (Issa and Mutis, 2015.)

Several ontologies were developed and standardised. A couple of these are the following:

- SNOMED (large standardised structured vocabularies in medicine.) (Noy and McGuinness, 2001).
- UNSPSC (terminology for products and services under the auspices of the United Nations) (Noy and McGuinness, 2001).
- UNIFORMAT II (an organisation system for building elements.) (Noy and McGuinness, 2001).

- E-COGNOS Project (European construction industry – a construction-specific ontology that comprises an open model-based infrastructure and a set of tools that promote effective knowledge management. (Including capturing, organising, retrieving and disseminating) within collaborative construction environments. One of the objectives is to provide ‘a single point of entry’ to enrich knowledge acquisition.)
  (Wetherill *et al.*, 2002; Zarli, 2000.)

At the time of this research, no other ontology could be discovered in the field of civil engineering, except for the E-COGNOS project relating to the construction industry.

e) Types of knowledge

When dealing in the field of computing and knowledge sharing it is considered worthwhile to relate the previous work on types of knowledge with that understood by the computing world. This topic was covered in paragraph 2.3.4 of this study.

Gašević, Djuric and Devedžić (2009, pp.4-7) discuss knowledge representation in the field of Artificial Intelligence (AI). This branch of computer science “attempts to approximate the results of human reasoning by organising and manipulating factual and heuristic knowledge.” Furthermore, AI endeavours to mirror the workings of the human mind. This involves “gathering and structuring knowledge, problem-solving, and processing natural language.” Storage and retrieval of knowledge are where AI begins. When the desired knowledge is found, it can be used for reasoning and devising problem-solving strategies by means of intelligent programmes to come to conclusions, inferences and explanations. “An important prerequisite for these processes is knowledge acquisition – gathering, organizing, and structuring knowledge about a topic, a domain, or a problem area, in order to prepare it for putting into the system.” Gašević, Djuric and Devedžić (2009, pp.8-11) explain how cognitive science forms a basis for developing theories of the functioning of the human mind so that such theories could be used to emulate human thinking processes. There are currently six widely established cognitive theories about the nature of the representation and computations that can be used to explain how the mind works (Stanford Encyclopedia of Philosophy, 2008). These are:

- formal logic
- rules
- concepts
- analogies

- images and
- neural connections

Gašević, Djuric and Devedžić (2009, p.12) state that cognitive psychologists identified different types of knowledge that humans use and that can be utilised in AI techniques. Humans are capable of organising knowledge in a structured way and use such knowledge to solve problems efficiently. Critiques of cognitive science purport that emotions, consciousness, physical environment in human thinking and social aspects of thought are not incorporated in AI. Critiques also expressed doubt that the human mind can be described by a computational system in the standard sense and suggest that the human mind is a dynamic system or system of quantum physics instead. In this respect, the work done by Mandelbrot (2004) on fractal science may be of great significance as it offers explanation to natural phenomena which may very well present itself in the human mind. This needs further research in future.

Humans organise knowledge, and the following types of knowledge are described by Gašević, Djuric and Devedžić 2009, pp.12-13):

- Procedural knowledge (how to do something)
- Declarative knowledge (details of concepts or objects)
- Meta-knowledge (knowledge about knowledge)
- Heuristic knowledge (rules of thumb guiding problem-solving)
- Structural knowledge (mental knowledge and the organisation thereof)
- Inexact and uncertain knowledge (not precise measures)
- Common-sense knowledge (knowledge that cannot easily be put into precise theories)
- Ontological knowledge (provides meaning to various kinds of categories)

In paragraph 2.4 of this chapter, Zack (1999, p.2) gave an exposition of the different kinds of knowledge, overlapping with the above. Although emanating from a different perspective, it is considered appropriate to augment the above list with the items contemplated by Zack. The additional knowledge types are:

- Causal knowledge (broad, often publicly available, independent of particular events).
- Specific knowledge (context-specific knowledge).

These different types of knowledge need different tools to handle it. There are many knowledge representation languages and each language has its *pros* and *cons* and applicability concerning the knowledge type it can handle the best.

f) Development of an ontology

An ontology models information and knowledge in the form of concept hierarchies (taxonomies), interrelationships between concepts and axioms (Noy and Hafner, 1997; Noy and McGuinness, 2001). Axioms, along with the hierarchal structure and relationships, define the semantics, the meaning of the concepts. Ontologies are thus the foundation of content-based information access and semantic interoperability over the web (Costa and Lima, 2014, p.43).

Noy and McGuinness explains briefly how the ontology is developed (note that there is no "correct" way or methodology for developing ontologies) (Noy and McGuinness, 2001, p.3).

The sequence of developing an ontology is described as follows:

- Define classes in ontology. This is based on language expressivity and formality and the scope of the objects described by the ontology (Roussey *et al.*, 2011).
- Arranging the classes in a taxonomy (sub-class – super-class) hierarchy.
- Defining slots (properties, descriptions, roles, etc.) and the describing of allowed values of the slots.
- Filling in the values of the slots for instances. For example, if a slot is defined as the *maker* of a car, the value of the slot named "maker" may be, for example, "*Toyota*".

Noy and McGuinness further remark that:

- "There is no correct way to model a domain – there are always viable alternatives. The best solution almost always depends on the application that you have in mind and the extensions that you anticipate.
- Ontology development is an iterative process.
- Concepts in the ontology should be close to objects (physical or logical) and relationships in your domain of interest. These are most likely to be nouns (objects) or verbs (relationships) in sentences that describe your domain."

Other characteristics of ontologies are that they should be intuitive, extensible and maintainable. “An ontology is a model of the reality of the world, and the concepts in the ontology must reflect this reality.”

The questions that will define the scope of the ontology are the following:

- What is the domain that the ontology will cover?
- What will the ontology be used for?
- What types of questions must be answered by the information contained in the ontology?
- Who will be the users and who will maintain the ontology?

During the design process of the ontology, these questions may change. Noy and McGuinness explain that one way to determine the scope of an ontology is to sketch a list of questions that the knowledge base, based on the ontology, should be able to answer. Reference is made to “competency questions”. The aim is to determine if the ontology contains sufficient information to answer the anticipated questions. Noy and McGuinness describe the following steps for developing an ontology:

Step 1: Determine the domain and scope of the ontology (including competency questions).
Step 2: Consider reusing existing ontologies (examples are: Ontolingua, DAML, UNSPSC, RosettaNet, DMOZ and E-COGNOS).
Step 3: Enumerate important terms in the ontology.
Step 4: Define classes and class hierarchy (classes and sub-classes).
Step 5: Define properties of classes – slots.
Step 6: Define facets of the slots (including slot-value types and the domain and range of a slot).
Step 7: Create instances.

The different types of knowledge as described in the preceding paragraph, as well as its applications, will be different and therefore require different ontologies. Roussey *et al.* (2011, pp.12-14) mentions that the components of an ontology will be consistent with the purpose. For example, components can also be concepts, instances and their relationships or actors, objects, activities and documents, or can show the different of a decision in a plan.

2.10 KNOWLEDGE-REPRESENTATION TECHNIQUES

Because of the varied nature of knowledge, there is no best theory that has a complete explanation of human knowledge. The same holds for knowledge-representation techniques. **Table 2.5** summarises the knowledge-representation techniques in use.

Table 2.5 Summary of knowledge-representation techniques

TECHNIQUE	BRIEF DESCRIPTION	COMMENT
Object-Attribute-Value triplets (O-A-V triplets).	Example: Colour (Attribute) Ball (Object) → yellow (Value) ***”*** has an <u>attribute</u> whose <u>value</u> is ***“yellow”.***	A single object may have multiple attributes and associated values.
Uncertain Facts.	(Attribute) / uncertainty (Object) / Value (CF) Example: River → length → long → CF= 0,5 The “***river*** “has a <u>property</u> ***“length,”*** it has the <u>value</u> ***”long”*** and <u>uncertainty</u> about the length is ***50%*** (expressed as 0.5).	This is an extension of the O-A-V triplets by adding a value assigned to reflect the uncertainty (CF- uncertainty factor of some specific value).
Fuzzy facts.	Different people interpret things differently.	Statements make up “fuzzy sets”.
	IF, AND, THEN functions.	Fuzzy rules contain fuzzy sets in their IF and THEN statements.
Semantic networks.	Graphs made up of objects, concepts, and situations in some specific domain of knowledge (network consisting of nodes and connections showing relationships).	Difficult to handle exceptions.
	A data structure for representing stereotypical knowledge of some concept or object.	

There are several knowledge representation languages to specify ontologies. “Examples are first-order logic, MODEL, CML, IDL, Prolog, Clips, LOOM, Epikit and the Ontolingua system. Most specification languages are based on predicate logic or meta logic. The syntax of Ontolingua definitions is based on a standard notation and semantics for predicate calculus called Knowledge Interchange Format (KIF)” (Borst, 1997, p.12).

Borst explains that “in Ontolingua terms, an Ontology is called *theory*, a term borrowed from logic. A theory consists of definitions of classes, relations, functions, class instances and axioms. Furthermore, a standard Ontolingua theory called *Frame-Ontology* defines concepts like frames, slots, and slot constraints that enable ontological engineers to express knowledge in object-oriented and frame-language terms."

When Information Retrieval (IR) is done from databases, most people use general-purpose search engines, such as Google or Yahoo! etc., Issa and Mutis (2015, p.3) reported that by using a general-purpose search engine to a domain-specific document, collection results are often unsatisfactory. The main reason being that technical documents mostly have complicated structures and multiple concepts. In their research, they found that domain knowledge must be organised to support the chosen search engine. It was found that two problems were encountered when they tested the efficacy of search engines on domain-specific documents. The first problem related to the lack of relevance attached to queries on certain topics, because documents contain multiple topics. The second was, when a document was found, that search results were not clearly resented. "It takes time to populate the system with knowledge (conditioning of the system by linking, ranking, commenting etc. the documents), especially for the first users."

The system architect in E-COGNOS uses a construction-specific ontology as a basis for specifying adaptive mechanisms that can organise documents according to their contents and interdependencies, while maintaining their overall consistency. In the civil engineering domain, the E-COGNOS project successfully presented the ontology application of knowledge management and information retrieval. The purpose of the E- COGNOS project is to establish a single point of entry to search knowledge bases. E-COGNOS has a web-based infrastructure and include services allowing to create, capture, index, retrieve and disseminate knowledge. It also promotes the integration of third-party services, including proprietary tools (E-COGNOS Project, 2003).

2.10.1 Applications of ontologies

The purpose of ontologies is to model information and knowledge in the form of concept hierarchies (taxonomies), interrelationships between concepts to also enable and enhance effective information and knowledge retrieval. In a particular domain, it is most useful to base all knowledge bases on standardised taxonomies. As an illustration of the application of ontologies, the following example is given. In the example of a civil engineering construction project, one may have a suitable taxonomy and have a concept or taxon called "reinforced concrete". As sub-taxons or concepts, one can have "pre-stressed concrete". One can also identify relationships between other concepts such as the geometry of concrete elements and lengths of spans of concrete elements. These relationships bring conditions into the ontology such as, if the ratio of span to the thickness (depth) of a concrete beam exceeds a particular value, pre-stressing of the concrete beam could be the most economical option. Furthermore, specification (values of instantiations) or supplier information can be linked to this taxon. In such associated document, one can find that there are very specific specifications associated with particular tendons pertaining to a prestressed system. For example, Tendon A123 positioned in location XYZ must be stressed to a maximum of 1 200 Mpa. The taxon “pre-stressed tendons” then has a sub-taxon of “Tendon number A123” and it has the property “maximum stress” and the value of 1 200 Mpa, and perhaps many other properties that are peculiar tendons or class of tendons. The ontology of tendons will then contain the taxon or object (refer to O-A-V triplets), the attributes and properties and the specific values. Retrieving of this information is then quite easy. If one wants to know to what tendon no. A123 has to be stressed to, one can easily retrieve the information. It is, however, important to realise that the specific information or knowledge must be “loaded” onto the system first.

Knowledge concepts or knowledge units can be treated similarly to the pre-stress tendons in the example above. For example, a knowledge unit or concept can be: “the vehicle’s engine overheats if the revolutions are consistently kept above 4 000 rpm”. In an ontology on off-road motorsport, the ontology for “vehicles” could start off with the taxonomy for “off-road vehicles” and one of the sub-taxons could be “engine performance” under the “document” for “engine performance”. One can then identify the concept “engine heat” and then the property of “overheating”. The attribute for overheating can be a “value” stating that “it overheats when engine revolutions are consistently over 4 000 rpm”. (There could be a multitude of properties associated with the concept of engine performance and a multitude of properties associated with engine heat.) Furthermore, if one advances the development of an ontology on off-road vehicles, one can link the concepts of terrain difficulty and average speed to engine performance. The logic being that the more difficult the terrain is that needs to be negotiated, the slower the average speed would be and the longer an engine need to perform at high revolutions, leading to the potential overheating of the engine. The ontology, therefore, together with the relationships convey a complete sequence of cause-and-effect concepts, not only providing the capability of retrieval of knowledge, but also leading users through logical arguments.

Knowledge features in this ontology when one has a systematic ontology that was developed to cover, for instance, all possible engine performance aspects. Logic arguments can be used to generate the possible engine performance aspects. This is, in reality, the functions of the logic base. Knowledge creation techniques, such as case-based reasoning, word-trigger, brainstorming or checklist techniques can be used to develop the ontology as far as possible.

One can then apply problem-solving techniques such as RCA or FMECA, HOT- or TRIZ-techniques to arrive at the taxonomy and to populate the ontology. One can even embed a logic process such as a guide to fault finding in the ontology. The logic process will guide users to think and to discover answers to particular questions to problems that the user might have. This approach is supported by Gómez-Pérez and Benjamins (1999, p.119) who state that "One of the main motivations underlying both ontologies and problem-solving methods (PSM) is to enable sharing and reuse of knowledge and reasoning behaviour across domains and tasks. PSMs and ontologies can be seen as complementary reusable components to construct knowledge systems form reusable components."

2.10.2 Remarks on ontologies and taxonomies

There is much confusion regarding the use of the different terms and definitions of the terms, classifications, taxonomies and ontologies. Some authors use the terms ontologies and taxonomies interchangeably (Bailey, 1994, p.3). Van Rees (2003, p.1) states that "There is a lack of clarity when discussing the following three terms: classification, taxonomies and ontologies." He observed a trend (at a conference) for speakers to use the word "ontology" as most fashionable of the three (classification, taxonomy and ontology), without much qualification. In summary, he gives the following new definitions:

Classifications: "A grouping of entities according to some external criteria […]. It is basically a set of boxes (with labels) to sort things into."

Taxonomy: "Classification or simple ontology. A hierarchy grouping of entities according to data internal to the taxonomy. When used as a simple ontology, the taxonomy's hierarchy should be based upon a subclass hierarchy."

Ontology: "A set of well-defined concepts describing a specific domain. The concepts are defined using a subclass hierarchy, by assigning and defining properties and by defining relationships between the concepts et cetera. [...] An ontology's goal is to provide a common, referenceable set of concepts for use in communication. It is quite common to use multiple ontologies, each providing concepts for a particular domain, together forming a rich vocabulary for communication" (Van Rees, 2003, p.6).

When considering the above definitions, the following summary is given of "what ontology means" (Van Rees, 2003):

- It is shared set of referenceable conceptualisations and terminology (domain vocabulary).

- It explains the types of things in a knowledge domain.
- In involves a formal structure (scaffolding) to concepts.
- It involves the classification and study of concepts.
- It includes some kind of hierarchy.
- It supports generalisations, inheritance, aggregation (part-of) and instantiation.
- It involves the relationships among concepts.
- It represents the properties of concepts.
- It provides the values to the properties.
- It describes events and their causes and effects.
- It describes processes.
- It related concepts to time.

To further examine the differences between taxonomies and ontologies, the following summary and comparison between the characteristics of taxonomies and ontologies as shown in **Table 2.6:**

Table 2.6 Comparison of characteristics between taxonomies and ontologies

Taxonomies	Ontologies	Comments
• Nomenclature must be unambiguous.	• It is a shared set of referenceable conceptualisations and terminology (domain vocabulary).	
• Classification system.	• Classification and study of concepts.	
• Organised and must contain rules and logic.	• It involves a formal structure (scaffolding) to concepts.	
• Hierarchical.	Includes some kind of hierarchy.	
• Shows connected or interrelationships between or among objects or groups.	• Involves the relationships among concepts.	
• Patterns and attributes will determine the classification.	• It displays types of things in a knowledge domain.	
• A taxonomy forms part of a whole.		• Ontologies are not restricted and can be part of the whole.
• Taxonomies are multi-layered/multi-tiered.		• Ontologies are not restricted and can be multi-layered of multi-tiered.

Taxonomies	Ontologies	Comments
• Lower order taxons inherit properties or attributes of higher order taxons.	• Supports generalisations, inheritance, aggregation (part-of) and instantiation. • Properties of concepts • Values to the properties.	
	• Involves events and their causes and effects.	
	• Describes processes.	
	• Relates concepts to time.	

From **Table 2.6**, it is evident that there are only a few differences between taxonomies and ontologies. Ontologies have a wider content and have additional characteristics.

2.10.3 Concluding remarks on ontology and taxonomy

The terms *ontology* and *taxonomy* are often used interchangeably in the literature (Bailey, 1994, p.3). However, the conclusion is made that ontologies refer to the high-level groupings or classification of domains. It can have relations with many other domains. It contains descriptions of attributes which can include values or any other specifications peculiar to the specific element of the ontology. These are described by ontology representation languages in machine-readable form. There are some specific rules to the construction of ontologies. The most important application of ontologies is to define a common vocabulary to share information in a domain.

Taxonomies are sub-elements or embedded in ontologies. Taxonomies, therefore, are seen as part of or belong to a specific ontological domain. Taxonomies have a very specific hierarchical structure and each element has a “belongs to” or “part of” or “a kind of” relationship to other elements in the taxonomy related to a specific ontological domain.

The best way to iron out the vagueness of terms is to follow two possible approaches. Firstly, one may start by the development of a taxonomy for a specific knowledge domain. After that, each taxon can be expanded to include all the other attributes and values to represent an ontology.

The second approach is to develop an ontology, meaning that it is not necessary to have a hierarchical structure, but one can have a logic structure. After that, depending on the purpose, one can then structure the knowledge domain into a taxonomy and then proceed with the development of the ontology. Concept diagrams (or maps) are introduced and in section 2.3.2

of this study and further elaborated on in Chapters 4 and 5. Concept diagrams depict a logic structure of knowledge, defining a "logic ontology" that can act, not only as a repository of knowledge, but also as a tool for the creation of knowledge.

The process of construction of a knowledge base is depicted in **Figure 2.25.**

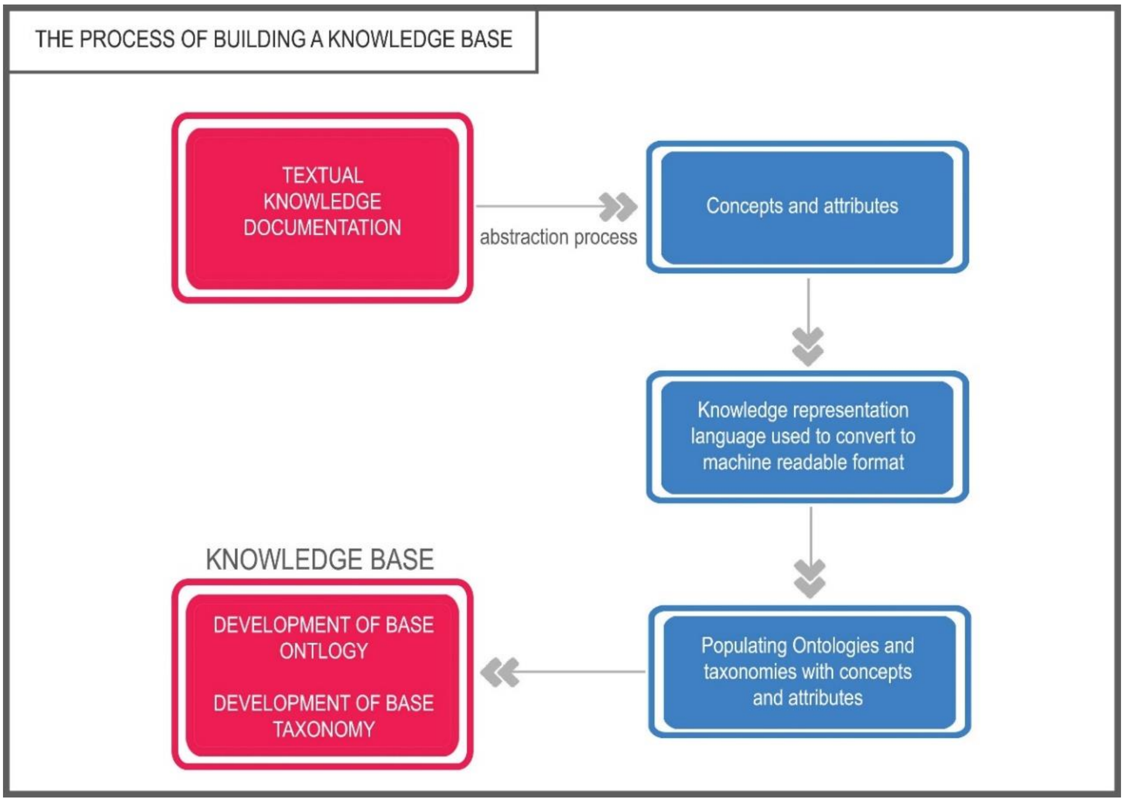

Figure 2.25 The process of building a knowledge base

The above diagram depicts the process of designing a knowledge base. The process starts with source documentation containing the knowledge to be taken up into the knowledge base. The important knowledge concepts (knowledge units) are then identified and abstracted and turned into a knowledge-representation language (machine-readable language). This also entails the identification of all the attributes and values attached to a knowledge unit. A base ontology and taxonomy is developed for the knowledge domain under consideration. The knowledge units or concepts and attributes are then filed in the appropriate fields in the base ontology. The final product constitutes the knowledge base. Further developments on concept maps are done in Chapters 4 and 5.

The foregoing section on ontologies answers the research sub-question c).

How can existing engineering knowledge be reused?

In answer to this sub-research question, the following questions need to be answered:

i) *What methods and processes are there for transferring knowledge to individuals for reuse?*
ii) *How would one understand or assimilate the context of existing knowledge?*

When knowledge is structured and classified into an ontology, content and context can be given to knowledge. The ontologies in itself provide the means to transfer knowledge to individuals for reuse. Ontologies were developed to support electronic media which is used for transferring of knowledge.

2.11 SYSTEMS ENGINEERING

A systems approach was already alluded to in Chapter 1 of this study. (Refer to paragraphs 1.4.3 and 1.4.4.) It is a very important component of the proposed logic base and deserves further literature study.

The question now arises as to what the structure should be of new knowledge, or how systematic should the knowledge be? This is considered essential so that knowledge reuse and knowledge creation can be contemplated. To investigate the structure and the dynamics of knowledge creation, a systems approach is proposed. A systems approach is described below. This will be followed by the main sections where the structure of the logic base is designed.

2.11.1 Definitions

The Oxford Dictionary (OED. 2010) defines “system” as: “An organized or connected group of objects.”
“1a. A set or assemblage of things connected, associated, or interdependent, so as to form a complex unity; a whole composed of parts in orderly arrangement according to some scheme or plan; rarely applied to a simple or small assemblage of things (nearly = ‘group’ or ‘set’).”

“II. 8. A. The set of correlated principles, ideas, or statements belonging to some department of knowledge or belief; a department of knowledge or belief considered as an organized whole; a connected and regularly arranged scheme of the whole or some subject; a comprehensive body of doctrines, conclusions, speculations, or theses” (OED 2010).

The Dictionary defines “system” as (Webster 1913 Dictionary, online):

1. An assemblage of objects arranged in regular subordination, or after some distinct method, usually logical or scientific; a complete whole of objects related by some common law, principle, or end, a complete exhibition of essential principles or facts, arranged in a rational dependence or connection, a regular union of principles or parts forming one entire thing, as, a system of philosophy, as system of government; a system of divinity; a system of botany; or chemistry; a military system; the solar system.

2. Hence he whole scheme of created things regarded as forming one complete plan of whole; the universe.

Blanchard (1991, p.1) explains that “a system constitutes a complex combination of resources (in the form of human beings, materials, equipment, software, facilities, data, etc.) to accomplish a specific function classifies as a natural system, man-made system, dynamic system, and so on. A system may vary in form/fit, and/or function.”

Haines (1998, p.vi) defines the term *systems thinking* as “A new way to view and mentally frame what we see in the world; a worldview and way of thinking whereby we see the entity or unit first as a whole, with its fits and relationships to its environment as primary concerns.”

Blanchard and Blyler (2016, pp.1-3) remarks that the main concern is to improve performance, quality, cost, efficiency and effectiveness in the development and acquisition of new systems, as well as in operation and maintenance of systems and the support of existing ones.

According to Blanchard (2016, pp.1-4), a system has the following general characteristics:

a) A system constitutes a complex combination of resources and must be combined in an effective manner – it is too risky to leave it to chance.
b) A system is contained within some form of hierarchy. The system under consideration is highly influenced by the performance of the system at higher taxonomic levels.
c) A system may be broken up into sub-system and components. One has to have a thorough understanding of the system as a whole. Breaking down into components can be done and components individually studied, as well as their interrelationships. It can then all be put together again.
d) The system must have a clear purpose, be functional, be able to respond to some identified need and must be able to achieve its objectives in a cost-effective way.

Blanchard and Blyler (2016, p.1) also defined the following categories of systems:

a) Natural and man-made systems (river systems, hydroelectric power systems).

b) Physical and conceptual systems (physically refers to real components occupying space and conceptual systems such as the organisation of ideas, plans and specifications). The conceptual system often leads directly to physical systems. These must also be put into the context of the hierarchy level system and the overall hierarchy.

c) Static and dynamic systems. The static system refers to, for instance, structures such as bridges, buildings or warehouses while dynamic systems refer to the transportation systems, software, manufacturing systems, conveyors, etc.

d) Open-and-closed loop systems. A closed loop system is one that is relatively self-contained and does not significantly interact with its environment. Conversely, an open system interacts with its environment and boundaries are crossed (through the flow of information, energy, and/or matter) and there are numerous interactions both among the various system components and up and down the hierarchy structure (Blanchard and Blyler, 2016, p.1).

Furthermore, a system is not static, but performs certain functions. The most basic system is defined in **Figure 2.26**.

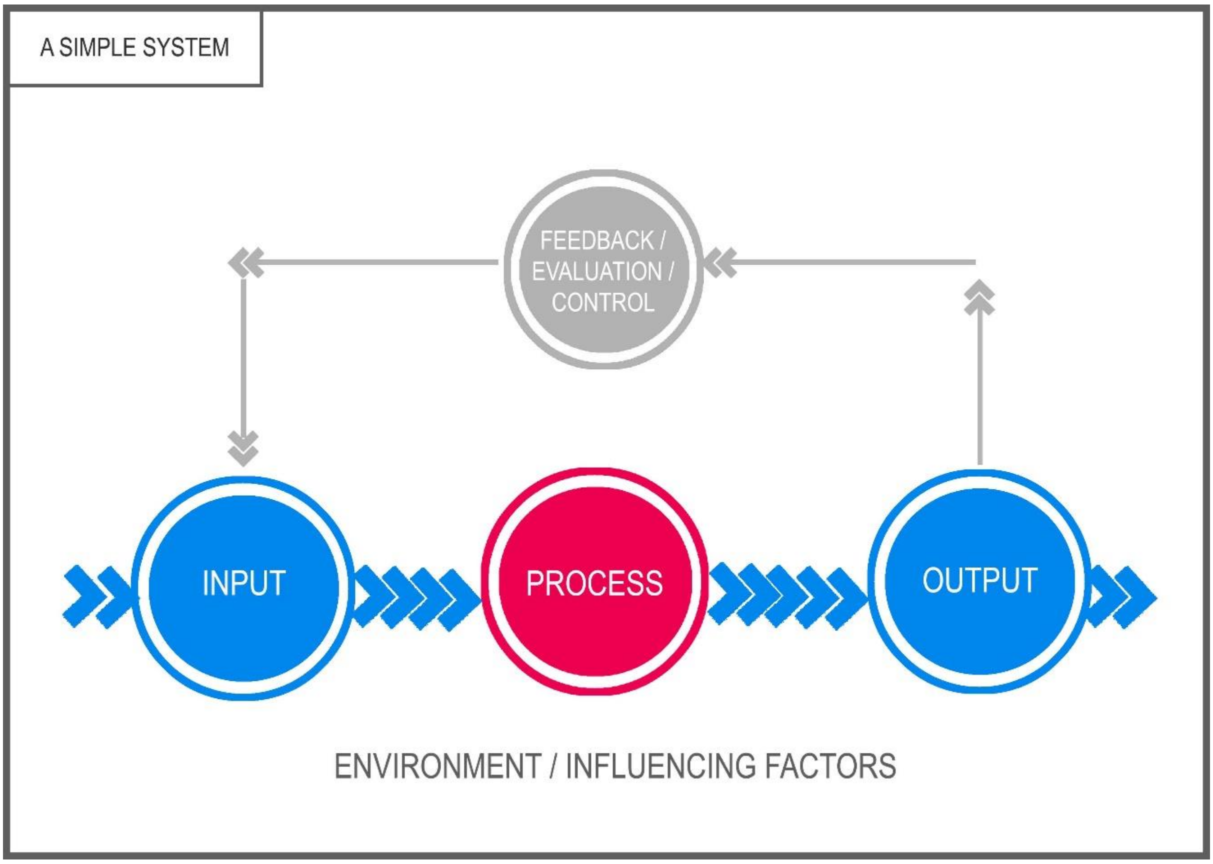

Figure 2.26 A simple system

Figure 2.26 depicts a simple system that consists of a processing unit that receives certain inputs. The process does something or performs a function, based on the input received. The outcome of the process (output), represents an outcome or product. However, the output is monitored against the process-performance requirements. If performance requirements are not met, feedback is provided to adjust or amend the input. Controls, when necessary, initiate certain changes to the process which would then deliver different output. The entire process may be influenced by the environment or may be influenced by factors external to the system's input, process or outputs. Complex systems comprise combinations of simple systems, whereby the output of one system becomes the input to another. Dependencies and interrelationships exist between various elements of sub-systems. Feedback and controls are put in place for each sub-system, thereby forming a network of controls.

In the development of a logic base, use is made of the concept of systems to define individual components and the relationships between the sub-systems.

Another important type of system is neural and adaptive systems, where the leading characteristic is the adaptivity. "Instead of being built a priori from specification, neural and adaptive systems use external data to automatically set their parameters" (Principe, Euliano, and Lefebvre, 2000, p.2). The adaptive systems are made "aware" of their output through performance feedback looping, which may, for instance, include a cost function. The output is then evaluated and subject to systematic adjustment (also referred to as "learning") through rules or algorithms. Thereby, input parameters or process parameters are adjusted automatically accordingly and output, in turn, is changed, thereby striving to meet certain output parameters or objectives (Principe, Euliano and Lefebvre, 2000, p.2). By way of illustration if, for example the system's output cost is measured and found to be too high, process adjustments or input adjustments are made to deliver the required cost. When designing a system, it is necessary to decide and design the systems typology. One must also decide on performance criteria and design the adaptive algorithms. In neural systems, the parameters are often modified in a selected set of data which is called the training set and these are fixed during operations. The designer must design the input and desired response parameters, and specify when to stop the training phase. In adaptive systems, the parameters are continuously adapted during operation with the current data.

An example of an adaptive system is shown in **Figure 2.27**.

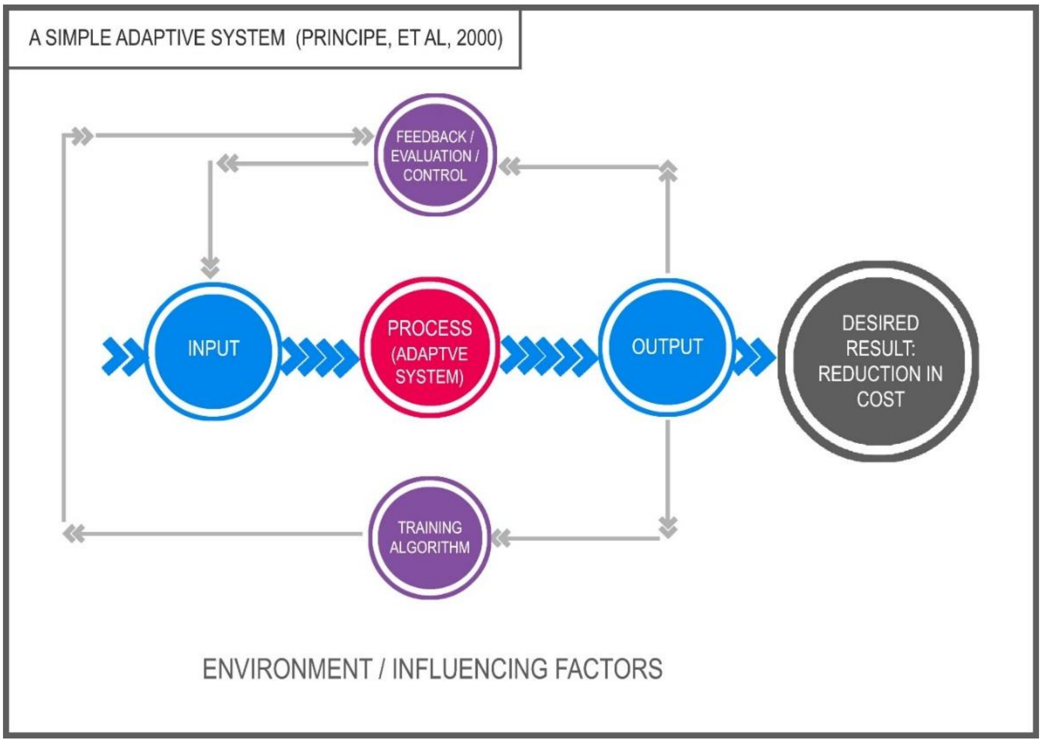

Figure 2.27 A simple adaptive system (Principe et al., 2000)

Engineering systems can become very complex. As the number of sub-systems increases, the interactions among systems increase exponentially. As systems are designed to interact directly with the environment, the complexities of the external world are brought into the engineering design environment. A very apt example is the Mars Pathfinder mission, whereby the vehicle interacted with the environment by receiving signals from cameras and other sensors of the terrain. The movements of the vehicle were autonomously determined and executed without interventions by humans. This had to be done because of the long timelag in communications between the earth and Mars. The use of autonomous (driver-less) vehicles is increasing. This is only possible by employing adaptive system technology.

A very important function of neural and adaptive systems is the utilisation of adaptive algorithms. Instead of systems "being built a priori from specification, neural and adaptive systems use external data to automatically set their parameters [...]. The performance feedback is utilized directly to change the parameters through systematic procedures called learning or training rules, so that the system outputs improves with respect to the desired end goal" (Principe, Euliano and Lefebvre, 2000, p.2). Some search engines on the Internet utlise adaptive systems, and when doing successive searches for information, it "trains" itself to look for concepts similar or relating to the previous search (mostly keywords) and outputs information accordingly.

In knowledge management, it is immensely important to be able to abstract information from existing documents and to classify the information into appropriate ontologies for easy retrieval and reuse. Adaptive systems are therefore most appropriate. (It may be possible to design algorithms, using the 40 inventive principles of TRIZ, to form an adaptive system, automatically suggesting appropriate solutions to contradictions. These algorithms may also be extended to incorporate learnings from case studies.)

Considering the definitions of ontology and taxonomy given in sections above, systems are also of a hierarchical structure and have numerous attributes that need to be described. One could, therefore, conclude that systems fit well into the definitions of ontology.

2.12 SYNTHESIS OF METHODS

The way forward with the development of the logic base is to now develop the tools that comprise the logic base.

Concepts are the basic building blocks of knowledge management and more specifically that for the design of the logic base. A knowledge unit discussed earlier is further defined as a concept or a conceptualisation with all its attributes, values and relationships. It consists of words, sentences or narratives, describing the concepts. A knowledge base consists of a collection of concepts. Concepts are seen as the aggregate thoughts or ideas incorporating several attributes.

A logic base is a step-up from just concepts that are recovered from knowledge bases. Knowledge is logically organised and turned into algorithms for knowledge creation.

The TRIZ (Theory of Inventive Problem Solving) technique is an excellent example of a logic base. In the procedure to analyse problem cases, knowledge is abstracted from existing patents or other appropriate documents (referred to as source documents). Semantic keywords searches are done through narratives found in the source documents that signify contradictions, such as “but”, “however”, etc. (utilising appropriate software). “Having identified a conflicting pair (or ‘pairs’ – sometimes there can be multiple subject words adjacent to a contradiction signifier), the final stage is to map the identified pairs in some kind of framework.” Here, not surprisingly, is where the ‘universal ontology’ offered by TRIZ Contradiction Matrix tools comes into play. That “ontology, coupled with our old contradiction parameter mapping tool and its list of synonyms and antonyms for each of the parameters that make up the sides of the Matrix now allows us to map and uncover conflict pairs in the Contradiction Matrix" (Mann, 2015).

In this case, the logic base is described by TRIZ's Contradiction Matrix. This matrix enables the search for generic solutions to a set of 50 contradictions.

2.13 THE WAY FORWARD

Knowledge bases are the roots of logic bases. Many and a great variety of types of knowledge bases exist. The list given in **Table 2.2** of knowledge management practices has reference. This list was published by Tobin and emanated from the knowledge-management practices in a large organisation. Apart from the list given, other sources of knowledge can be found in publications on the subject matter. The last column in **Table 2.7** summarises topics of knowledge found in other sources. The second and third columns, represent knowledge topics or elements available in practice and compared with the types of knowledge defined in column 1.

The following table puts together the various types, common knowledge practices and the knowledge types from published knowledge (Gašević and Devedžić, 2009; Tobin, 2006; Zack, 1998).

Table 2.7 Summary of different types of knowledge

Types of knowledge	**Knowledge sources from corporate management practices – consolidated from Table 2.2**	**Knowledge from published subject knowledge sources ***
• Procedural knowledge *(How to do something, or how something occurs, or is performed).*	• Codes of practice. • Work instructions. • Specifications. • Embedding knowledge into processes. • Communities of practice. • Guidelines. • Expert networks. • Coaching (on the job training). • Peer assists. • Knowledge education/training (off the job).	• Development of techniques. • Application of theory/technology. • Development/interpretation of standards and specifications. • Management.
• Declarative knowledge (Knowledge about something, details	• Process modelling.	• Development of theory, including the study of cause-and-effect relationships.

Types of knowledge	Knowledge sources from corporate management practices – consolidated from Table 2.2	Knowledge from published subject knowledge sources *
of concepts or objects).		• Determination of system (or design) parameters.
• Meta-knowledge (Knowledge about knowledge).	• Benchmarking. • Libraries.	• Theories and applications developed from existing knowledge and techniques.
• Heuristic knowledge (Rules of thumb guiding problem-solving).	• Mentoring. • Learning by doing.	• Identification and resolving constraints/contradictions.
• Structural knowledge (Mental knowledge and the organisation thereof).	• Gap analysis. • Measurement systems.	• Development of theory and applications. • Measurement.
• Inexact and uncertain knowledge (Not precise measures).	• Scenario planning.	• Systems modelling and characterisation of parameters.
• Common-sense knowledge (Knowledge that cannot easily be put into precise theories).	• After action review/Retrospect's • Suggestion schemes.	• Systems performance reporting. • Sharing of knowledge.
• Ontological knowledge (Knowledge of why something occurs, provides meaning to various kinds of categories). • Causal knowledge (Broad, often publicly available, Independent of particular events).	• Legal reviews. • Knowledge workshops.	• Systems behaviour and response. • Determination of needs. • Identification of challenges. • Sharing of knowledge. • Legislation.
• Specific knowledge (Context-specific knowledge).	• Business intelligence. • Stories and storytelling (oral, written, drama, combined). • Incident reports. • Learning from incidents. • Environmental scanning. • Surveys (internal and external).	• Subject matter theories and applications.

Knowledge sources referred to are mainly subject literature, for example articles published in journals and magazines of the South African Institution of Civil Engineering.

Considering the above classifications, knowledge contained in the published literature adequately fits the different descriptions of the types of knowledge.

As a brief inspection of existing published literature, **Appendix C** provides a summary of the types of knowledge made explicitly available in subject matter magazines and subject matter journals in civil engineering.

When inspecting the third column of **Table 2.7** of knowledge types from published literature, the following main knowledge types can be abstracted to take further in this study. Root-driving factors are defined to describe the most basic reason for the type of knowledge to come about or to be for developed. For example, the development and application of theory have most likely come about, due to the need to enable analysis and obtain a deeper understanding of some phenomena. This also implies that the current theoretical predictions or modelling are not satisfactory, i.e., the causes and effects are not clear and need to be quantified. Further development would be required. It can also mean that some problems were experienced or aspects of a proposed design are not properly understood or accounted for satisfactorily. There is then a requirement to solve the problems and develop cause-and-effect relationships.

Techniques need to be developed to overcome certain constraints and problems that can be solved by applying certain techniques. Standards and specifications are devised for regulation, i.e., so that causes and effects can be adequately controlled and risks are minimised. Engineering continuously studies systems and systems' parameters and performance where measurement and management play vital roles.

Broad-base knowledge sharing takes place so as to update engineers on new engineering matters. **Table 2.8** provides a summary of the above.

Table 2.8 Main classification of knowledge types and root-driving factors

Main classification of knowledge types	**Root-driving factors (reasons for knowledge to come about or developed)**
• Development and application of theory.	• To solve problems. • To study cause-and-effect relationships to uncover knowledge.
• Development of techniques.	• To solve problems. • Dealing with constraints.
• Standards, specifications, guidelines and legal issues.	• To effectively deal with causes and effects.
• Measurement and management tools.	• To enable the management of the performance of systems.

• Sharing of knowledge.	• To build capacity among practitioners.

When distilling the above driving factors further, cause-and-effect are essentially a systems driven parameter and so is the dealing with constraints. There are then only three driving factors remaining, i.e.:

- Problem-solving
- Systems performance
- The sharing of knowledge (this is a rather obvious factor that has to be taken up into a logic base in any event)

From the preceding, and in particular the summary in **Table 2.8,** it shows that appropriate knowledge is readily available from normal knowledge-management practices (Tobin, 2006). Therefore, if logic bases are developed to cater for the driving factors as listed in **Table 2.8**, and more particularly, problem-solving and systems performance are sufficient coverage would be given for the engineering field. Sharing of knowledge is a basic prerequisite for all knowledge management functions.

The focus for the development of logic bases should, therefore, be on the root drivers. It is argued that if the logic bases are designed to share knowledge, to solve problems and to look at systems performance, such logic bases will cover the essential parts of knowledge creation and knowledge reuse. This will enhance knowledge-management practices in general.

The above will be dealt with in subsequent chapters of this study.

2.14 SUMMARY

In this chapter, the various theories of knowledge are discussed. These theories describe the various knowledge elements which will be included in the logic base (this is described in chapters 4 to 6). The definitions of knowledge are considered, as well as the way knowledge is represented in the human mind. Types of knowledge were discussed, as well as methods of knowledge transfer. Various methods of knowledge acquisition and reuse were discussed. Regarding the creation of knowledge, the focus is on problem-solving techniques. In the civil engineering domain, there are various sources of knowledge, some in highly structured format and other sources are unstructured. Various institutions designed ontologies for specific domains, but it was found that there is no existing ontology for general civil engineering. Finally, consideration is given to systems engineering. All the above research will form the basis for the development of the logic base.

The above process is summarised in **Appendix H**. **Figure H1** shows how the various elements discussed in this chapter fit together and are integrated into the design of the logic base.

The foregoing sections provide the answers to sub-sub-research questions b), i) and ii) .

Sub-research question (b) asks the following questions:

What sources of existing knowledge are available and how does this knowledge relate to the proposed logic base?

The following sub-sub-research questions pertain:

- *i) In what form or structure is existing knowledge available?*
- *ii) How usable is existing knowledge to the practising engineer?*

(A complete summary of all the research questions in this study is shown in **Appendix I**.)

The usability is enhanced by considering that ontologies are provided to enable retrieval of knowledge by the practicing engineer. In this way knowledge will become more accessible and useable.

CHAPTER 3 : RESEARCH DESIGN AND METHODOLOGY

3.1 INTRODUCTION

In this chapter, various research methods are investigated with the intention of establishing the best way of dealing with engineering knowledge. The logic base will be structured by way of suitable ontologies and will contain existing engineering knowledge that will contain procedures to create new knowledge. The integration of knowledge structures, existing engineering knowledge and new knowledge are addressed in this chapter.

The establishment or compilation and updating of a logic base in practice will always involve research and interpretation, and is a type of "living" logic base that is always subject to new knowledge that evolves from various sources.

3.2 RESEARCH QUESTIONS

The research questions are stated in Chapter 1 of this study. In this chapter, sub-research question (e) is addressed. The question is as follows:

What research methodologies are most applicable for the discovery and application of engineering knowledge?

To answer this question, one has to establish ways in which knowledge in the civil engineering environment is derived and also how it is structured. This information will assist in the development of a suitable ontology. This ontology will provide a basic structure for knowledge, also indicating what knowledge is required by a civil engineer in practice. The best way to research this will have to be determined and is discussed in this chapter.

3.3 RESEARCH IN GENERAL

In this section, consideration is firstly given to general aspects of research. After that, a brief overview is given of various research methods. The various research methods are then analysed to identify which research method or methods will best serve the objectives of this study.

3.4 DEFINITION OF RESEARCH

First, it is necessary to consider what research is. Research is defined as:
"1. The act of searching carefully for or persuing a specific thing or person; (OED, 2010),

2a. Systematic investigation or inquiry aimed at contributing to knowledge of a theory, etc., by careful consideration, observation or study of a subject. In later use also: original critical or scientific investigation carried out under the auspices of an academic or other institution,

2b. Investigation undertaken in order to obtain material for a book, article, thesis, etc.

2c. The product of systematic investigation, presented in written (esp. published) form."

Research is defined by Mason and Bramble (1989, p.3) as "*the search for answers to questions".* (Mason and Bramble, 1989, p.xiii) also defines research as being "*about finding, structuring, and understanding the complexities of knowledge".* (Italics were added for clarity.)

Research is further described by Welman, Kruger and Mitchell (2005, p.2) as "a process that involves obtaining scientific knowledge using various objective methods and procedures. The term objective indicates that these methods do not rely on personal feelings or opinions and that specific methods are used at each stage of the research process." Mason and Bramble (1989, pp.3-5) put it that, "This knowledge may be used to build theory, to develop policy, to support decision making or to find out something. Research is a knowledge building process with purposes, contexts, values and perspectives, and very definite limitations." Research may have different purposes. Some research could be aimed at finding answers to commercial market performance and aimed at advising managers for taking action or for making certain decisions.

For the purpose of this study, and considering the above definitions, research is defined as a systematic and objective process involving materials and sources to find, structure and understand the complexities of knowledge and to find answers to questions.

3.4.1 Scientific versus non-scientific research

Research can also be aimed at developing “generalizable knowledge, knowledge that can be used to formulate a theory” (Mason and Bramble, 1989, pp.3-5). The latter is referred to as scientific methods that are used to do a systematic investigation of a question or a problem. The term “systematic” is used as against “haphazard”. Mason and Bramble (1989, p.5) explains that the scientific method of research leads the researcher to develop or test a theory, which is used to explain and predict phenomena.

Scientific knowledge differs from a naïve, or layperson’s knowledge of human behaviour and is not limited to particular fields of study, such as chemistry, physics and medicine. In contrast to scientific, non-scientific research relies on the following (Mason and Bramble, 1989, pp.6-7; Welman, Kruger and Mitchell, 2005, p.4):

- Opinions of peers – instead of calling on the opinions of experts.
- Personal experience – This can be misleading and subjective, based on perceptions and interpretations.
- Statements by persons in authority – as being the so-called experts.
- Traditions – Holding those certain traditional ways of thinking and doing as the only and best ways, whereas some traditional ways are based on incorrect premises and may be illogical.
- Debating – Sometimes illogical arguments ensue and persons can come to illogical conclusions.
- Reasoning – This often comes in the form of general observations argued to hold in specific cases (also called *deductive* reasoning). Reasoning can also be done from the specific to the general (called *inductive* reasoning).
- Common sense – This is difficult to define, but is generally non-systematic.
- Accidental observations – Only a single observation of a phenomenon is used to come to conclusions. No systematic and planned observations are used which may cause various persons to come to entirely different conclusions.
- Documentation – The source and the way a document was compiled and became available, must be considered. There are two types of documentation,

primary documentation and secondary documentation. Primary documentation may contain reliable records, but if the primary documents were lost and re-constituted, for example, the secondary documentation could be less reliable.

Scientific research is different to the form of research used to gain information and which is not used or usable to develop theory.

Scientific research involves planned and systematic observations in a controlled manner. Scientific research refers to “using scientific methods to expand knowledge in a particular field of study” (Welman, Kruger and Mitchell, 2005, p.3). As Page and Meyer (2000, p.11) put it, “The foundation of the scientific approach is the generation and testing of theories and models that explain and predict reality. The result of a scientific study is the accumulation and organisation of a body of knowledge relevant to a subject area.” The manner in which scientific knowledge is obtained, must be replicable (Welman, Kruger and Mitchell, 2005, pp.5-6). Mouton (2001, p.138) describes scientific research as being when research matter is subject to “systematic and rigorous enquiry”. Mouton (2001, p.138) states that “The search for ‘truth’ or ‘truthful knowledge’ is the overriding goal of science” and also that “the aim of science is to generate truthful (valid and reliable) descriptions, model and theories of the world.” Mouton (2001, p.138) remarks that “Although it is, of course, not possible to produce scientific results that are infallible and “absolutely” true for all time and contexts, we are motivated, as scientists to constantly strive for the most truthful and most valid results.”

For the purpose of this study, the above points of view are supported, whereby planned systematic and rigorous methods are used for the generation and testing of theories and models that explain and predict reality. As seen above, it is important to differentiate between scientific and unscientific research, because, in the context of this study which is qualitative in nature, one has to guard against the use of unscientific research.

3.5 RESEARCH METHODS

Two distinctly different methods of research are described in the literature, namely quantitative and qualitative research methods (Guba and Lincoln, 1994, p.106; Page and Meyer 2000, p.17; Welman, Kruger and Mitchell, 2005, pp.5-10).

A positivist or quantitative approach holds that research "must be limited to what we can observe and measure objectively, that is, that which exists independently of feelings and opinions of individuals" (Welman, Kruger and Mitchell, 2005, p.6). Page and Meyer (2000, p.17) describe that "a quantitative approach places greater value on information that can be numerically manipulated in a meaningful way, and this is the traditional scientific approach to research." This approach underlies the natural-scientific methods. The qualitative or anti-positivist approach contrasts that of the quantitative approach. A qualitative approach holds that "the natural scientific method is designed for studying molecules or organisms and is therefore not applicable to the phenomenon being studied in human behavioural sciences." Welman, Kruger and Mitchell (2005, p.6) argue that human experience cannot be separated from the person who is experiencing it. This is one of the important reasons why a qualitative approach is more suitable for research involving experiential or behavioural research. Summarising from Marshall and Rossman (1999, p.2) and Page and Meyer (2000, p.18), the qualitative research approach focuses on words, feelings and the quality of an event or experience and is intrigued by the meanings the participants themselves attribute to social interactions. Qualitative research is pragmatic, interpretive and grounded in experiences of people.

This study focuses on experiential aspects, and qualitative research methods are therefore of specific importance.

Summarising from Marshall and Rossman, (1999); Page and Meyer (2000); Welman, Kruger and Mitchell (2005), **Table 3.1** indicates the differences between quantitative and qualitative research methods.

Table 3.1 Differences between quantitative and qualitative research methods

Quantitative	Qualitative
Evaluates objective data.	Deals with subjective data. Also, deals with the complexity of social interactions.
Presented in numbers.	Presented in language.
Analysis based on complex, structured methods to confirm or disprove hypotheses.	Based on flexible and explorative methods.

Quantitative	Qualitative
Does not deal with everyday life, but rather with an abstraction of reality.	Based on day-to-day events and behaviour of people and investigates constraints.
Study facts from outsider's perspective. Researcher is detached from facts and has an objective view, free from bias.	The researcher has insider view. Believe in the first-hand experience of the object under investigation. Observe behaviour in a subjective way.
Try to keep the process as stable as possible. Focus on causal aspects of conduct that won't easily change.	Researchers work on dynamic and changeable nature of reality.
Researchers control investigation and are interested in identifying and isolating variables.	Follows a holistic approach.
Specific measuring instruments are used to collect data.	Collect a wide array of data (documents, records, photographs, observations, interviews and case studies).
Focus more on reliability.	Focus more on validity. Studies must be representative of what is being investigated. Is interpretive.
Usually, employs a large number of cases and results are analysed statistically.	Employs small samples of people, studied using in-depth methods.
Controlling observations and using remote, empirical, and inferential methods.	Uses structured, semi-structured and unstructured interviewing and detailed observations processes.
Used in comparative studies, typically statistically analysed.	Numerical data is not normally used.

Guba and Lincoln (1994, p.196) purport that historically there was a great emphasis on the qualification of science. “Scientific maturity is commonly believed to emerge as the degree of quantification found in a given field increases […] Finally, there is a widespread conviction that only quantitative data are ultimately valid, or of high quality” (Guba and Lincoln, 1994, p.197). However, Guba and Lincoln (1994, p.107) argue that there are some specific instances that must be considered when evaluating quantitative research. Guba and Lincoln (1994, p.197) mention the following:

Context stripping – precise quantitative methods focus on subsets of variables, leaving out other important aspects.

Exclusion of meaning and purpose. Reference is not made in quantitative research to the meaning and purposes attached to a situation by the human actors.
Disjunction of grand theories with local context: etic/emic (outside/insider respectively) dilemma. Quantitative research usually forms an etic point of view (or the hypotheses being tested); may have little or no bearing within the emic view of studied individuals.
Inapplicability of general data to individual cases. Although in quantitative research, conclusions are made which are based on statistically significant results, individual cases can still be very different. Guba and Lincoln (1994) remark that qualitative research could be used to bridge this gap.

Although considered historically more valid and scientifically correct, quantitative research has limited applications and pertains mainly to cases where theory is to be developed and results are to be interpreted from numbers and statistical manipulation. Qualitative research applies more to behavioural sciences and relates better to the emic or insider's perspectives. However, both methods have merit, and the applications can be seen in some instances as complimentary. The eventual purpose of the enquiry will determine what method or methods should be employed in the research.

The best methodology for this research study and having regard to the above is to employ the qualitative approach. The reason for this choice is that the knowledge contained in a knowledge base forms the starting point for the abstraction of knowledge and the development of the logic base. This study aims at the design of a logic base where the structuring of knowledge and procedures to create knowledge are of prime importance. Such knowledge is mostly descriptive and not numerical. Each knowledge base contains largely different knowledge elements and therefore does not lend itself to numerical comparative studies as most often found in quantitative studies.

3.5.1 Basic versus applied research

Basic research is described by Welman, Kruger and Mitchell (2005, p.25) as research done at universities and applied research as research done in industry. Page and Meyer (2000, p.19) refer to “pure research” and that it is also referred to as “basic research”. They define pure research as “being conducted by industries and organisations for the purpose of adding to knowledge and building a theory or model.” It is done to add to the body of knowledge about the subject. Applied research is research with a specific application in mind and done to solve specific organisational problems. The implication of the applied research is that there are actions to be taken as an outcome of a research project. Implementation issues must therefore also be considered. “For managers in a cost-conscious environment, this means that implementation, change management, and research evaluation issues are critical” (Page and Meyer, 2000, p.19).

Mason and Bramble (1989, p.18) explain “basic” versus “applied” research as “The major purpose of basic research is to develop a base of knowledge upon which theory can be built. The main purpose of applied research is to answer practical and useful questions about policies, programs, projects, procedures, or organizations. Applied researchers are also found in settings in which the application or practitioner's role is primary” (Mason and Bramble, 1989, pp.18-19).

Mason and Bramble say that knowing the purpose of the research is essential. Even when the purpose of the research is clear, a study intended to be applied can contribute findings to basic research. Alternatively, a basic research study might have direct implication for the use in an applied setting (Mason and Bramble, 1989, p.25). One further aspect that can be of interest in this study is the role or influence of the researcher on the research. Summarising Mason and Bramble’s (1989, pp.20-21) discussions, the researcher in the behavioural sciences and education may inadvertently become part of the research investigation and can affect the results of the investigation in at least four ways:

- The selection of topics.
- The design of the experiment.
- The interaction between the researcher and the experimental conditions.
- Interpretation of the results.

While experimenters may be mindful of possible problems regarding their influence, there may be effects that may not be consciously noticed. This may manifest in two ways; firstly by the researcher not reporting on events as objectively as they happened and secondly, there may be a researcher's bias emerging from the interaction of the experimenter with the subject. Another manifestation of researcher effects is in “going beyond the data” (Mason and Bramble, 1989, p.23). They came to a conclusion that “the reader should bear in mind that the particular way in which a researcher conceptualise a study, is probably not the only way it could have been done. Also, honest interest in obtaining the truth on the part of the researcher is essential to the study, to be objective and valid. Further care should be taken to emphasise objectivity when research data is interpreted” (Mason and Bramble,1989, p.23).

From the above discussions, it is concluded that the nature of this research study is mostly that of an applied research study, because this research has specific applications in mind. However, it is also a form of basic research, because specific models are developed. This approach conforms to Mason and Bramble’s inference that a study intended to be applied research, might contribute findings useful to the theory of basic research.

3.6 OTHER RESEARCH METHODS

A summary of research methods reported on by various authors is given in **Table 3.2**. (Authors are referenced in the table.)

In Table 3.2, a listing and description is given of a series of research methods. Comments are made about the applicability of the research methods in relation to the objectives of this study. The objectives are as follows:

a) To consider the best and appropriate way of dealing with engineering knowledge
b) To establish suitable ontologies
c) To establish procedures for the creation of knowledge.

In order to evaluate the various research methods, the following criteria are defined:

i) Would the research method yield results that could provide engineering knowledge?

ii) Will it be possible to derive ontological structures from the method?

iii) Will there be analysis done to report problems and constraints?

A qualitative evaluation is made of the various research methods and qualitative ratings are given as follows:

- “Weak” rating when none of the above criteria are met.
- “Moderate” if some of the above criteria are met.
- “Good” rating if all the above criterial are met.

Table 3.2 Summary of research methods and applicability rating

No.	Research method	Brief description of method	Reference	Comments and motivation incorporating comments about strengths and weaknesses
1.	Quantitative research.	Observations, measurements, causal relationships statistical analysis. This method includes statistical, analytical, model-based, subspace, spectral, grid-based, graph-based, fuzzy-k modes, affinity propagation, and self-organising maps. Focus on the phenomenon that is quantifiable and is typically represented as statistics. Emphasis is usually put on predicting a hypothesis.	• Welman et al., 2005.	The research can yield quantitative results as part of engineering knowledge and solutions to problems. It will not yield knowledge about structures. The method is rated as moderate.

No.	Research method	Brief description of method	Reference	Comments and motivation incorporating comments about strengths and weaknesses
2.	Qualitative research.	Relationships between researcher and object of study, subjective, flexible and explorative. Qualitative studies focus on phenomena that can be qualified (or interpreted) and often highlight lived human experience through personal accounts.	• Welman *et al.*, 2005. • Marshall & Rossman, 1999. .	The strength lies in the fact that it covers phenomena of experience and the results of explorative research that would lead to the creation of knowledge. A good rating is given to this method.
3.	Comparative analysis.	Reasons for differences or similarity are investigated.	• Hofstee, 2006, p.124. • Page & Meyer, 2000, p.23.	Comparative analysis pertains to experiments where control groups are involved and comparisons need to be made of differences in behaviour. This is not the case in this study and the weakness lies in the fact that engineering situations are mostly unique in nature with little room for comparison between cases. A weak rating is given for this method.
4.	Historical research or ex-*post facto* or archival.	Finding new explanations for or interpret existing and historical information.	• Welman *et al.*, 2005, p.24.	This type of research may be applicable in the population of the logic base, because new interpretations from

No.	Research method	Brief description of method	Reference	Comments and motivation incorporating comments about strengths and weaknesses
			• Mason & Bramble,1989, pp.38,50. • Hofstee, 2006, p.125.	historical information involves analysis by using the latest techniques. However, for the purpose of this study it does not contribute to the design of knowledge structures and is thus weak in this respect. This method is given a moderate rating.
5.	Hypothesis – testing study.	Statistical techniques are used to test whether research findings do, or do not support the predictions arising a theory at a statistically significant level.	• Page & Meyer, 2000, p.23.	Hypothesis testing could be valuable in later studies on the application of the logic base when it is tested in practice. In this study no hypothesis testing is foreseen. This method is therefore considered weak in relation to this study.
6.	Content analysis.	To discover the non-obvious meaning contained in the record.	• Hofstee, 2006, p.124. • Welman *et al*., 2005, p.165.	This method may be valuable when considering engineering knowledge. Allowance is made in the theory of knowledge, as discussed in Chapter 2, in particular, for the application of sense-making techniques to resolve complexity. This is deemed to cover the intent of content analysis. This method exhibits strengths

No.	Research method	Brief description of method	Reference	Comments and motivation incorporating comments about strengths and weaknesses
				for purposes of this study and is given good rating.
7.	Case study research. Alternatively, field studies.	Investigate the uniqueness of some single bonded system, typically of social nature such as a family, group, community or participants in a project, institution or practice.	• Welman *et al*., 2005, p.25. • Mason & Bramble,1989, p.39. • Hofstee, 2006, p.122.	Case studies are accounts of reality. This is one of the best sources of uncovering engineering knowledge. Each case study follows a logical structure, hence suggesting ontological structures. Case studies often report on problems and constraints and how these were resolved. This research method has a considerable strength relating to the purpose of this study. A good rating is given.
8.	Action research.	Finding a solution for a particular practical problem in a specific applied setting. It enables practitioners to in every job and walk of life to investigate and evaluate their work. Case study research can add strength to what is already known through previous research. It emphasises detailed	• Welman *et al*., 2005, p.25. • McNiff & Whitehead, 2011, p.7. Mason & Bramble,1989, p.37. • Page & Meyer, 2000, p.19. • Hofstee, 2006, p.127.	Action research and case studies are closely related since action research is often the forerunner of a case study. Action research, when reported, could share similar knowledge as that obtained form case studies. This method, together with case studies, has a considerable strength relating to this study. A good rating is given.

No.	Research method	Brief description of method	Reference	Comments and motivation incorporating comments about strengths and weaknesses
		contextual analysis of a limited number of events or conditions and their relationships.		
9.	Descriptive research.	A broad range of activities that have in common the purpose of describing situations or phenomena. Can be quantitative or qualitative. Similar to case studies.	• Mason & Bramble,1989, pp.36-37.	Descriptive research can add to engineering knowledge and add much to the context of engineering problems and the solutions thereof. Descriptive research, by its very nature will be logical and would suggest structuring of knowledge. A good rating is given.
10.	Correlation research.	Study relationships between various factors.	• Mason & Bramble,1989, p.43. • Hofstee, 2006, p.120.	This method focuses mainly on quantitative correlations and is therefore considered to be rather weak in terms of this study.
11.	Developmental research.	Research that focuses on changes that can be observed over time.	• Mason & Bramble,1989, p.47.	This method could lead to case studies and add to engineering knowledge and to the solution of problems and constraints. Structure can follow. This method is given a moderate rating.
12.	Exploratory study	Looks for ideas, patterns or themes. It is an exploration of a phenomenon/even/	• Page & Meyer, 2000, p.22.	This research method has commonalities with developmental research, but is seen to be focused

No.	Research method	Brief description of method	Reference	Comments and motivation incorporating comments about strengths and weaknesses
		problem.		on uncovering specific problems. This method could be more structured than developmental research and is given a good rating.
13.	Survey-based research.	Used to do study distribution of characteristics in a population. Questionnaires and interviews are used to collect information.	• Hofstee, 2006, p.122. • Mason & Bramble,1989, p.52. • Welman *et al*.,2005 p.152.	Relating to this study, it is unlikely that survey-based research will be of value and is therefore considered weak.
14.	Experimental and quasi-experimental research.	Systematic manipulation of experimental conditions in which extraneous influences are controlled or eliminated.	• Mason & Bramble,1989, p.54. • Hofstee, 2006, p.128. • Page & Meyer, 2000, p.16. • Welman *et al.,* 2005, p.155-160.	The results of this research will normally be reported in the form of case studies. As a research method on its own, it will not produce structure and is therefore considered weak.
15.	Descriptive study.	Describes a phenomenon or event as it exists, without manipulation or control of any elements involved.	• Page & Meyer, 2000, p.22.	In terms of the objectives of this study, this method complements descriptive studies and exploratory studies. The results of such research would

No.	Research method	Brief description of method	Reference	Comments and motivation incorporating comments about strengths and weaknesses
				normally be reported in case studies. In itself and is given a moderate rating.
16.	Policy research and evaluation.	The development of a foundation of information to be used as a basis for making plans and decisions that will impact policy.	• Mason & Bramble, 1989, p.56.	Policy research is seldom used in civil engineering studies and therefore considered weak.
17.	Focus groups.	This comprises of a form of a group interview with interaction within the group and is used to facilitate the elicitation of participants' views. Focus groups are a qualitative research methodology used to obtain information about opinions, perceptions, attitudes, beliefs, and insights of a small group of people.	• Kress & Shoffner, 2007, p.190.	This method may add to engineering knowledge but structure may not be produced. A moderate rating is given.
18.	Methodological pluralism.	Signifies a flexible approach to the selection of research methods and the nature of the research problem will dictate the best method to use.		This method displays flexibility, however, it will not necessarily contribute much to the design of knowledge structures. A moderate rating is given.

No.	Research method	Brief description of method	Reference	Comments and motivation incorporating comments about strengths and weaknesses
19.	Triangulation.	This involves several methods, measures, methodologies or theories on the assumption that the weakness of a single method is compensated through the strength of others. Both qualitative and quantitative methods are used to study the same phenomenon to endeavour the improvement of credibility. An attempt is made to corroborate findings according to at least three different approaches.	• Hussein, 2015, p.2. • Welman *et al.,* 2005, p.194.	In terms of the requirements of this study, this method does not seem to be of immediate value and is considered weak.
20.	Extended literature reviews/ synthesis of scholarships.	Produce new perspectives on what was done before.	• Hofstee, 2006, p.121.	For population of the logic base this can constitute a way to do knowledge mining and reporting it in the logic base and is considered good.
21.	Critical theories.	The term critical refer to a systematic process of review and analysis of cultural phenomena. Explicitly political.	• Hofstee, 2006, p.125.	This method does not seem to apply to this study and is considered weak.

No.	Research method	Brief description of method	Reference	Comments and motivation incorporating comments about strengths and weaknesses
22.	Evaluative research.	The success level of some happening or intervention is evaluated. Evaluation is the systematic acquisition and assessment of information to provide useful feedback about some project.	• Hofstee, 2006, p.126. • Page & Meyer, 2000, p.20. • Welman *et al*., 2005, p.158.	Evaluative research is of much value in the analysis of cases. Structure may be lacking. It is given a moderate rating.
23.	Ethnographic research / Participant observation.	Observations of a group. It is a social science research method, relying on up-close, personal experience and possible participation, not just observation.	• Hofstee, 2006, p.125. • Welman *et al*., 2005, p.149.	This method is not regarded as applicable to this study and is given a weak rating.
24.	Experiments (laboratory and field work).	Laboratory and field tests are conducted to test a hypothesis or theory or the study the effects of a given intervention.	• Hofstee, 2006, p.127. • Page & Meyer, 2000, p.16. • Welman *et al*., 2005, p.78.	This method is predominantly qualitative and is therefore given a weak rating.
25.	Secondary data analysis.	This involves a study of data previously collected by other researchers to check the theory or to	• Hofstee, 2006, p.128. • Koziol & Arhur (2011).	This method is also predominantly quantitative and is therefore given a weak rating.

No.	Research method	Brief description of method	Reference	Comments and motivation incorporating comments about strengths and weaknesses
		answer other questions.	• Welman *et al*., 2005, p.164.	
26.	Simulations/ statistical modeling.	These capture the essence of a process by identifying key variables and then create a representation thereof. The results of various scenarios relating to the effects of changes in the key variables are studied.	• Hofstee, 2006, p.129. • Welman *et al*., 2005, p.163.	This method is also predominantly quantitative and is therefore given a weak rating.
27.	Interdisciplinary research.	Methods, concepts or ideas form one discipline; are applied to a problem in another discipline.	• Hofstee, 2006, p.125.	This method ties into knowledge acquisition techniques and is given a good rating.
28.	Theory development.	Lies at the heart of academic work. New ways of understanding of the world around us are sought.	• Hofstee, 2006, p.125.	Due to the practical application of the logic base it is not considered appropriate in this study and is therefore given a weak rating.

Research methods are closely linked to the purpose of the research. This will determine the required inputs and how the various outputs will be arrived at. The above summary is by no means exhaustive and serves as a basic summary to illustrate different approaches to research. There are often more than one research question, and therefore more than one research method may apply to gain the required knowledge.

From the above list of methods, the following methods were given "good" ratings. For purposes of this discussion, only the methods rated the highest ("good") will be considered further. These methods are:

- Qualitative research
- Content analysis
- Case-study research
- Action research
- Evaluative research
- Descriptive research
- Extended literature reviews/ synthesis of scholarships
- Interdisciplinary research
- Exploratory research

Of the above methods, qualitative research is considered to be a broad category of a research approach and stands in contrast to quantitative research. A more detailed exposition of quantitative and qualitative research methods was given in section 3 and **Table 3.2**. All the other methods stated above, fall under the category of qualitative research. As per point 9 in **Table 3.2**, descriptive and evaluative research are very similar to case study research and will be treated, for this study as being the same. Exploratory research constitutes a method of analysis pertaining, amongst others, to case studies. By searching for patterns, a theory can be developed (Page and Meyer, 2000, p.22). Extended literature reviews, interdisciplinary and exploratory research may be seen to have some commonalities. Evaluative research aligns with case study research and with exploratory research in that methods and techniques referred to in case studies, projects or systems are evaluated for the discovery of feedback on chosen parameters.

From the above list, action research and case studies are chosen for further consideration, because the methods are seen to encapsulate all the other methods that were given "good" ratings. In the following section further consideration will be given to these methods. (The discussion below on only two methods does not imply that any of the other methods listed in **Table 3.2** will be excluded from this study. Due to the complexities of research, situations may arise during the research where other methods may be applied.)

3.7 ACTION RESEARCH

Firstly, it is necessary to consider what action research is since it has many different meanings. “Action research is conducted with a view to finding a solution for a particular practical problem situation in a specific applied setting. It, therefore, corresponds to case study research” (Welman, Kruger and Mitchell, 2005, p.25). In the case of action research, Mason and Bramble (1989, p.37) state that “Research designed to uncover effective ways of dealing with problems in the real world can be referred to as *action research.*” Page and Meyer (2006, p.20) describe the philosophy of action research as similar to that of evaluation research, “where there is a desire to effect ongoing developmental change, monitor results, and determine whether and where further change is required. An assessment of the impact and effectiveness of change is an integral part of the process.” Furthermore, that “the researcher is an expert who guides the process by feeding back the findings to participants along the way so that they have input on what happens next.” Mason and Bramble (1989, p.38) remark that “action research is more systematic and empirical than some of the other approaches to innovation and change, but it does not lead to carefully conducted scientific experiments that are generalisable to a wide variety of situations and settings.” This point of view is rather different to that of McNiff and Whitehead (2011) who argue that action research can well be done so that practitioners can submit their emergent personal theories to the same rigorous process, testing and critique as happens to the traditional theory – creating knowledge. Mason and Bramble’s point of view regarding the carefully conducted experiments does not necessarily hold in all cases, since progress was subsequently made in the field of action research to follow a more rigorous approach. If personal theories are subjected to critique by subject matter experts or peers, research must, by implication, be done with a reasonably high level of care.

McNiff and Whitehead (2011, pp.10-11) describe action research as follows:

“Action”: Taking action to improve practice.

Research: Finding things out and coming to new understandings, that is, creating new knowledge. In action research, the knowledge is about how and why improvement has happened.” This newly created knowledge contributes to the development of theories.

McNiff and Whitehead (2011, p.11) explain that the most common form of action research is where an external researcher watches and reports on what other practitioners are doing and is referred to as interpretive action research. The less common form of action research is where practitioners offer their explanations of what they are doing. This form is referred to as "Self-study action research, first-person action research, living theory action research, or just plain action research" (McNiff and Whitehead, 2011, p.11).

Action research is further described by McNiff and Whitehead (2011, p.1) as research that is undertaken typically at one's workplace (but not limited to) and a high-quality report is produced on the research for public and further dissemination. (The need for action research often stems from the requirement for continued professional development, which is often required by professional institutions.) Elements that are covered in action research are:

- The identification of a research question.
- Mapping out an action plan.
- Utilise appropriate methodologies to do the research.
- Generate evidence from the data to test the findings against the most stringent critique.

The main reason for doing action research is first to enhance learning, to improve workplace practices. Secondly, "you can advance knowledge and theory, that is, new ideas about how things can be done and why. All research aims to generate knowledge and theories […] about learning and practice, your own and other people's" (McNiff and Whitehead, 2011, p.1). Learning from the research forms the basis for improving practice. The generation of theories is regarded by many practitioners as something beyond their capabilities and irrelevant. However, McNiff and Whitehead (2011, p.1) believe that theory should be "re-conceptualised, not as an abstract, seemingly esoteric field of study, but as a practical way of thinking about social affairs and how they can be improved."

Although action research is widely used in the social sciences, action research equally applies to applied sciences, and for the purpose of this study, also in the engineering environment. As mentioned above, action research is similar in many ways to reflective and experiential learning and which applies to areas in applied sciences such as was described in the previous chapter of this study.

Action research is increasingly seen as a form of professional learning. It is used by individuals as well as groups who investigate their collective work and put their stories of learning into the public domain. Action research is essentially insider research (McNiff and Whitehead, 2011, p.8). The process of action research involves observation, then reflection on the observations. Actions are then devised in response to the observations and reflections. The actions are then evaluated and modified as required to produce the desired outcome or results from the actions. Observations are then made and the process is repeated. This process is presented schematically in **Figure 3.1.** The information was adapted from McNiff and Whitehead (2011, p.9) and Page and Meyer (2006, p.20).

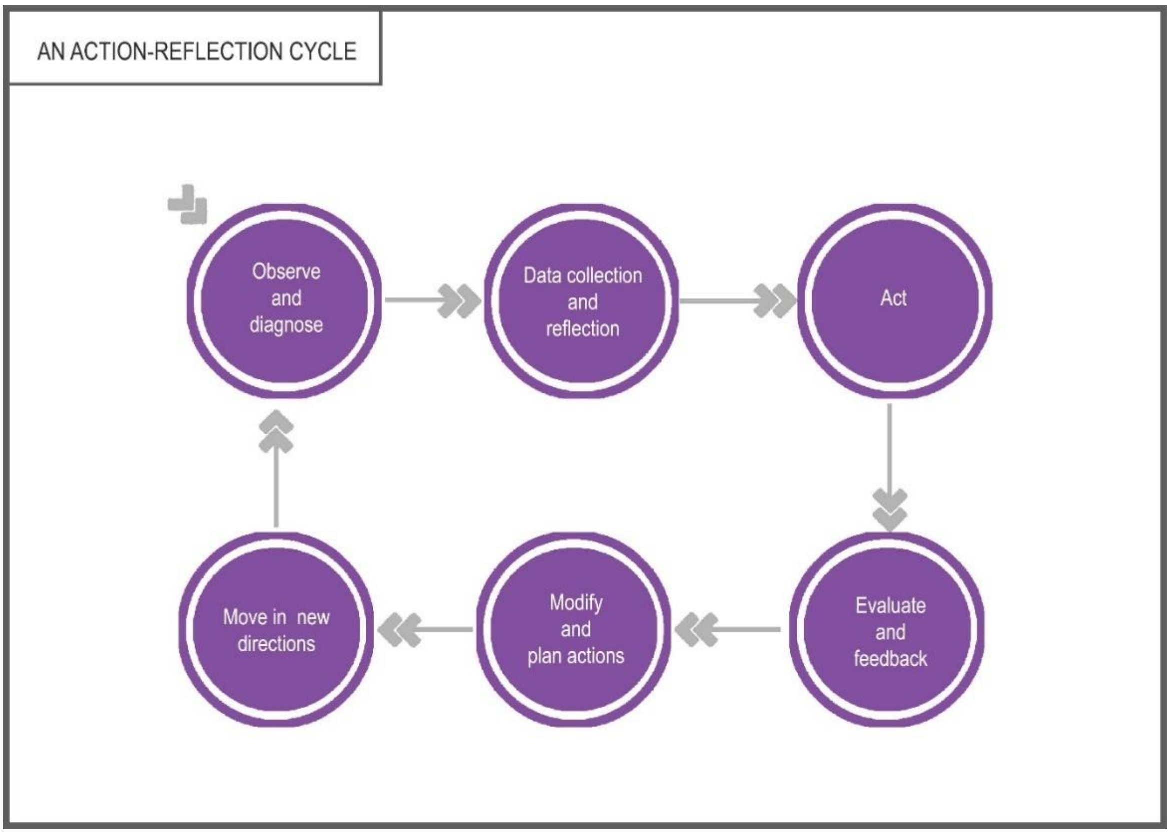

Figure 3.1 An action-reflection cycle

The above processes are the same as experiential learning and reflective learning described in Chapter 2, of this study under the topic of *knowledge-acquisition methods*. McNiff and Whitehead (2011) argue that, unlike traditional research, action research is essentially work-place based and does not aim for closure, nor do practitioners of action research expect to find certain answers. Action researchers let the story evolve. Concrete answers do not pre-exist, but are created by real people in negotiation with others. “Instead of beginning with a hypothesis, which they aim to accept or reject, action research starts with an idea and follows it where it leads them. […] many practitioners still tend to see themselves a working in a practice context and not in a knowledge context, and action research tends to be seen as a form of professional development rather than a form of practical theorising” (McNiff and Whitehead, 2011, p.61). It is interesting to note that the Cynefin model supports action research, especially in a chaotic and complex environment (refer to discussions in Chapter 2). The role of problem-solving techniques also plays a key role in action research.

In addition, a strong focus is given by McNiff and Whitehead (2011, p.18-25) on the development of own theories that adds an important dimension to the concept of action research, which is not covered by other authors, such as Mason and Bramble (1989) as well as Welman, Kruger and Mitchell (2005).

The question is, how can action research contribute to the objectives of this study? This researcher argues that an action research approach constitutes a dynamic environment with both practical and theoretical components. It is important to note is that most engineering practitioners, as part of their everyday life, seek to improve their work – referring for example, to the projects that they work on. This is done mostly without recording or documenting the action research that took place in the background. Theories are also seldom recorded as such, but remains in the memories of the practitioners as tacit knowledge. It is against this background that this research seeks to uncover the hidden action research that took the place of which theory and practice reside in the tacit dimension. Action research, however, endeavours to formalise learning and experience and to create a new theory. As put by McNiff and Whitehead (2011, p.2), “Your practice is the grounds for your theory.” Case studies are essentially the result of action research. The logic base would seek to extract and record the fabric of this knowledge to enable replication. When designing research methods, it would have to be done with the above in mind.

3.8 CASE-STUDY RESEARCH

In this research, it is considered that case studies would form a major source of engineering knowledge and have the potential from which to derive knowledge structures. The reason is that case studies report comprehensively about a case and will therefore, most likely, contain knowledge in a structured format. This will be seen in a later section. It is important to understand the structure and characteristics of case studies so that case studies can be analysed in the best possible way. The sections below look into case studies to discover more about their nature, characteristics and structure. Furthermore, case study research is considered relevant to this study since it is a study of a "single bounded system", typically of participants in a project or practice. It involves a limited number of units for analysis (often only one) that can be studied intensively (Welman, Kruger and Mitchell, 2005, p.193). Case studies are therefore valuable sources of knowledge that can be analysed for contributions to the logic base.

Case study research is, according to Page and Meyer (2000, p.22), a common form of descriptive research in management. It is an in-depth description of an individual, group, or organisation, either for the purpose of testing whether one or more cases fit a particular theory better than another or to determine what makes a case superior, inferior or different to another. Welman, Kruger and Mitchell (2005, p.25 and p.193) describe case study research as "directed at understanding the uniqueness and idiosyncrasy of a particular case in all its complexity. The objective is usually to investigate the dynamics of some single bounded system, typically of a social nature, such as a family, group, community, participants in a project, institution and practice. It does not have to be human but may also involve personal documents and records." Welman, Kruger and Mitchell (2005 p.193) state that "The term *case study* does not refer to a specific technique that is applied." Hofstee (2006, p.123) remarks that a case study examines a single case in a tightly structured way. It can be done to test a hypothesis about the case itself and also to find principles that can be extrapolated to similar cases. It is useful to note that Zainal (2007) states that "Case study research, through reports of past studies, allows the exploration and understanding of complex issues. It can be considered a robust research method, particularly when a holistic in-depth investigation is required." According to Kardos and Smith (1979), a good case study has the following features:

- It is taken from real life.
- It consists of many parts and each part usually ends with problems and points for discussion. There may not be a clear cut off point to the situation.
- It includes sufficient information for the reader to treat problems and issues. (It enhances knowledge through the capacity to act.)
- It is believable to the reader. (The case contains the setting, personalities, sequence of events, problems and conflicts.)

Yin (2003, p.xi) remarks that case studies have been "associated with *process* evaluations", however it can also be used to "document and analyse *outcomes*". The definition of a case study is given by Yin (2003, pp.4-5) as follows: "Case study means conducting an empirical investigation of a contemporary phenomenon within its natural context using multiple sources of evidence." Zainal (2007) identifies case studies to be single or multiple. He also further classifies the single and multiple case studies into three types, namely, exploratory, descriptive and explanatory. Case studies can, therefore, be seen as forming 2 x 3 dimensions. "A *single-case* study focuses on a single case only. *Multi-case studies*, however, include two or more cases within the same study. An *exploratory* case study (whether based on single or multiple cases) is aimed at defining questions and hypotheses of a subsequent study (not necessary a case study), or at determining the feasibility of the desired research procedures. A *descriptive* case study presents a complete description of the phenomenon within its context. An *explanatory* case study represents data-bearing, cause-effect relationships – explaining how events happened." The above discourse presented must also be understood against the background of social research, which is the main area of Yin's research. In the field of engineering, which is the subject of this research work, it is not entirely applicable. The main difference being that in the case of social research studies many more variables are involved and are more complex in nature. Reference is also made by Yin (2003, p.11) of the "Unit of Analysis". This term refers to the delineation of the entities involved in the case study research. In social research, it is a challenge to identify the participating entities and to delineate the scope and details of the research. In this regard, exploratory research may assist the researcher to first conduct a sample probe into the areas under investigation to enable better definition to be given to the research.

However, in the case of engineering matters, descriptive research or explanatory research would be more applicable in case study research. The reason being that in engineering, and more specifically in the approach followed in this study, the focus will be on the technical issues rather than that of the social or human sciences where the approach would be somewhat different.

One has to have a proper goal, and roadmap (layout) to conduct the studies (Zantal-Wiener, 2017). It covers the scope, depth and the start, the end and the object (case) of the case study. Furthermore, the roadmap also describes who will participate or be involved and what criteria will be used to answer the previous questions.

Reviewing the work of Yin (2003) and Zainal (2007), explanations are given of descriptive case studies and explanatory case studies. This will be discussed in the section below.

In the case of descriptive case studies, a well-developed theory, as described above, is essential. In descriptive case studies, data is gathered in various ways and analysed by using qualitative and/or quantitative analysis. Pre-considered questions are then answered by analyses of the data and information obtained through various forms of surveys.

Explanatory case studies “are the most difficult and most frequently challenged.” Each case study seeks to explain how and why some event(s) occurred. Embedded in the explanation is a potential causal path, whereby a case study seems to be making an inroad into the attribution problem. In the discussion of a particular case study (Yin, 2003, p.69), reference is made to a one-page abstract from a final report on a particular subject. Yin remarks that, “Serendipitously, the abstract’s logic contains the essential ingredients of an explanatory case study […] to demonstrate the usefulness of the logic.” This is illustrative of the application of a logic base in the context of an explanatory case study and reinforces the contention that explanatory case studies will be well-suited for this study, albeit in a different context and format.

In the engineering environment, case studies are published frequently in subject matter published on websites and in journals and books. **Table 3.3** provides examples of the sources of case studies in engineering.

Table 3.3 Examples of sources of case studies in engineering

No	TOPIC	Remarks	Reference
1.	Engineering failures.	This website is dedicated to case studies in engineering design, construction,	• www.engineeringfailures.org.

No	TOPIC	Remarks	Reference
	Case studies in engineering.	operation, maintenance, management and interface with non-engineering organisations and personnel.	
2.	Case studies in engineering failure analysis (Journal)	A forum is provided "for the rapid publication of short structured case studies in engineering failure analysis."	• Bettge, 2017.
3.	Engineering case studies – Department of Civil Engineering and Environmental Engineering, University of Carlton, CA.	"This is a collection of information on engineering cases. These are accounts of real engineering projects that are written for use in engineering education."	• https://carleton.ca/cee/?s=engineering+case+studies.
4.	Handbook of case studies in failure analysis.	This textbook deals with how others have solved common and uncommon failures in various industries.	• Esaklul (1992).
5	Engineering case studies online.	Numerous websites reporting in all engineering disciplines.	• Customer engagement team 2014. Jones, 2001.

Kardos and Smith (1979) said that an engineering case describes an engineering activity, event or problem containing some background and complexities encountered by an engineer. Cases are used in engineering studies to enhance learning about engineering principles and practices. Engineering cases differ from technical articles. Authors try to make their points as simply and directly as possible using a logical sequence for presenting findings, conclusions and opinions. This sequence seldom reflects how the engineer arrived at his point. Engineering cases, however, describe series of events which reflect the engineering activities as they actually happened, warts and all. The case writer suppresses his opinions and conclusions so the reader can deal with the information and learn from the experience of drawing his conclusions. The major objective of an engineering case is to provide a medium through which learning (e.g., analysing, applying knowledge, reasoning, drawing conclusions) takes place. Imparting addition specific information is relatively minor and coincidental.

A good case study:

- Is taken from real life (a necessity).
- Consists of one or more parts, each part usually ending with problems and/or points for discussion.
- Includes sufficient data for the reader to treat problems and issues.

To make a case believable to the reader, a good case usually includes the following topics:

- Setting
- Personalities
- Sequence of events
- Problems
- Conflicts/constraints/contradictions

Delatte (2009, p.3) organised the topics of his case studies on forensic studies in engineering as follows:

a) Introduction
b) Description of design and construction
c) Narrative describing the failure
d) Discussion of investigation, people involved and their relationships
e) Technical lessons learned – possible changes in codes of practice or procedures
f) Procedural and ethical lessons learned, legal repercussions
g) Educational aspects
h) References – reports, published papers, journal accounts and essential reading

This approach by Delatte (2009, p.3) adds useful additional perspectives to the list above.

Summarising from the above discourse, and the inspection of numerous published case studies, it is deduced that case studies can be analysed and should exhibit the following characteristics (Delatte 2009; Jones 1998; Jones 2001; LePartner & Johnson 1982):

- Examines a single bounded system in a tightly-structured way (but can also involve multiple cases).
- Involves a limited number of units of analysis.
- Contains a hypothesis about the case.
- Case studies can be exploratory, descriptive or explanatory.
- Provides real examples (including, where necessary, the setting, persons, sequence of events, problems and conflicts – depending on the nature of the case).
- Encourages replication.
- Is generally practical in nature.
- Provides innovative ideas.
- A case study must have a hypothesis or theory. This is also referred to a roadmap (also a goal, scope, depth, or plan) and contain criteria for evaluation.
- Provide a narrative describing the case (including design and construction).
- Describes the setting or context.
- Describes which people and entities (e.g., designers, contractors, role players, stakeholders were involved, and their relationships).
- Describes the investigation.
- Describes the sequence of events.
- Defines the problems encountered.
- Presents specific processes and outcomes (for dealing with the case or solving a problem). This includes actions taken to overcome problems.
- Describes technical, legal, procedural and ethical lessons learned.
- Describes educational aspects.
- Describes what events took place and describe a causal path.
- It must make inroads into attribution problems.
- Interpret the applied processes and outcomes or solutions (for example from modelling).
- States principles that can be extrapolated to similar cases.
- Provides references to reports, papers, journals, other media, etc.

In the case studies as described by various authors (Hofstee, 2006; Page and Meyer, 2000; Welman, Kruger and Mitchell, 2005; Yin, 2003) accounts are given of actual (real) cases. In these cases, problems were analysed, processes identified and solutions or outcomes discovered that could be replicated or extrapolated to similar cases. For purposes of this research, case studies are seen as most important resources of knowledge that can be used for the design and application of the logic base.

Re-stating and summarising the above, a list of topics which should be typical of case studies is given below:

a) Introduction. The introduction should summarise the case and broadly describe the scope. This will lead the reader to understand if the case study involves single or multiple cases. It should also describe if the case is exploratory, descriptive or explanatory.
b) Description of the design and construction and highlighting the hypothesis or theory (if applicable) and evaluation criteria.
c) Setting and context/narrative/role players and relationships/real examples.
d) Description of the sequence of events.
e) Discussion on investigation and defines the problems/constraints and issues encountered, and also the causal paths identified, including attribution problems.
f) Interpretation of the processes, outcomes and solutions. Show specific processes and outcomes (for dealing with the case or solving a problem). This includes actions taken to overcome problems.
g) Description of technical, legal, procedural and ethical lessons learned.
h) Describes educational aspects and principles that can be extrapolated to other cases.
i) Provision references. This can be documents, photographs, videos, etc.

3.9 THE STRUCTURE OF CASE STUDIES

The above topics of case studies emanated from a large number of case studies done over many years. The case studies were all put into written format under the typical headings or topics, representing a classification (refer to section 2.3.2 c in chapter 2). These topics provide a classification structure to the case studies. The knowledge contained in case studies needs to be communicated. This takes place by moving ideas from one person's mind to another via written text. Written communication can be understood through a process approach (Bruce *et al.*, 1978). In this study, a process approach means to move ideas (which could be mostly tacit knowledge) from one person's mind to concept diagrams. The concept diagrams also contain language that supports the visual presentation. For coherence, the tacit relationships among ideas need to be explicitly connected to enrich understanding. Ideas need to be created or discovered and collected from cases and grouped according to some form of hierarchy. The structuring of ideas leads to new ideas. Mendeleev's periodic table is a good example. The two-dimensional table was based on an atomic number structure and led to the discovery of new elements which filled the missing cells in the structure. If a structure of ideas (concepts) reflects coherence in logic, missing ideas or concepts can be discovered. The connected concepts are the building stones of knowledge. "Knowledge is not found ready-made in nature. Instead, knowledge is constructed in the interplay between nature and the symbol systems we use to structure and interpret it" (Winsor, 1990, p.58). The connections between ideas or concepts are open to interpretation and manipulation. External influences may alter the connections and change the process parameters and therefore change the meaning. Too many relationships between ideas complicate cases.

The topics of case studies and be decomposed into lower hierarchical levels, adding more interconnected ideas or concepts. This decomposition enables increased conveyance of ideas, and meaning thereby, increasing the communication ability.

3.10 RESEARCH DESIGN

The discussion on research methods in preceding sections led to the choice of case-study research for the design on the logic base. When a case study is done, the various topics listed above will guide the researcher to obtain and analyse as much relevant information and gain as much knowledge as possible to enable proper reporting of a case. When considering the topics listed above, the inherent logic structure thereof and communicative properties, when placed into a form of hierarchy was indicated in the previous section. The logic base will make use of concept diagrams as a basis for knowledge communication. Problem-solving techniques are incorporated into this structuring of the logic base, thereby providing the basis for knowledge creation. The objectives of the logic base are to systematically record knowledge for reuse and to facilitate knowledge creation. The structure of case studies therefore, fulfils both these objectives.

In the following section, more details of the ongoing practical research are given that have a direct bearing on the functioning of the logic base.

3.11 KNOWLEDGE BASES IN CIVIL ENGINEERING

The acquisition and reuse of knowledge can be facilitated in the logic base by linkages to existing knowledge bases. There are numerous knowledge bases available to civil engineers when searching for information. However, it is always of paramount importance to add context to the information to turn it into knowledge.

Some references to knowledge bases were researched and are given in below:

- The American Society of Civil Engineers developed a “Body of Knowledge for the 21st Century” (CE BOK) (Koehn and James, 2006).
- The Project Management Institute (Project Management, 2008) published a guide to project management, referred to as the PMBOK® Guide.
- Publications by engineering societies publish papers, newsletters, magazines or provide web links to published material to cater for the distribution of knowledge.

Examples are:

- The South African Institution of Civil Engineering (SAICE)
- The British Institution of Civil Engineers (ICE)
- The Canadian Society for Civil Engineering (CSCE)
- The Institution of Civil Engineers (ICE, India)

Furthermore, there are several software packages, designed to compile knowledge bases. Examples are given in **Table 3.4**

Table 3.4 Examples of knowledge bases (in the field of engineering)

No.	Registered Trade Name	Description
1	Knowledgebase: ExtremeEase® (*BrowseLab*).	Makes it possible for anyone to create a professional web-based knowledgebase that runs in all browsers on all platforms.
2	Knowledge Base Software (*KnowBase)*.	This a trade name for a suite of civil engineering software packages providing interaction with Open Design Alliance (ODA). Embedded in the software is access to engineering-related knowledge libraries.
3	Civilax.	Comprising numerous civil engineering software modules. Modules contain learning modules and tutorials for the teaching of users. Imbedded in the software is access to engineering-related knowledge libraries.

(For the purpose of this study, reference will be made to a “knowledge base” as meaning any source of knowledge. This includes the content of any magazine, journal, subject matter, or any other document or content of discussions with one or more persons.)

The use of knowledge management software can be of great assistance to an organisation for enabling the systematic development and dissemination of knowledge. It should be noted that it is not the intention of this study to replace any existing software by new software that supports a logic base. If new software is deemed necessary to support a logic base, such software will most probably run in conjunction with *knowledge base* software. For example, users rely on knowledge embedded in the knowledge base software to assist or guide the user in engineering design.

The knowledge contained in knowledge bases could be evaluated against the knowledge structures in the logic base. The logic base can be populated with the knowledge derived from the logic bases.

3.12 CONCLUSIONS

The goals of this research were discussed, and the sub-research question (e) (Chapter 1) was answered in this chapter.

What research methodologies are most applicable for the discovery and application of engineering knowledge?

Attention was given to various research methods and the most applicable research methods were selected and discussed in some detail. Action research and case study research turned out to be most applicable to this study. Case studies are often the outcome of action research. To limit the extent of this research, it is proposed that only case-study research be included in this study for the design of the logic base. The focus will only be on written case studies. It was indicated that the topics of case studies could form a structured means of communication and are imminently suitable for designing of the logic base. Some of the sources of case studies were highlighted. It is important to note that the design of the proposed logic base will involve a synthesis of case study research, knowledge theories, problem-solving and knowledge structures.

The following chapter will involve research into the design of the logic base.

CHAPTER 4: THE DESIGN OF A LOGIC BASE

4.1 INTRODUCTION

In this chapter, the research done in Chapter 2 (Literature Review) and Chapter 3 (Research Design and Methods) are used as a basis for the design of the structure of the proposed logic base. The theory of knowledge (referring in this case to the various knowledge processes as described in Chapter 2) is applied. Chapter 3 outlines research methodologies and concluded that research through case studies is deemed to be the most practical method for this part of the research where the ontology of the proposed logic base is designed. The proposed logic base represents a process-driven investigation for the discovery of knowledge.

The sub-questions pertaining to this chapter are as follows: (Also refer to Chapter 1.)

f) What components are required for the logic base?

The following are sub-sub research questions:

- *i) How can knowledge acquisition, reuse and knowledge creation be translated into components of a logic base?*
- *ii) What are the relationships among the various components and how would the components contribute to the functioning of the logic base?*
- *iii) What criteria are required to provide the functionality of knowledge acquisition, reuse and knowledge creation?*

These questions are answered in this chapter where the design of the logic base is discussed.

g) What is an appropriate architecture of a logic base to fulfil the Functional Requirements (FRs) for the acquisition, reuse and for the creation of knowledge?

The following sub-sub research questions pertain:

- *i) What ontology and/or taxonomy can form the basis of the design of a logic base?*
- *ii) How sensitive are the ontologies for different applications?*

The methodology for the development of the logic base is summarised as follows:

Based on the research conducted in previous chapters, an ontology for the knowledge is first of all developed. This will enable knowledge from various sources, including case studies, to be structured by classification into applicable knowledge domains. These knowledge domains are interrelated and one domain connects to others. This process in itself can prompt for further knowledge in related domains. Once the ontology for the knowledge is developed, problem-solving techniques are applied to the available knowledge. This is used to document the basis of existing knowledge and also to enable the discovery of new knowledge. The logic base would then display such knowledge for onward use in engineering applications. Case studies (refer to sections 2.3.2, 2.4.4, in chapter 2 and 3.6 and 3.8 in chapter 3) present knowledge in a structured way and can be transported to the ontology by way of concept maps. Case studies are well-documented and accessible for analysis. A characteristic of case studies is that they are generally done according to some "roadmap" (Yin, 2003). This roadmap constitutes a classification of topics that a case study should cover. A roadmap also portrays a logical sequence (and form of hierarchy) or flow of the information in the case being studied, and therefore also of the knowledge domains contained therein.

In the first part of this chapter, consideration is given to the various types of knowledge that need to be incorporated into the logic base. This is based on sources of knowledge that can be found in a large mining corporation (Tobin, 2006). These sources of knowledge represent various knowledge types. These are compared with the types of knowledge that could be offered by case studies. Secondly, consideration is given to the desired attributes that should form part of the proposed logic base. User-friendly concept maps are tools to describe ontologies. Concept maps are drawn that essentially extend and expand the topics or knowledge domains of case studies into greater detail to accommodate the desired attributes of a logic base. The application of problem-solving techniques in the logic base is then discussed, as well as the proposed operation of the logic base. An example is given of the proposed operation of the logic base.

4.2 DISCUSSION ON TYPES OF KNOWLEDGE

In Chapter 2 of this study, a list was compiled of knowledge-management practices and of the sources of the knowledge found and in use in practice, in a large corporation (refer to **Table 2.2** in Chapter 2 of this study). In **Table 4.1** comments were added to the original details given in **Table 2.7** to form a new table, illustrating where case studies, would be able to provide knowledge to the logic base. Comments given in the table are shown in **bold and italics.**

Table 4.1 Summary of types of knowledge and examples of various sources

Types of knowledge	**Specific knowledge**	**Examples of sources (Comments given in italics)**
Procedural knowledge (how to do something or how something occurs or is performed).	• Standards. • Codes of practice. • Work instructions. • Specifications. • Guidelines. • Knowledge sourced from communities of practice. • Knowledge sourced from expert networks. • Interpretation of standards and specifications. • Application of theory/technology. • Management-related procedures.	• Applicable to subject matter from publications that can be found in case studies. ***Example: Describing the applicability of design procedures contained in design codes.***
Declarative knowledge (knowledge about something, details of concepts or objects).	• Process knowledge. • Describing how something was done.	• Specific to engineering disciplines and found as the subject of case studies. ***Example: How a structure is designed for a wind turbine. (Also: Object, attribute, value included. E.g., electrical dynamo, power rating, 3MW.)***
Meta-knowledge (knowledge about knowledge).	• Benchmarking. • Libraries.	• Subject matter publications report this in case studies.

Types of knowledge	**Specific knowledge**	**Examples of sources (Comments given in italics)**
Heuristic knowledge (rules-of-thumb guiding problem-solving).	• Mentoring. • Learning by doing. • Identification and resolving constraints and contradictions.	• Many large companies have mentoring programmes whereby suitably experienced individuals are tasked to mentor less experienced persons. This is also typical of training methods in various trades. • Mentoring is an essential component of the training of professional engineers. The requirement is set by professional institutions for candidate engineers to have the approval and sign-off by their mentors to enable professional registration. ***Case studies often report this type of knowledge. These can be formal or informal in nature.***
Structural knowledge (mental knowledge and organisation thereof).	• Gap-analysis measurement systems. • Development of theory and applications.	***Often reported in the subject literature in the form of case studies.***
Inexact and uncertain knowledge (not precise measures).	• Scenario planning. • Systems modelling and characterisation of parameters.	Internally done within organisations but also published as case studies. ***Subject-specific work which is often published as case studies.***
Common-sense knowledge (knowledge that cannot easily be put into precise theories).	• After-action reviews. • Suggestion schemes. • Systems-performance models. • Sharing of knowledge.	• Internal reviews in companies. • Internal practices in companies. • Subject-specific modelling. • Informal sharing.

Types of knowledge	**Specific knowledge**	**Examples of sources (Comments given in italics)**
		Case studies can report on the above matters.
Ontological knowledge (knowledge of why something occurs, provides meaning to various kinds of things. Incorporates causal knowledge).	• Legal reviews. • Knowledge workshops. • Post-event learnings.	Companies do reviews, workshops and post-event learnings to enhance organisational knowledge. ***Case studies can report on these.***
Specific knowledge (content-specific knowledge).	• Business intelligence. • Stories and storytelling. • Incident reports. • Learning from incidents. • Environmental scanning. • Surveys (internal and external). • Subject matter theories and applications.	These are mostly internal to companies and not necessarily published to the outside world. However, if the subject matter is of external interest and purpose to enhance the industry, specific knowledge is also published. ***Case studies can fulfil this function – either published internally in companies or externally.***

Table 4.1 shows that case studies can fulfil the reporting needs of every knowledge type as outlined in the first column of the table. The types of knowledge differ in nature. Some case studies can be formal and others informal. Some case studies could be simple and others complicated. Some could exhibit all the characteristics of a good case study, while others lack most of these characteristics. For example, reporting procedural knowledge such as the development of specifications could be methodical and exact, whilst reporting on rules of thumb as found in heuristic knowledge, is not necessarily methodical or exact. When classifying the knowledge types, some case studies will cover many or all of the typical topics in case studies, while others may be described by only a few topics. The ontology for case studies is flexible and can accommodate all the types of knowledge.

4.3 KNOWLEDGE PROCESSES AND CASE STUDIES

The classification of typical topics comprising case studies is given below (refer to Chapter 3, Section 3.8). The topics were classified to form ten distinct concepts that can be arranged in classes of schemas (groups of concepts) (Gašević, Djuric and Devedžić, 2009; Kellogg, 2002; Howard, 1987; Cebrian-Tarrason and Vidal, 2008). These classes should cover most cases (in its broadest sense) in civil engineering:

a) Introduction and scope.
b) Design and construction/manufacturing.
c) Operations and maintenance.
d) Setting and context/narrative/role players and relationships/real examples.
e) Sequence of events and causal path.
f) Investigation, problems, constraints and issues.
g) Interpret actions, solutions and actions taken.
h) Technical, legal and ethical lessons learned.
i) Educational aspects, extrapolation and replication.
j) References.

The above topics, when viewed holistically from a systems point of view, are all subject to a large number of influences. When studying any case, one has to make the enquiry how the case would be influenced by external factors. In order to adequately cater for such factors, the introduction of an additional class, “influencing domain” is suggested.

The significance of the list of typical or characteristic topics of case studies is that this list of topics is seen to be as a logical sequence for the development of an ontology for the logic base. This is discussed in the following section.

In order to ascertain if the above topics are in fact relevant and applicable to this study, a small random sample of articles was selected from subject literature. The reported cases were briefly analysed in terms of the above topics. This is reported in **Appendix F**. The conclusion from this brief study is that the topics are indeed relevant to each of the randomly selected cases. The emphasis will, of course, be different for each case study, but it is interesting to note that the topics are relevant for at least exploratory, explanatory and descriptive case studies which were covered in the selected sample.

4.4 DEVELOPMENT OF AN ONTOLOGY FOR A LOGIC BASE

4.4.1 The desired attributes of the logic base

From the **Table 2.4** in Chapter 2 of this study, a list of attributes of the proposed knowledge base is given. The following summary is compiled from **Table 2.4**. The summary is expanded and incorporates the list in **Table 2.4**. This list also serves as an outline for the logic base (not necessarily in a particular order):

- Classifications and hierarchies are required (topical and/or functional).
- Integration of organisational strategies, policies, cultures and supporting technologies.
- All phases of projects as well as operations, maintenance and retirement should be included.
- Uncertainties must be addressed. (Also, involving sense-making such as the Cynefin framework, if required.) (Refer to Chapter 2.)
- All significant external influences on the system should be evaluated.
- Assumptions must be challenged.
- Attributes of elements and relationships among them must be identified.
- Causes and effects of actions must be identified, where possible.
- Root causes must be identified.
- Issues must be explored.
- Clear purpose and goal setting (idealisation) is required.
- Appropriate Functional Requirements (FRs) and Design Parameters (DPs) must be defined.
- Processes must be in place to identify attributes and establish the relationships between them.
- Analysis of contradictions and constraints is required.
- Risks are to be identified. (Including all kinds of risks, such as the risks of failure, health, safety, financial, time, resources risks and business risks.)
- Expansion of knowledge to cover wider fields is needed.
- Analogies are made and context provided.
- Prompting, triggers and metaphors are to be used.
- Action is required through systematic analysis using HOT/FAST methodologies. (Refer to Chapter 2, Section 2.7.10 and 2.7.11.)
- Checklists can be generated as actionable items.

- Patterns and standard solutions must form part of the logic base (refer to the 40 “innovative principles” offered by TRIZ) (Mann, 2007a).
- Evidence and experiences must update knowledge.
- Recording or sharing of experience. (Where applicable, by way of media support such as video clips.)
- It must be adaptable and modifiable.

Reference is made to **Appendix H** for a discussion in the application of the above in the drafting of concept maps.

4.4.2 The applicability of the attributes to the logic base

The functioning of a logic base starts when the content of case studies is analysed and knowledge units abstracted, re-worked by way of identification of various key attributes and entered in the classified topics of an ontology. This ontology and the attributes of the various entities can then be reworked through the application of various problem-solving techniques into new knowledge for example, lessons learned. The attributes therefore play an important role in the compilation of the proposed logic base.

When considering the applicability of the attributes to the logic base, the following comments are made on the above desired attributes.

a) The classification and hierarchies would serve to organise knowledge units for easy retrieval from databases or knowledge bases. Effect will be given to this by the development of an ontology for the logic base. The ontology must constitute the main elements of the topic under consideration. An ontology, based on the topics and structure of case studies, is proposed.

b) Integration of organisational policies, cultures and supporting technologies is required for effective organisational support for knowledge management. (Refer to discussions in Chapter 2, Section 4.4.2 on the roles of organisations in knowledge creation.) A culture of sharing of information and more particularly to use case studies, could foster knowledge creation, which is one of the prime functions of the proposed logic base. Characteristics, peculiar of a specific organisation, can be defined and taken up in the logic base.

c) The logic base must make provision for all phases or stages of project development, such as conceptual, pre-feasibility, feasibility, implementation, commissioning, operations, maintenance and retirement. Each phase or stage has its own peculiarities and knowledge domains differ from one phase to the next. However, all phases are inter-related and form a complete system. The phases must therefore be properly interfaced and integrated. When dealing with a certain aspect, it is important to know to which phase the aspect relates so that the context could be correctly understood.

d) Influences from external factors need to be considered. Aspects such as economic, social and environmental issues need to be taken into account.

e) Uncertainty can be related to a lack of knowledge about something and can be addressed through the analysis of risks and/or by considering the use of the Cynefin framework to identify the domain(s) in which the issues lie and then to move from unknown domains to known domains.

f) As part of the analysis of knowledge, assumptions are often made. These should be identified and challenged to evaluate the generality and applicability of the knowledge. This would be necessary for the process of populating the logic base.

g) Attributes of elements and relationships among them must be identified. This is a basic characteristic of an ontology. The relationships among elements are of key importance when it comes to the creation of new knowledge. The relationships among elements define contradictions and constraints that lead to problem identification, definitions and solutions and therefore have a direct bearing on the performance of any system. It also leads to the creation of knowledge. A study of the interrelationships would also provide the opportunity to challenge assumptions and to deal with uncertainties. This also relates to the S-Fields in the TRIZ-system where the interaction and interrelationships among various elements are studied and interpreted. The qualities of the so-called fields are assessed and guidelines are given of what actions to take if relationships or types of interaction are deemed not to meet the system requirements (Interactions are classified as “effective”, “missing”, “insufficient”, “excessive” or “harmful” and solutions are offered to solve problems relating to interactions.) (Mann, 2007b, p.246).

h) Causes and effects must be identified. Case studies often report on this very aspect. It is, however, also important to ensure that the root causes are identified. Dealing with root causes is fundamental to knowledge creation and the quality of knowledge taken up in the logic base. It is always important to address the correct problem or constraint. This flows from the definition and study of relationships as discussed above and in the application of a Root-Cause Analysis (RCA). The Theory of Constraints (TOC) is primarily based on the study of cause-and-effect relationships to identify problems and constraints in systems and points to the root causes.

i) Exploring issues. This refers to problems that were identified and reported in case studies and subsequently resolved. There could also be other issues, not necessarily reported in the case study that come to the fore when a case is analysed. Such issues need further attention as it can point to new contradictions and constraints that need resolution (this is part of knowledge creation).

j) Clear purpose and goal setting (idealisation) is required. “Desire, not necessity, is the mother of invention. New things and the ideas for things come from our dissatisfaction with what there is and from the want of a satisfactory thing for doing what we want done” (Petroski, 2006, p.1). Desire leads to clear goals and goal setting. These goals lead to needs and needs can be translated into user requirements and Functional Requirements (FRs). These are essential parts of the ontology required for the logic base and drive the development processes.

k) Analysis of contradictions and constraints are required. This will also consider relationships and types of interactions among topics and attributes as discussed above. The use of standard solutions and inventive principles, as described by the TRIZ-technique of problem-solving, can be most useful in this instance.

l) Risks are to be identified. Risks can relate to that of failure, health and safety risks, financial risks, and risks related to time and capacity of resources as well as business risks.

m) The application of FMECA (Failure-Modes, Effects and Criticality Analysis) is of importance here. Testing the attributes and their relationships for potential failures must be part of the operation of a logic base.

n) Expansion to cover wider fields is needed. The case at hand can be extended to other analogous cases in other sub-disciplines in civil engineering and in other fields of engineering.

(In addition, although the development approach followed in this study relates to case studies in civil engineering, it should also be expandable into other engineering and non-engineering disciplines. The logic base should generalise knowledge and would then, as a result, also lead to expansion to other fields.)

o) Analogies are important for the expansion to wider fields and needs to be incorporated into the logic base as a separate function or routine to check if there are any analogies present. The same holds for prompting, triggers and metaphors.

p) Action is required. This refers to the operation of the logic base whereby methods of how to deal with things are part of the output. These methods must be actionable. This enhances knowledge in the sense that knowledge is defined as the “capacity to act” (refer to Chapter 2, Section 2.3.1; “Definitions of knowledge”). The use of analysis techniques such as FAST or HOT, must be part of the operation of the logic base.

q) Patterns and standard solutions must form part of the logic base (refer to TRIZ). From the analysis of contradictions and constraints among elements, guidance is given of what possible solutions could be. This is an essential way to update knowledge.

r) Evidence and experience must update knowledge. The logic base could have a feedback to an applicable world-wide knowledge base(s) to update knowledge.

s) Recording of experience by way of knowledge bases and other media (such as videos, animations, etc.) should be part of the logic base and can fulfil an important educational function.

4.5 DEVELOPMENT OF THE ARCHITECTURE OF THE LOGIC BASE

Taking into account the classification of topics of case studies and also the various attributes that are desired for a logic base. By synthesis the topics, the functions and the attributes are used to arrive at an ontology that will form the basis for the logic base. The question is how and to what extent do the characteristic topics of case studies serve or link the attributes required of a logic base. As a first step, a mapping is done in **Table 4.2** between the topics of case studies and of the desired attributes of a logic base.

Table 4.2 Mapping topics in case studies with desired attributes of logic base

TOPICS IN CASE STUDIES	DESIRED ATTRIBUTES OF LOGIC BASE
Introduction and scope.	• Clear purpose and goal setting required.
Design.	• Attributes of elements and relationships among them must be identified. • Functional Requirements (FRs) and Design Parameters (DPs) to be identified.
Construction/manufacturing.	• Techniques to construct/manufacture. Further objects and functions are required.
Operations and maintenance.	• Functional elements and relation to performance goals need to be determined.

TOPICS IN CASE STUDIES	DESIRED ATTRIBUTES OF LOGIC BASE
Setting and context.	• Background information is to be provided. • Attributes of elements and relationships among them must be identified. • Integration of organisational strategies, policies, technologies and cultures. • Phases of development such as conceptual, pre-feasibility, feasibility, implementation, operations, maintenance and retirement/closure.
Sequence of events.	• Attributes of elements and relationships among them must be identified.
Investigation.	• Assumptions must be challenged. • Issues to be explored. • Root causes must be identified. • Causes and effects must be identified. • FMECA to be applied. • Evidence to be recorded. • Problem-solving techniques to be applied – incorporate TRIZ- or TOC-techniques.
Interpretation.	• Uncertainties must be addressed. • Analysis of contradictions and constraints are required. • Risks to be identified. • Actions to be identified. • HOT- or FAST-techniques to be applied. • Patterns and standard solutions to be identified. • Effective actions to be identified. • Triggers to be identified. • Checklists to be provided if appropriate. • Solutions found and adopted.
Lessons learned.	• Lessons learned are deducted from case studies and could represent both tacit or explicit knowledge. Where possible, analogies and metaphors are to be formulated.
Educational/extrapolation.	• Expansion of knowledge over wider fields is needed. • Prompting, triggers and metaphors to be used. • Evidence and experience must update knowledge.

TOPICS IN CASE STUDIES	DESIRED ATTRIBUTES OF LOGIC BASE
	• Must exhibit knowledge sharing ability.
References.	• Knowledge sharing suggests that references should be made including the utilisation of related media.
Influences.	• The effects of external influences should be taken into account.

The *ontologies* in the logic base have to be hierarchally structured in a topical or functional way. This leads to the separation of the concepts of design and construction/manufacturing. Although design and construction/manufacturing have to do with the establishment of an asset or object, design always precedes construction/manufacturing. The separation is indicated in the **Table 4.2**. that shows that there are eleven main topics for case studies. Influences are added as a further topic that supplements all the other topics. This means that there are twelve topics. (The consolidation of lessons learned and education is suggested to simplify the concept map to eleven concepts.)

Although a clear hierarchy is not displayed, there is a logical sequence or structure, which resembles a hierarchy of information. Information about a topic requires information about the preceding topic to paint a complete picture of the case. For example, one cannot review lessons learned unless one knows all the details of an investigation and interpretation thereof. It is therefore deemed to satisfy the desired attribute of the topical arrangement as indicated. The mapping in **Table 4.2** depicts the incorporation of all the required attributes of a logic base into the characteristic topics of case studies. It is concluded that the topics of case studies can be used to develop an ontology. Furthermore, the content of case studies should be analysed to obtain as much detail of the attributes as possible.

4.6 AN ONTOLOGY FOR THE LOGIC BASE

4.6.1 Case study topics and ontologies

In this study, the approach followed is discussed below.

In Chapter 2, Section 2.9.2, the term ontology is discussed. In summary, ontology represents generalised concepts, associated attributes with values and relationships between concepts and attributes. (Per definition in Chapter 2, Section 2.9.2 [Gruber, 1993; Issa and Mutis, 2015; Borst, 1997] an ontology is "a formal, explicit specification of a shared conceptualization.") The topics of case studies qualify as a shared conceptualisation. When formal, explicit specifications are given to topics, it would then fully qualify the topics as capable of forming and ontology. The specification of topics can be done when attributes or properties are assigned. There are various ways of specification. Examples are:

a) Object – Attribute - Value (also known as the OAV triplets).
b) Function – Behaviour - Structure (FBS).
c) Function – Behaviour – State.
d) Behaviour-driven - Function - Environment - Structure (B-FES).
e) Function - Physical Principle -Technology (FPPT).

The terms "function", "behaviour" and "structure" are used to define a framework to model and represent system functionality. In the FBS framework, "function represents the functions that the system performs; Structure represents the physical elements of the solution and behaviour acts as the relationship between F and S" (Cebrian-Tarrason and Vidal, 2008). The treatise by Cebrian-Tarrason and Vidal is based on design processes and the outcomes of designs. An ontology called "OntoFaBeS" was introduced which "formalizes the knowledge about a product in order to infer different structures of that product from functional requirements set by the user, with the objective that knowledge is reused and shared between different applications" (Cebrian-Tarrason and Vidal, 2008, p.3).

The logic base is not limited to the incorporation of ontologies relating to design, but spans a much wider field and represents at least a substantial coverage of the functions and activities found in civil engineering.

The ontology represents a hierarchical structure. The eleven topics of case studies represent concepts that form a logically interrelated system. A case must be seen holistically where each topic adds information and knowledge. For example, the scope is necessary to do the required designs and design is necessary before construction can take place. Maintenance typically only commences after a facility operated for some time. This structure displays mainly function-dependent or information-dependent hierarchy and logic. Dependency can also be time-related. For example, an unwanted event can take place at any time and is not necessarily information-dependent. From the discussion in the preceding section, it is deduced that the topics of case studies, defined and concepts, fully qualify as an ontology.

Since the ontology is of a most generalised nature, it is defined in this study as the "Top-Level Ontology" (TLO).

Sub-concepts associated with each of the top-level concepts would then constitute another level of concepts and named as the "High-Level Ontology" (HLO).

In this study, the use of concept maps is now introduced to represent knowledge domains in ontologies.

4.6.2 Concept maps

In Chapter 2, the role of cognitive psychology was discussed (refer to section 2.3.2 in chapter 2). Mental representations by way of concepts in various forms were explained. Furhermore, the categorisation of concepts were discussed in section 2.3.2 (c). The discourse on cognitive thinking offers a strong motivation for consideration of concept maps or maps for the presentation and categorisation of thought processes (also knowledge processes) and for integration of problem-solving techniques with concept maps for enhancement of knowledge. (The terms concept map and concept diagram are used interchangeably and regarded as having the same meaning.)

By virtue of the processes of mental representation of concepts and the categorisation of concepts, concept mapping is of great interest in this study. The basis of concept maps stems from semantic network models. Semantic network models are organised, hierarchical structures found in cognitive psychology. These structures depict taxonomies and partonomies in a hierarchical structure. Concepts are categorised according to various methods, such as a rule-based, symbolic approach or the connectionist approach where human influences, experience and context play major roles. Concepts may comprise sub-concepts and all concepts may contain slots (instantiations). From an artificial intelligence point of view, Gašević, Djuric and Devedžić (2009, p.68) state that, "Ontologies represent concepts, their properties, the values of the properties, events, and their causes and effects, processes, and time." It is therefore deduced that concepts or schemas can be structured to form ontologies. Concepts and schemata are represented graphically in network diagrams (Kellogg, 2002; Howard, 1987). Concept mapping stems from the semantic network models or diagrams and "uses a notation to represent structure to some domain to be taught or learned. Concept mapping has been widely applied in education" (Howard, 1987, p.169; Novak and Gowin 1984; Weinbrenner, Engler and Hoppe, 2011).

Novak and Caňas (2008, p.1) explain that "Concept maps are graphical tools for organising and representing knowledge […]. We define *concept* as *a perceived regularity in events or* *objects, or records of events or objects, designated by a label.*" In the graphical representation, concepts are placed in boxes of some type and relationships between them are indicated by arrows linking the concepts. Words on the linking lines specify the relationship(s) between the concepts. The label can be a word, symbol, such as + or %, or more than a word can be used.

A further characteristic of concept maps is that they represent the concepts in a hierarchical manner with the most inclusive and most general concepts at the top of the map and the more specific and less general concepts hierarchically lower down. "The hierarchical structure for a particular domain of knowledge also depends upon the context in which the knowledge being applied is considered. Therefore, it is best to construct concept maps with reference to some particular question we seek to answer, which we have called a *focus question.* The concept map may pertain to some situation or event that we are trying to understand through the organization of knowledge in the form of a concept map, thus providing the *context* for the concept map" (Novak and Caňas, 2008, pp.2).

Cross-linking is another useful characteristic of a concept map. There are relationship links between concepts in other domains of the concept map. In the creation of new knowledge, cross-links often represent creative leaps on the part of the knowledge producer (Novak, 2008). Concept maps are specific examples of events or objects that help to clarify meaning to a given concept. These are not placed in boxes since they are specific events or objects and do not represent concepts (Novak and Caňas, 2008). Concept mapping represents a way to make tacit knowledge explicit.

Reference is made to the definition of knowledge in Chapter 2, Section 2.3.1 of this study, whereby knowledge is defined as "an awareness, consciousness, familiarity, perception or understanding that causes the possessor to have a practical command of, or competence, skill or expertise in or capacity to act". A concept map portrays perceptions and understanding of a situation and when studying the concept map, provides the practical command or competence or capacity to act in a particular case.

From the foregoing it is concluded that concept maps represent a suitable and useful way of developing an ontology whereby the concepts contained in **Table 4.2** could be represented and expanded to reflect the related concepts, and to add context to the various knowledge domains. For the purposes of this study concept maps can be developed for each class or topic such as the characteristic topics of case studies, representing the Top-level Ontology (TLO). From there on the TLO can be broken down into sub-ontologies as the need may be. The terms "concept maps" and "ontology", from this point onwards, are used interchangeably in this study.

4.6.3 Categorisation

In Chapter 2, Section 2.3.2, an exposition is given of categorisation (or classification) of concepts as found in the field of cognitive psychology. Mental processes of thinking and problem-solving involves categorisation of concepts and schemata. This classification can take place automatically or tacitly. How an individual classifies concepts and form schemata depends on the context, purpose and experience. In summary, the following aspects are of particular interest in concept maps (refer to: Lakoff, 1987; Sternberg, 1999). Reference is made to Section 2.3.2, subsection c) of Chapter 2:

a) Categorisation can be classified according to common properties, attributes, functions, etc.
b) A member of a category does not need to possess all the properties.
c) Family resemblance can be used in categorisation where members of a category may be related to one another without all members having any properties in common that define the category.
d) Category boundaries are flexible and gradation takes place where at least some categories have degrees of membership and no clear boundaries.

The logic base mainly represents a qualitative technique rather than quantitative, and a rigorous classification of concepts is not essential for the functioning of the logic base and categorisation can be done by considering perceptual compatibility of elements in each category. As discussed in sections 2.6 on knowledge acquisition and 2.7 on problem-solving, the aims are to identify, define and to discover contributing elements and context of phenomena or situations that need resolution. To establish an environment conducive for such discovery, a user should have the freedom to think without placing constraints on the methods and ways a person would initially formulate concept diagrams. For that reason, The initial drafting of concept diagrams should be unconstrained with no rules, other than to identify concepts and their relationships as far as possible. The structuring and classification of the concepts follows the “free” phase.

As an illustration, a concept may be “Introduction and scope”. This concept represents the initiation of a project. The discourse on this topic can, for example, include thinking of the end goals of project or a system, all the functions that need to be taking care of, all the user requirements, when and who would be involved in a project, etc. When all these concepts were formulated one may start with categorisaton or classification processes. In this instance a single class may be defined, focusing on the purpose of an engineering matter. This may be subdivided into two categories of concepts, namely “introduction” and “scope”. The “introduction” and “scope” can be classified as two different knowledge domains and represent sub-concepts, belonging to a class called “introduction and scope”. It can therefore be deduced that within the context of the initiation of an engineering endeavour, the classification of introduction and scope are coherent concepts within the context of the initiation of engineering work. This is in line with Lakoff’s statements above, in particular that of (c), “family resemblance” and d), “gradation of membership”.

Concepts as found or classified in the topics of case studies represent schemas since it represents selection and grouping of concepts. The grouping of sub-concepts or other concepts can follow the descriptions of points a) to d) above or more comprehensively, as shown in Chapter 2. A hierarchical structure does, to some extent, underlie the ontology. The hierarchy is more in terms of an information or functional hierarchy where one category or schema forms a prerequisite requirement for other concepts or schemas to exist. It can also represent some type of flow of information or attributes from one concept to another. Cross-linking of concepts can militate against forms of hierarchy. When drawing concept maps, however, the natural tendency could be to conform to some type of functional hierarchy as a point of departure. The TLO represents a flow of information or functionality that influences the order and relationships. The subsequent lower-level ontologies follow the same pattern. It should be noted that in some cases it may be found that some duplication might occur; however, the context may be sufficiently different to warrant such duplication or redundancy.

4.6.4 Drawing of concept maps

For the purpose of this study, a concept map is described as a collection of concepts, entities, elements, components and/or activities (all these are referred to as “concepts” for convenience in this study) that are linked by relationships among the concepts and their attributes. The collection of concepts and their relationships portray an understanding, consciousness, familiarity or perception of a system, or of a case or a situation. This will enable analysis thereof and to identify problems and constraints that can generate knowledge of the system, enabling the capacity to act. Concept maps can be drawn graphically to enhance understanding. Concept maps can be described as a visual language to communicate in an understandable way.

A concept map is graphically presented in **Figure 4.1**.

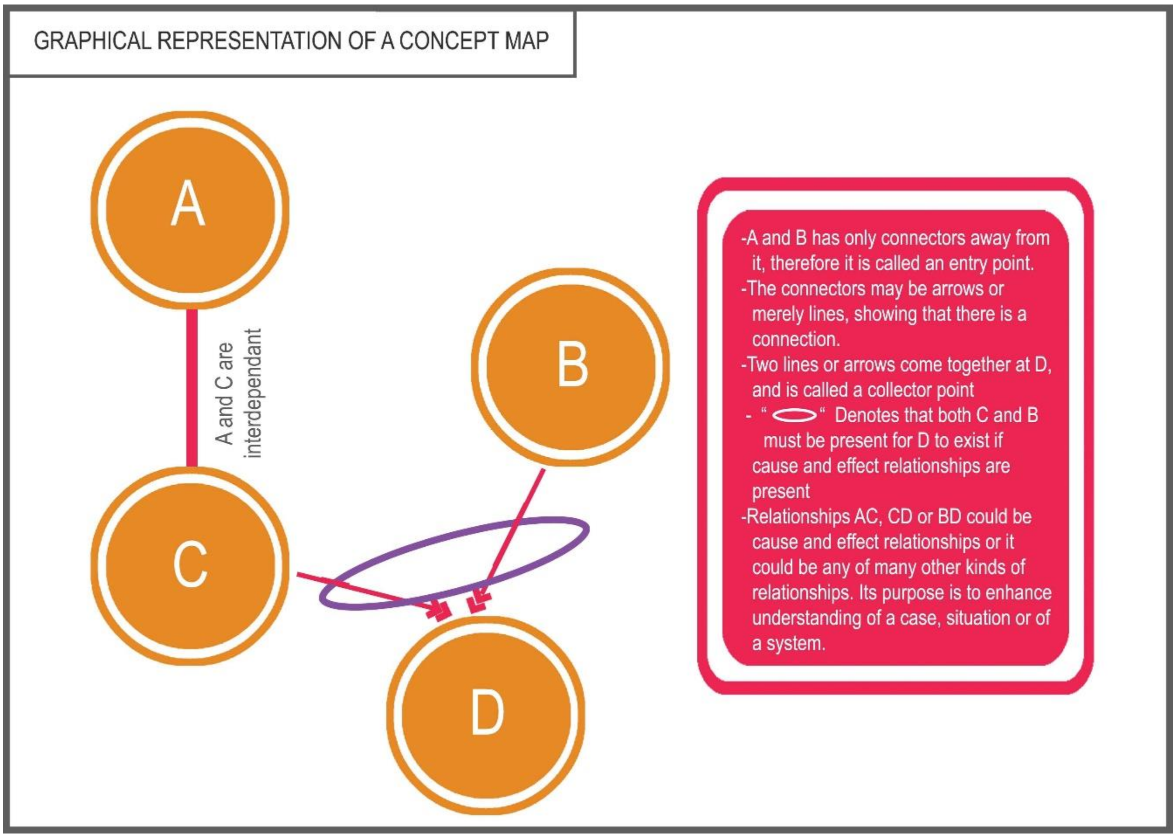

Figure 4.1 Graphical representation of a concept map

Concepts, entities, elements and components are formulated and suitable descriptive wording filled into the circles. The circles are linked or interconnected by lines or arrows. These links can convey information about the way the concepts relate to or interact with each other. Arrows are most often used in the drafting of concept maps. A combination sign may be used to indicate that both (or more) of the relationships are essential for the target concept to exist or function. Where required, concepts may be broken down into sub-ordinate concepts with specific attributes and values. These may also be included in the concept maps and relationships with other concepts and attributes indicated. Concepts at the highest level (referred to as the top-level) can also be described as knowledge domains since these top-level concepts represent all the sub-concepts, relationships, applications of problem-solving techniques and the outcomes of the analysis which result in knowledge. The quality of the relationships could also be considered. Relationships could have the following attributes (could also be interpreted as qualities of relationships. (Adapted from Mann, 2007a and 2004; Scheinkopf, 1999; Silverstein, Samuel and DeCarlo, 2012.)

a) The existence and/or validity of a relationship.

b) Significance of the relationship. (How necessary is the relationship? How would the system perform or the situation change if a particular relationship was not there?)
c) Strength of the relationship. (Is it strong or weak, direct or indirect?)
d) Temporal nature. (Is it time-dependent, parameter-dependent or random?)
e) Nature of relationship. (Effective, missing, insufficient, excessive or harmful?)
f) Conditional relationship. (This comes only into being if some other relationships first manifest.)

The types of relationships are fairly wide and can be any statement to enhance understanding. This will be discussed in more detail in subsequent sections.

The Top-Level Concept map constitutes the Top-Level Ontology. For each Top-Level Concept, a group of High-Level Concepts are chosen and put together to form a High-Level Ontology(HLO). . The HLOs are formulated and presented in sections below. These HLOs are by no means exhaustive or unique. Should one need these HLOs to be further expanded and more exhaustive, further research may be conducted with the view of obtaining buy-in and approval or ratification by industry. This is not contemplated as part of this study.

4.7 CONCEPT MAPS

4.7.1 Concept map for the Top-Level Ontology (TLO)

The TLO can also be defined as a foundational ontology or core-reference ontology and can be viewed as a meta ontology. It will be used to define other ontologies. It will be seen that the granularity will increase as subsequent ontologies are defined (Roussey, 2011).

Note regarding the TLO:
In order to simplify the TLO, technical, legal and ethical lessons learned and educational aspects, extrapolation/replication are combined into ‘Lessons learned/education’.
‘Design’ and ‘construction/manufacturing’ are split into two concepts.
The TLOs comprise the basic topics of case studies and are graphically represented in **Figure 4.2**.

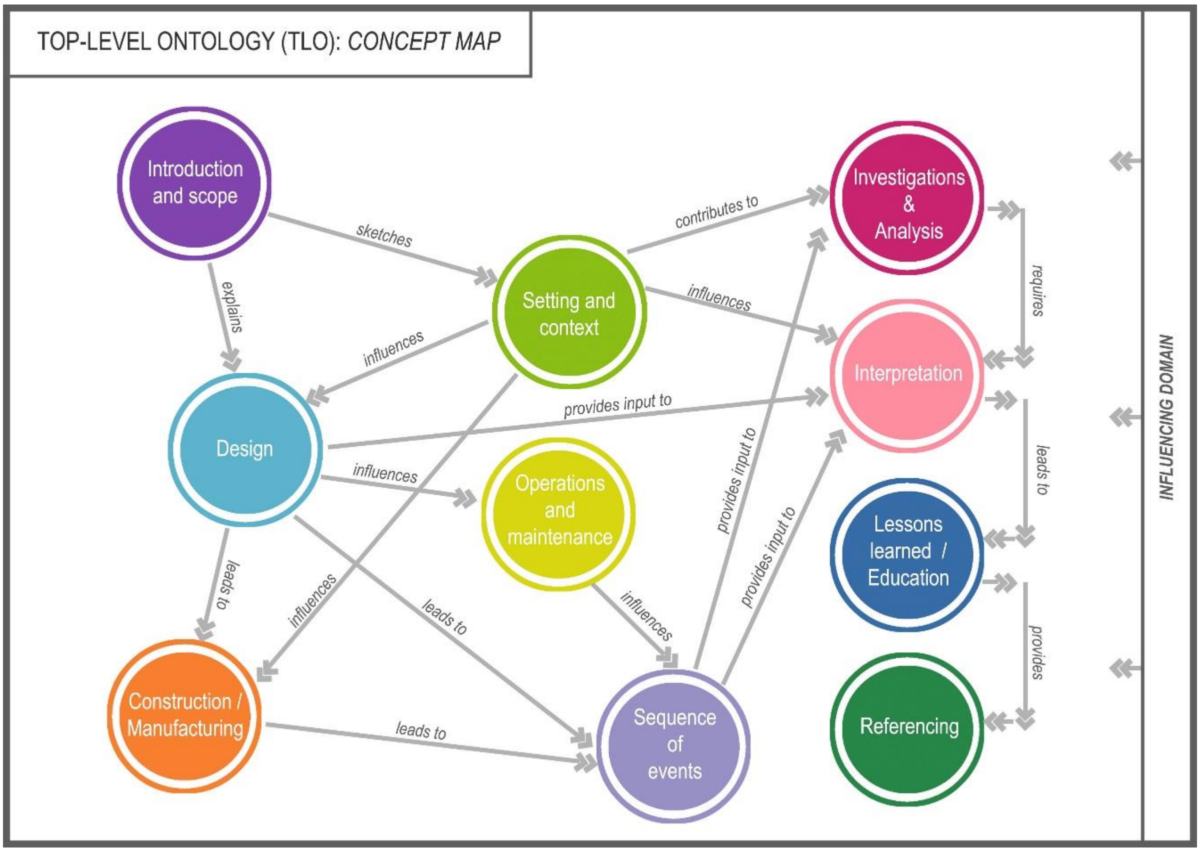

Figure 4.2 Top-Level Ontology (TLO): *Concept map*

(Note: Each concept (knowledge domain) is colour-coded.)

Each circle in **Figure 4.2** contains one or more concepts, representing knowledge domains, capable of being broken down into further sub-domains. The TLO consists of concepts and when put together in a concept map, it is called the Top-Level Ontology. Each collection of sub-domains is hierarchically connected to an upper domain. This means that each Top-Level Concept in **Figure 4.2**, comprising the TLO, possesses sub-domains, referred to High-Level Concepts and are put together to from High-Level Ontologies (HLO).

The arrows linking the circles can mean a number of different things. The primary purpose is to enhance understanding by showing the relationships between concepts**.** At the TLO and HLO levels, the wording of the labels on the arrows are limited to verbs or high level associations. It is generally at the lower level ontologies, such as at the Case-Specific Ontologies (CSO), that more detailed descriptions of relationships between concepts can be specified and analysed.

4.7.2 Discussion on TLO Concept: *Introduction and scope*

The word "introduction" is a common term and not easily misunderstood; however, the word "scope" needs further definition**.**

The OED (2010) describes the meaning of the word "scope" as follows:

"2 a. Something aimed at or desired; something which one wishes to effect or attain; an end view; an object, purpose, aim.

2. b. The sphere or area over which any activity operates or is effective; range of application or of subjects embraced; the reach or tendency of an argument, etc.; the field covered by a branch of knowledge, and inquiry, concept, etc."

In a project-management context, "Project Scope Management includes the processes required to ensure that the project includes all the work required, and only the work required, to complete the project successfully" (Duncan, 1996, p.47).

When considering the above definitions, the following concepts can be abstracted from the definitions above: purpose, desires, objectives, applications, concepts and work content. (In an engineering or architectural sense, it is also described by the word "brief". In project management a project is initiated by the compilation and approval of a "project charter".) Concepts would also describe the system components that need to be established or studied. It is also necessary to understand the purpose of the study and hence to establish what type of knowledge is being studied, i.e., whether the study is of a descriptive, explanatory or exploratory nature, or of any other nature (refer to **Table 4.1**).

In the deliberation and analysis of engineering case studies, one has to realise that these case studies often reflect studies that describe something about physical assets. Engineering is mainly directed towards the establishment and maintenance of physical assets. In this respect, the term "engineering asset management" is used to describe the management (including development) and maintenance of physical assets as opposed to financial assets (Amadi-Echendu *et al.*, 2007, pp.117-120). Engineering-Asset Management (EAM) also has a financial component as it reflects the economic value of the asset. It is against this background that one has to understand the definition of scope. The purpose and objectives can be explained to reflect what the owner's purposes or desires are and what the user requirements and Functional Requirements (FRs) are. These are then translated into concepts and sub-concepts.

User requirements define what is needed and what and who are involved. The first aspect from a project management point of view regarding the development of any asset is to define the user requirements. This is done from a basic desire of a person or entity to establish an asset for achieving particular objectives. Idealisation plays an important role as the end goal of the asset is idealised. From the basic desires, needs come to the fore and from the needs, user requirements are defined.

As an illustration, an entity may desire the establishment of a large stadium to host parts of the Olympic Games. The needs for the type of sports to be hosted and the size of the stadium must be defined. Involvement of sports institutions will be required, to – amongst other things – confirm the specifications of each of the sports facilities. User requirements would then follow and contain an enormous amount to detail relating to the sports facilities and things like the number of seats, types of seats, location and layout of seats, the access routes to and from the stadium, the commercial aspects, etc. It is most important to develop the user requirements with inputs from relevant stakeholders, ensuring thereby that the stadium would eventually fulfil its intended purpose. Each of the components, such as the seats of a stadium, can have sub-components. These components and sub-components will have attributes; for instance, the number of seats, their material properties, their sizes, shapes, location, fittings and colours. (These can be referred to as Functional Requirements (FRs) and represent upper-level concepts. The specific type of seat represents an instance of a class or type and has certain specific attributes or properties and values, such as cup-type seats with specific fixing brackets, made of polyurethane and are coloured yellow. This represents a full specification in terms of an ontology.)

The choice is made of the concepts, ‘purpose’, ‘scope/the job to be done’, ‘user requirements’, ‘contents/system components’ and ‘sub-component/work content’, that would best describe the knowledge domains and sub-domains of the main knowledge domain of “Introduction and scope”. This represents the High-Level Ontology as a sub-domain of the TLO.

The concept map and relationships are shown in **Figure 4.3**.

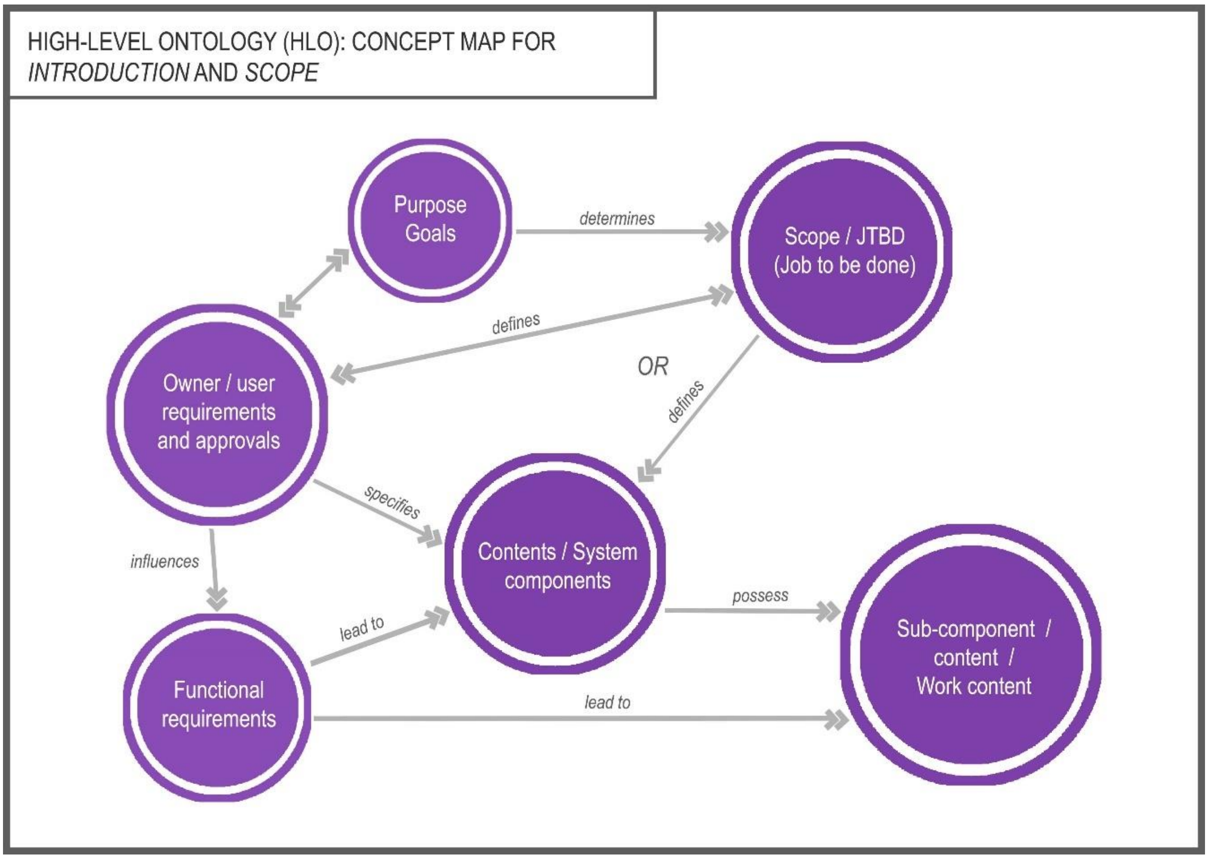

Figure 4.3 High-Level Ontology (HLO): Concept map for *Introduction and scope*

4.7.3 Discussion on *design*

In the ontology the concepts “design and construction” were put under one heading as a single concept. The terms “design” and “construction” are very closely related, but design always precedes construction. Each represents a vast knowledge domain of its own and should be treated separately as unique, but overlapping knowledge domains. General remarks about design were discussed in Chapter 2 of this study, but with an emphasis on its role in the conversion of knowledge and knowledge creation. The remark made in that exposition was that the process of engineering design always starts with the definition of what one wants to achieve and delivers a final design that best satisfies needs. Design, therefore, follows directly after “scope” which is of prime importance in defining what the design must achieve. Regarding specific design projects, designers have to conduct a cycle of evaluation, study, research, development and again re-evaluate and repeat the development cycle until an optimum, workable design is achieved (Wearne,1973, p.14). A design produces a certain functionality which must at least meet or exceed the user requirements. The knowledge domains that are part and parcel of and acting as resources for engineering design are manifold and include, inter alia, legislated or non-legislated standards, codes of practice, procedures, laws and by-laws. These specify requirements that must be met in civil engineering design. In addition, there are also best-practice guidelines, specifications and published case studies that, in effect, are also obligatory rules, information and knowledge that designers must take into consideration to meet industry norms. However, fundamental to engineering are the constitutive laws of natural sciences that govern designs. These laws of nature relate to physics, chemistry and biology. Mathematical, numerical and computer sciences are overarching knowledge areas to all aspects of engineering. Each of these main subjects or knowledge areas represents a knowledge domain with an associated body of knowledge. A design is also client dependent and the interests of stakeholders must be taken into consideration.

Design involves the definition of operational principles and the mechanism of operation. It describes how a specific system would function or operate. Examples are gravity-dam walls and arch-dam walls. Gravity-dam walls resist the forces exerted by the water it stores through friction or soil resistance at the base of the wall, and by way of the weight of the wall itself. Arch dams resist the water forces through transferring the forces to springing points or supports at the ends of the dam wall, usually in the mountain sides. The operational principles of the two types of dam walls are distinctly different, although both types of walls fulfil exactly the same function of storing water. Operational principles (i.e. gravity versus arch walls) are therefore also important for the classification of assets into categories having different operational principles. (Types of, or instances of, the concept “dams”.)

Designs lead to the definition of physical things, the selection of materials and how they fit together. This is referred to as the configuration and is described in the dictionary as the “Arrangement of parts or elements in a particular form, or figure; the form, shape, resulting from such arrangement; conformation; outline; contour (of geographical features, etc.)” (OED, 2010). In the case of this research, configuration defines the various components of a system and how they all fit together. For example, a steel member in a structure can be a “type of”, of the configuration. The “type of” concept (steel member) has attributes, such as its geometry and strength properties and how it relates to other structural members. The configuration is therefore, a High-Level concept that defines how the various components fit together and describes the functions of each component and how the different components interact with one another. The functions of the components can be time and space dependent and can change in response to system demands. The components can also change quality such as to deteriorate over a period of time. This is typically when steel corrodes and loses its capacity to perform certain functions. The functions of the components are also determined by physical laws and rules.

A further example of configuration is a steel bridge that consists of many structural steel members. Each member has a specific function. The behaviour of a specific steel member depends (among other things) upon its specific location in the structure and the interface with connecting steel members. The function and the stress conditions the member will experience will be determined by the loading conditions at a specific point in time. The response of the steel member is a function of the geometry of the steel member and how it is connected to other steel members, thus defining its behaviour by the laws of nature and the operational principles. Discipline-specific technology (in this instance, structural engineering) plays an important role and refers to the technical modelling of a system, based upon formulae or simulations developed to predict stress conditions and resulting performance.

Configuration in a broader sense can also refer to entities participating in a system. For instance, it could refer to the stakeholders and the relationships among them.

Domain: Top-Level Concept: Design

High-Level concepts forming the HLO for Design

a) Research and design informants.
b) Evaluation and current status.
c) Design study and conceptualization.
d) Application of science and discipline technology.
e) Rules and legal requirements.
f) Analysis: Design criteria/development/choice of materials and resources/choice of parameters/calculation and simulations/constructability review/performance review
g) Actions/operational principles/behaviour.
h) Outputs: Configuration/deign detailing/design drawings/specifications/Cost analysis.
i) Performance: Functionality/operability/maintainability/monitoring.

There could be several sub-domains under each of the above High-Level concepts. Some of the sub-domains are: (More domains and sub-domains may be added as required.)

- **Domain: Rules and legal requirements**
  - Internal/external requirements
  - Strategies/policies and procedures

- Building codes/regulations
- Best-practice codes
- Best-practice guidelines
- Special-client/user requirements
- Stakeholder requirements
- Legal requirements (could also be site-specific e.g. bylaws of local authority).

- **Domain: Analysis**
  - Design criteria
  - Design development (and configuration)
  - Choice of materials/resources
  - Choice of parameters
  - Calculations and simulations
  - Constructability review
  - Performance review

- **Domain: Output**
  - Configuration
  - Design details
  - Design drawings
  - Specifications
  - Cost analysis

When considering the knowledge domain of design, many knowledge sub-domains are applicable, such as outputs of the design process. The process of design plays an important part throughout the various stages of development. This involves project stages of conceptualisation, pre-feasibility, feasibility studies, detailed design, implementation, commissioning, improvements, rehabilitation, upgrades and eventual retirement of any asset.

There may be some overlap with other knowledge domains and cross-referencing is required.

The final output of design is an executable design, displaying the required functionality, maintainability and operability of the designed object at the optimum cost and with an optimum execution plan.

Putting the above all together a concept map for the “design” is shown in **Figure 4.4**.

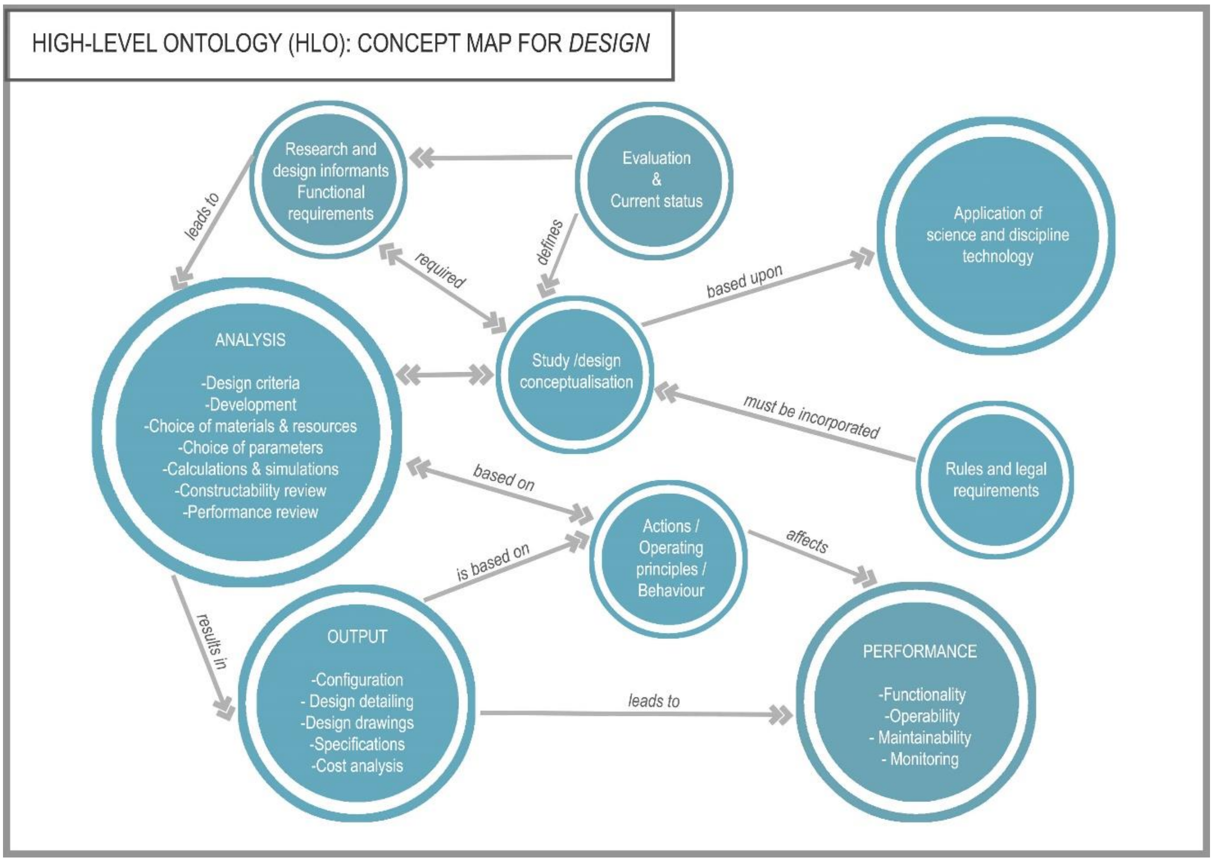

Figure 4.4 High-Level Ontology (HLO): Concept map of *design*

4.7.4 Discussion on *construction/manufacturing*

The action of construction is defined as "the action of framing, devising, or forming, by putting together of parts; erection, building" (OED, 2010). In civil engineering, construction involves, inter alia, the management and deployment of resources (human, financial, equipment and material resources) to construct some physical asset. This brings about several requisite knowledge domains (Duncan, 1996):

Domain: Top-Level Concept: Construction/Manufacturing

High-Level concepts forming the HLO for Construction/Manufacturing:

a) Construction information (including Cost control, reporting, integration and interfacing).
b) Contracts and legal agreements (including all contract documentation).
c) Site management.
d) Procurement and costing.

e) Work planning and scheduling.
f) Management of resources (important sub-domains).
g) Finances.
h) Human resources, development and skills development, industrial relations.
i) Materials supply/manufacturing/selection/ handling/controls.
j) Plant and equipment/care and maintenance.
k) Logistics.
l) Methods and techniques/ constructability/manufacturability (specific to the application of materials, equipment, and other resources).
m) Project execution.
n) Systems and controls/quality assurance/administration/change management.
o) Risks management: Business risks as well as health and safety.
p) Final product delivery (including close-out documentation).

The knowledge domain of "methods and techniques" deserves special attention since it is often the subject of case studies. This item covers all descriptions of methods used to manufacture, construct or maintain any system. A special method could have been reported or a special innovative technique could have been developed to achieve the desired results.

Sometimes very brief "tips" or "points to remember" are published (Mishra, 2017). These could be taken up (not necessarily academically verified) in the logic base and classified under "design", under "discipline-specific technology" and cross-linked to "methods and techniques" in the "construction"-domain.

An overlap occurs with other knowledge domains such as with human resources, development of skills, quality assurance, cost controls, risk management, and interfacing. The general applicable knowledge domains will be specified separate from the construction domain.

The concept map for "construction" is shown in **Figure 4.5**.

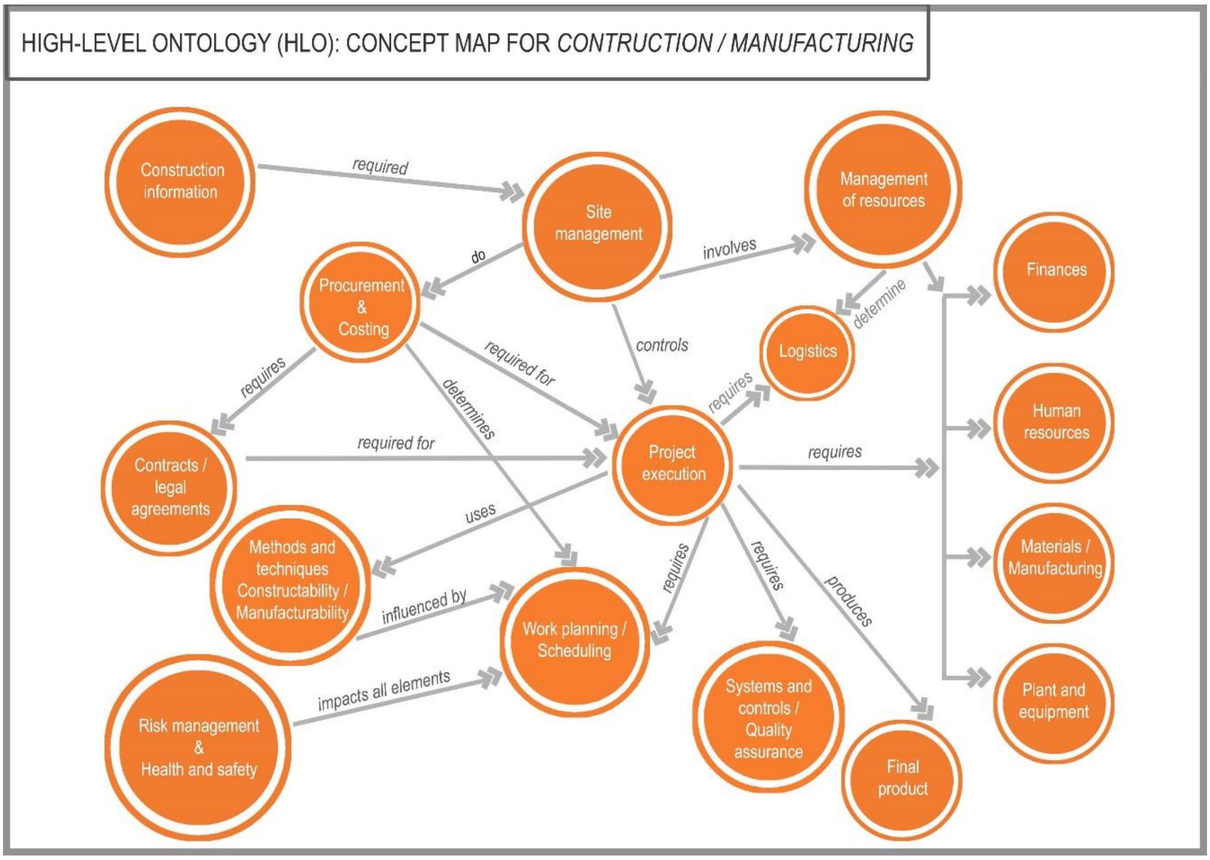

Figure 4.5 High-Level Ontology (HLO): Concept map for *construction*

(and manufacturing).

4.7.5 Discussion on *operations and maintenance*

Once something has been constructed and commissioned, the operational and maintenance phases follow. The bodies of knowledge associated with operations and maintenance are unique, but with some overlapping with other domains, such as design and construction. When an asset is put into service, it enters the operational phase. During this phase the asset is subject to all the inputs and conditions pertaining to its functions. (This enters the multi-disciplinary field of Facilities Management.) The inputs to the asset or system may be similar or may vary considerably during the period from its design to its retirement phase. Several modifications and upgrades may be done. A structure might be subject to excessive corrosion that was never foreseen by designers. The operating principle of chemical corrosion takes effect. The corrosion may change the attributes of a structural member, causing malfunction. During operations, the monitoring of performance is essential to ensure that performance requirements are met. If any deterioration (such as caused by corrosion) takes place, maintenance is required to restore the original attributes of a component. This may require replacement of a component.

The above process requires proper monitoring, administration, data-keeping and analysis to ensure that operational and maintenance functions are carried out.

In the operational phase, it is necessary to have a complete inventory of all assets and of every significant component of every asset. Operational manuals and supplier information need to be safely stored and updated as and when required. The assets need to produce and production strategies and statistics are needed. For example, will a piece of equipment be run to its absolute maximum capacity and for how long will it function before a breakdown? The operational strategies directly impact on the maintenance strategies. This, in turn, affects the inspections and performance monitoring. The maintenance strategies will determine the levels of spares being held in store. All these have influence on the costs of using the assets and also impact production schedules. Training of staff on maintenance actions and philosophies should take place regularly.

Domain: Top-Level Concept: Operations and Maintenance

High-Level Concepts forming the HLO for Operations and Maintenance:

a) Asset and component definition and records.
b) Operational philosophies and strategies.
c) Maintenance strategies (e.g., reliability-centered maintenance).
d) Performance monitoring and inspections.
e) Cost engineering and optimisation.
f) Maintenance actions and logistics.

The HLO concept map for Operations and Maintenance is shown in **Figure 4.6.**

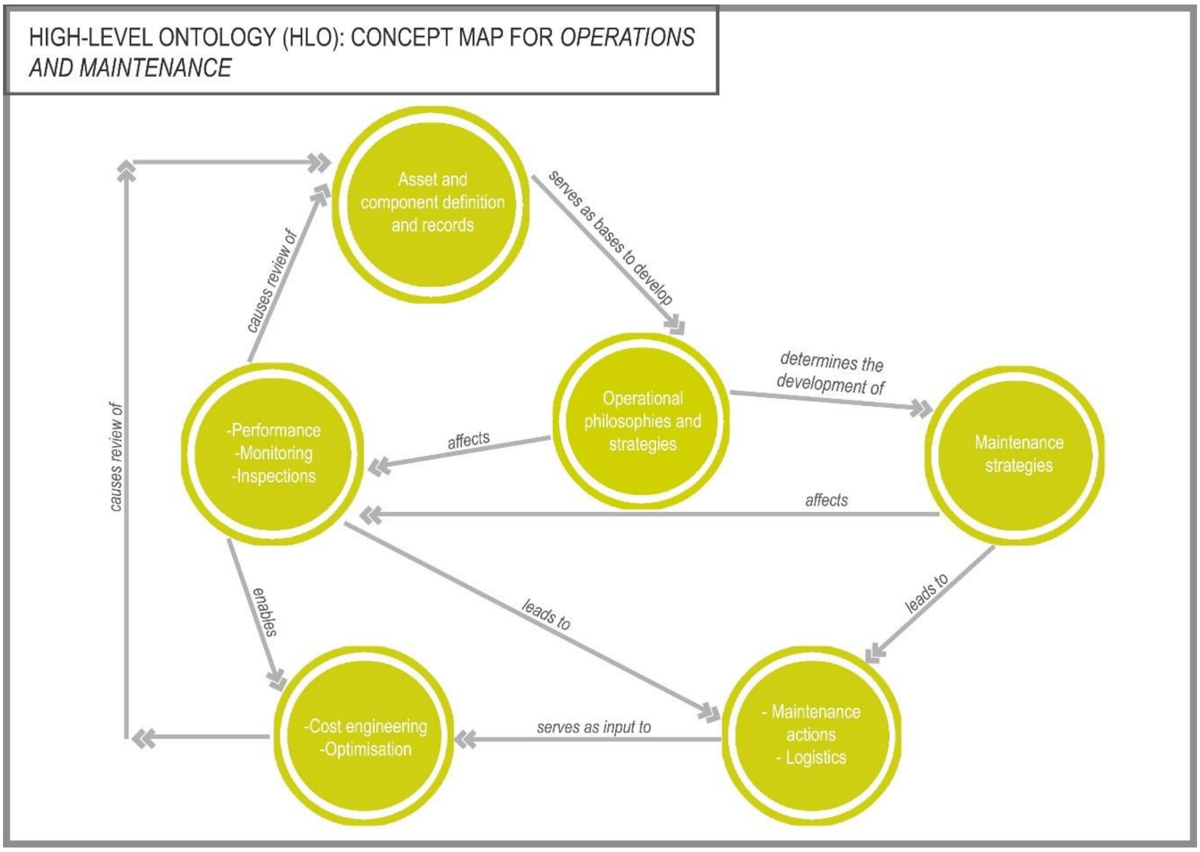

Figure 4.6 High-Level Ontology (HLO): Concept map for *operations and maintenance*

4.7.6 Discussion on *setting and context*

A dictionary definition (OED, 2010) of context is, "The circumstances that form the setting for an event, statement, or idea, and in terms of which it can be fully understood."

The online Business Dictionary (2016) describes "context" as:

"1. Background, environment, framework, setting, or situation surrounding and event or occurrence."

The choice is made to use the latter definition of "context" that best suits the knowledge contained in case studies.

The setting and context are determined by the project or physical asset or object. The way the asset came into being needs consideration (i.e., whether it is a new asset or extensions or modifications to existing). Also important is whether changes in ownership or functions took place. These provide background information – historical and current. The location of the asset determines many other factors. For example, constructing a bridge in a remote area is very different when constructing the same bridge in the middle of a large city. The functions of the asset determine operational and maintenance requirements. These functions stem from user and functional requirements. The most important setting issue regarding operations of an asset has to do with the owners, the operational staff and the organisational structure and management. People are the operators and decision-makers and function within the bounds of an organisational structure. Schedule and time-related aspects often determine actions of engineers. The engineers may, for example, be forced by circumstances to do designs under severe time constraints. Space constraints often determines how things are done. People are always involved in civil engineering. The roles and responsibilities of all the people involved, as well as their qualifications and experience, are important background information. If, for example, unskilled labour is used for building a road, the design and specifications and execution will be very different from the design for construction with automated machinery. The technology employed and the sustainability are part of the context. The technology is mostly coupled with the configuration of components or elements. The background and context also involves construction methods and techniques. A project or asset usually implies a legal and regulatory framework that forms part of the context.

External aspects are part of the setting and context. The climate and weather conditions play a role in design, construction, operations and maintenance. External aspects, such as environmental aspects, have a strong influence on the background and context. Since external aspects are common to all the concepts in civil engineering, it is dealt with under the so-called "influencing domain". This is discussed in subsequent sections and is not taken up in the HLO concept maps as separate concepts; however, each concept needs to be tested for influences as listed under the influencing domain.

From the above, the list of concepts chosen for the concept map of setting and context are as follows:

Domain: Top-Level Concept: Setting and Context

High-Level Concepts forming the HLO for Setting and Context:

a) Location
b) Organisational structure
c) Management (Including decision making)
d) Professional appointments, people, roles and responsibilities
e) Administration and record keeping
f) Communication and coordination

g) Stakeholders and interested and affected parties
h) Relationships among people with organisation
i) Physical assets, configuration and location
j) Legal and regulatory framework/review/audits
k) Social aspects

The above list considers the physical as well as non-physical aspects.

There is overlap between setting and context and other ontologies. For example, operations and maintenance is important under setting and context, but there is already a TLO for operations and maintenance. This demonstrates that the ontologies cannot be seen in isolation and comparisons among ontologies are required to cover as many aspects as possible.

The HLO concept map of setting and context is shown in **Figure 4.7**.

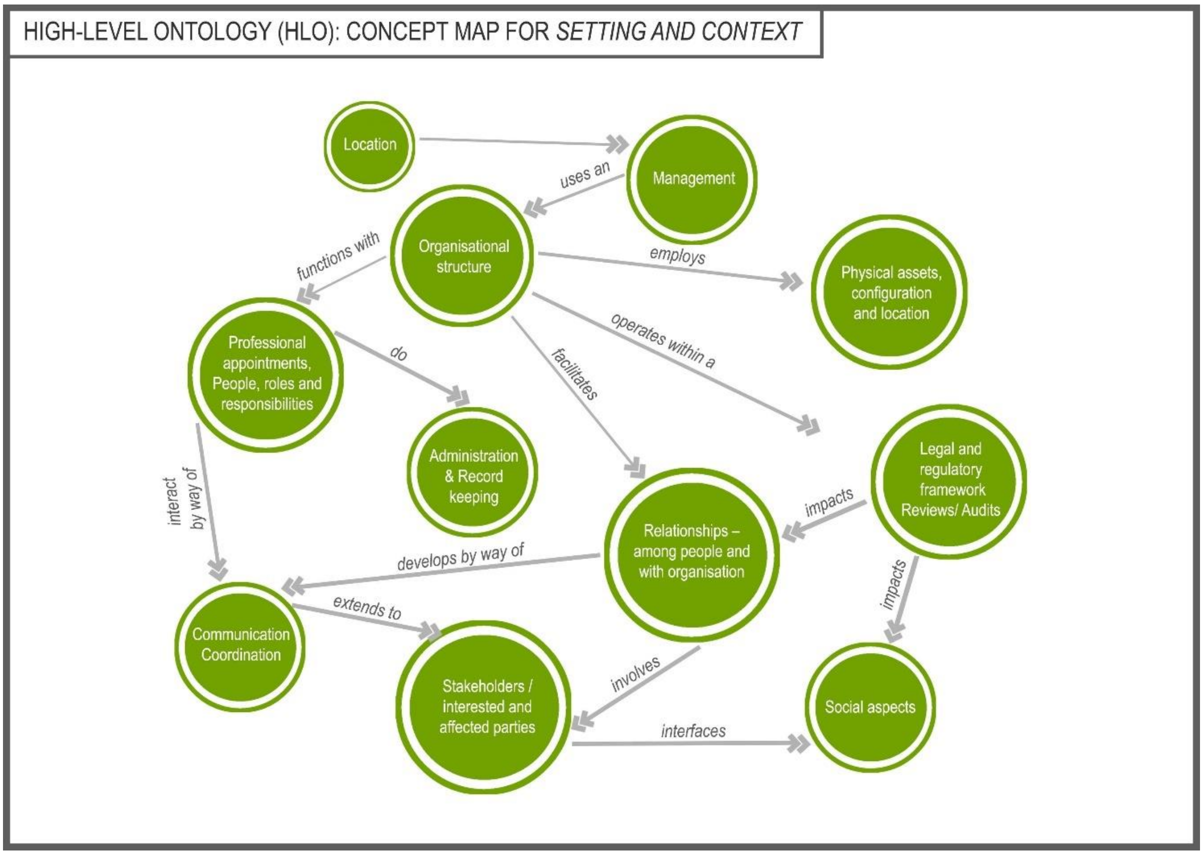

Figure 4.7 High-Level Ontology (HLO): Concept map for *setting and context*

4.7.7 Discussion on *sequence of events*

The sequence of events is not necessarily a part of all case studies. Certain case studies do not reflect any specific events. This would be the case when research is conducted and reported on, or when particular situations are analysed. Other types of case studies, such as case studies on structural failure, will normally describe a sequence of events. When new work is designed, the application of Failure Mode and Effect Analysis (FMEA) will test various unwanted events and sequences of events. One can also describe the sequence of events in the form of a narrative. Events are sometimes caused or triggered by something or by a particular coincidence of circumstances, changes in circumstances, locations or situations. The question is: “What initiated an event?” Once an event was initiated, the question is: “What followed on after the event?” This defines the response of the system to some triggering event. For example, the wheel of a car can burst. This is a triggering event. If an accident subsequently took place, it could be regarded as another event. Other drivers may stop to assist which can be seen as a system's response to the events. Mobilisation/initiation also refers to the details of the action that cause a mechanism to function. For example, in the case of an internal combustion engine, mobilisation or triggering takes place when the ignition key is turned on, and the engine is turned/cranked. A further triggering event is required in addition to the turning on of the ignition key. This happens when the correct fuel and oxygen mixture is injected into the cylinders. A consequence of the forgoing two necessary conditions is that ignition takes place and the engine starts to run. Other example of an initiating event relates to a bridge (seen as a system). The bridge structure will resist the forces exerted on it when a train passes over it. The passing train can be the initiating event. Wind force can be another trigger or initiating event. The two initiating events, when happening at the same time, can result in or can have the consequence that the bridge fails.

Finally, after an event, remedial actions may need to be taken to restore the system to its original state. Case studies often address these issues.

Domain: Top-Level Concept: Sequence of Events

High-Level concepts forming the HLO for Sequence of Events:

a) Narrative/context

b) Changes in circumstances/location

c) Triggering/initiating/mobilisation events or actions

d) System responses/measurements/controls

e) Consequences

f) Remedial actions/solutions to problems

As mentioned in the preceding section, integration between all the ontologies is required to identify, for instance, the "changes in circumstances".

The above is depicted in the concept map in **Figure 4.8**.

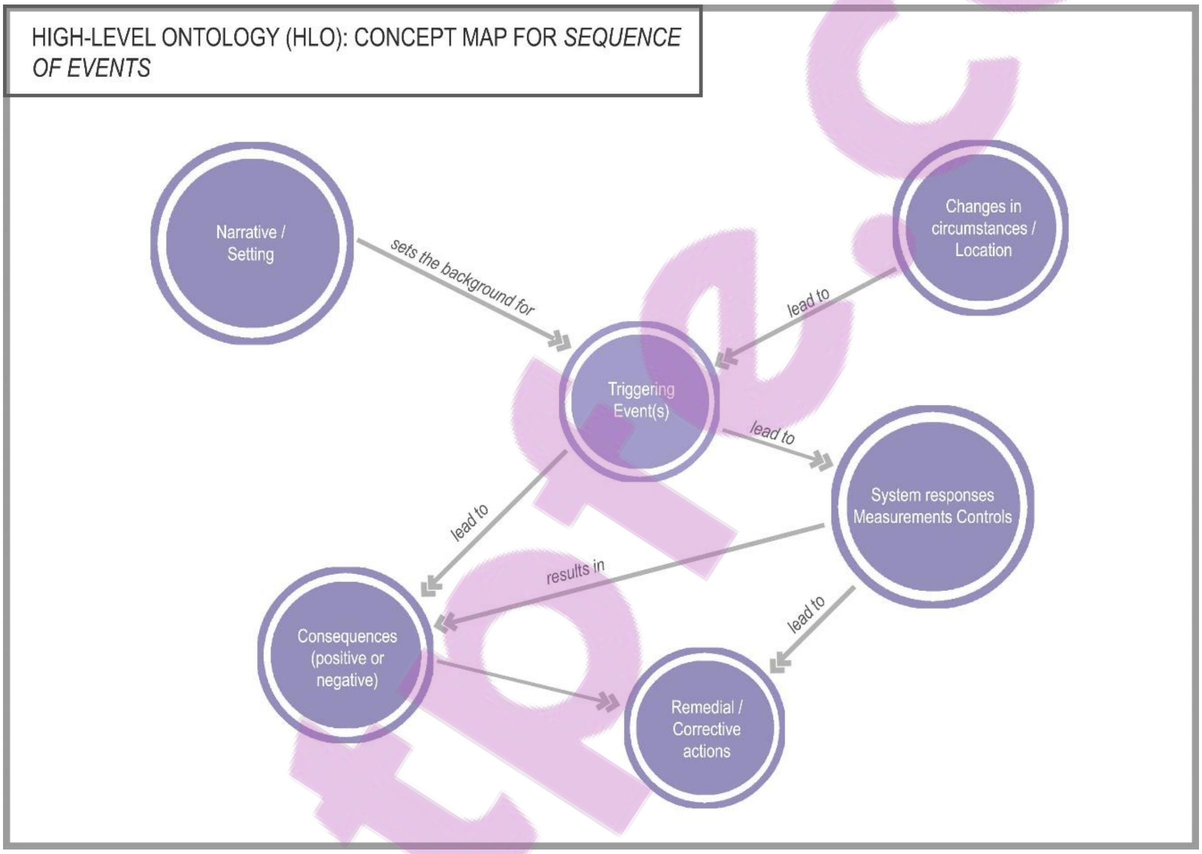

Figure 4.8 High-Level Ontology (HLO): Concept map for *sequence of events*

4.7.8 Investigation

In case studies, the process of investigation is often reported. This may refer to formal inquiries and reports on an engineering failure (or success) or it may be more informal investigations and findings. It can also refer to action research conducted. Examples are the introduction of new techniques or of new products. These introductions often describe the characteristics and capabilities of the new techniques or new products. When investigations are carried out with the view of publishing these characteristics, it is most useful to follow the ontology for investigation. Tie-back to other ontologies is always required.

An investigation could be multi-faceted and incorporate the elements below.

Domain: Top-Level Concept: Investigation

High-Level concepts forming the HLO for Investigation:

a) Identification of issues and analysis thereof
b) Thorough investigation of history (For convenience, a list of typical identifiers of issues is included in the concept map.)
c) Risk analysis
d) Problems and constraints
e) Unwanted events
f) Evidence
g) Root causes
h) System response

When analysing any case study one has to endeavour to identify the assumptions underlying the case. A comprehensive analysis would incorporate each of the elements in the above list. Issues in the form of anything that hindered the achieving of the goals must be identified. The other elements (referring to root causes and FMECA) were already discussed in Chapter 2 of this study as well as Root-Cause Analysis (RCA). A thorough investigation of the history of development or of operations is of great value. Evidence of issues can be identified by the following typical identifiers:

a) Change
b) Precursors
c) Striking incident
d) Repeated instances
e) Direct experience
f) Complaints
g) Notification

The HLO for Investigation is shown in **Figure 4.9**.

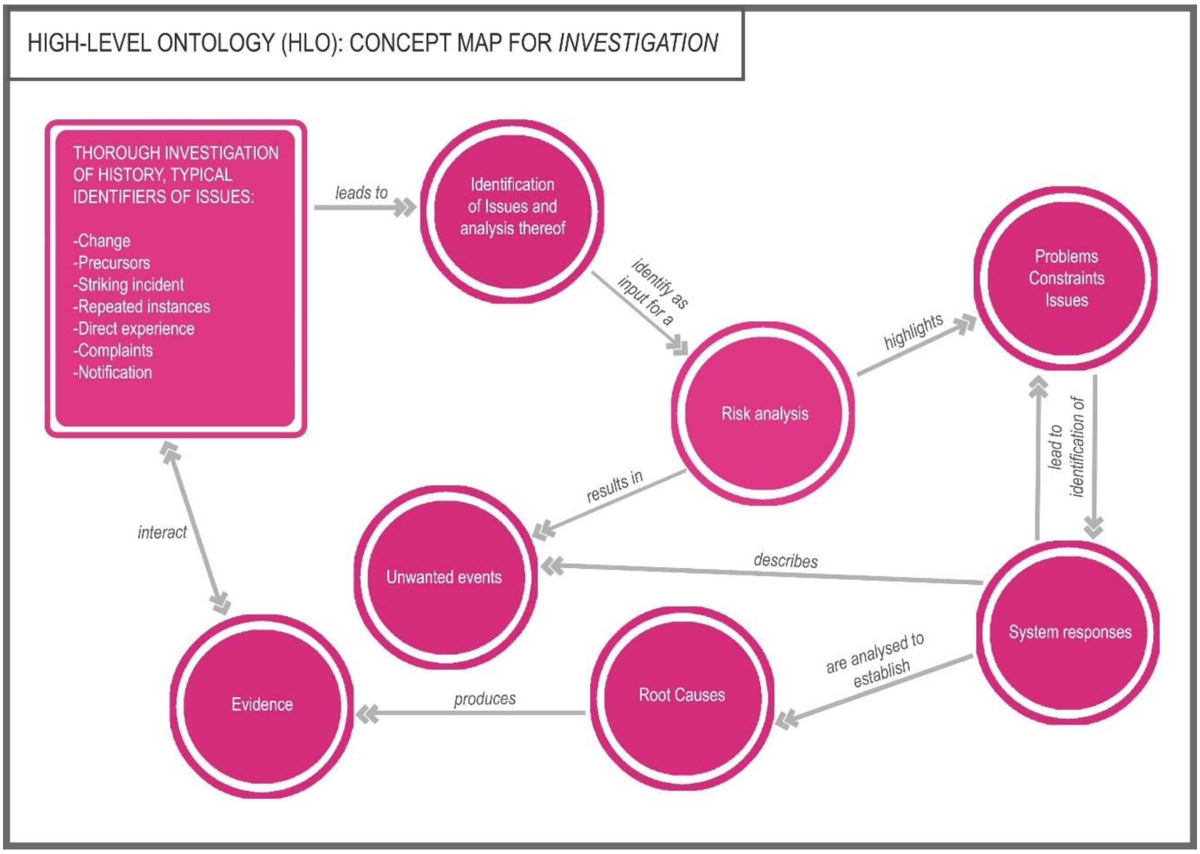

Figure 4.9 High-Level Ontology (HLO): Concept map for *investigation*

4.7.9 Interpretation

This is one of the most important parts of the logic base, where problem-solving techniques are applied to all the information at hand. This section searches for the identification of problems and constraints and for appropriate solutions and actions to be taken. When a case study reflects uncertainties, these should be identified and attempts should be made to understand the reasons for the uncertainties, amongst others, to determine ways to treat the uncertainties. The same argument holds for risk and the treatment of risks. The best way is to apply appropriate problem-solving techniques. A summary of aspects of problem-solving techniques is shown in the concept map in **Figure 4.10**. HOT- or FAST-techniques are methods to expand on the “how to do” things and are drawn up as outputs from problem-solving techniques. All the outcomes from the interpretation of case studies can be inputs into the HOT-diagrams, which were originally developed for recording of knowledge.

In the various case studies, mention is made of problems or constraints that were addressed and overcame. Some problems are very obvious and need no further analysis. However, one could find that problems are more complex and difficult to identify. By using the various techniques, such as by employing the Cynefin framework, TRIZ-techniques and TOC techniques, a study of the interrelationships between different elements can be done. TRIZ identifies problems by searching for any contradictions in the interrelationships among elements/parameters. Reference is made to the technique used by TRIZ regarding substance-field (S-fields) relationships (refer to discussions in Chapter 2). One can apply this to the individual system components and sub-components and all the relationships between the components and between all the attributes of the components. This provides a wider base for analysis and therefore a sound foundation for extrapolation, replication and lessons learned. When a case study is read, one can apply these techniques to challenge the case study, thereby discovering aspects not reported in the case, but that may contribute greatly to knowledge and the reuse thereof.

The proposed concepts are as follows:

a) Inputs from other HLOs
b) System response
c) Application of problem-solving techniques
d) Generation of appropriate solutions to problems
e) Record the lessons learned
f) Record new knowledge discovered
g) Draw the HOT or FAST diagrams for the solutions (if appropriate)
h) References to media, checklists or actions

The High-Level Ontology (HLO) concept map for interpretation is depicted in **Figure 4.10**.

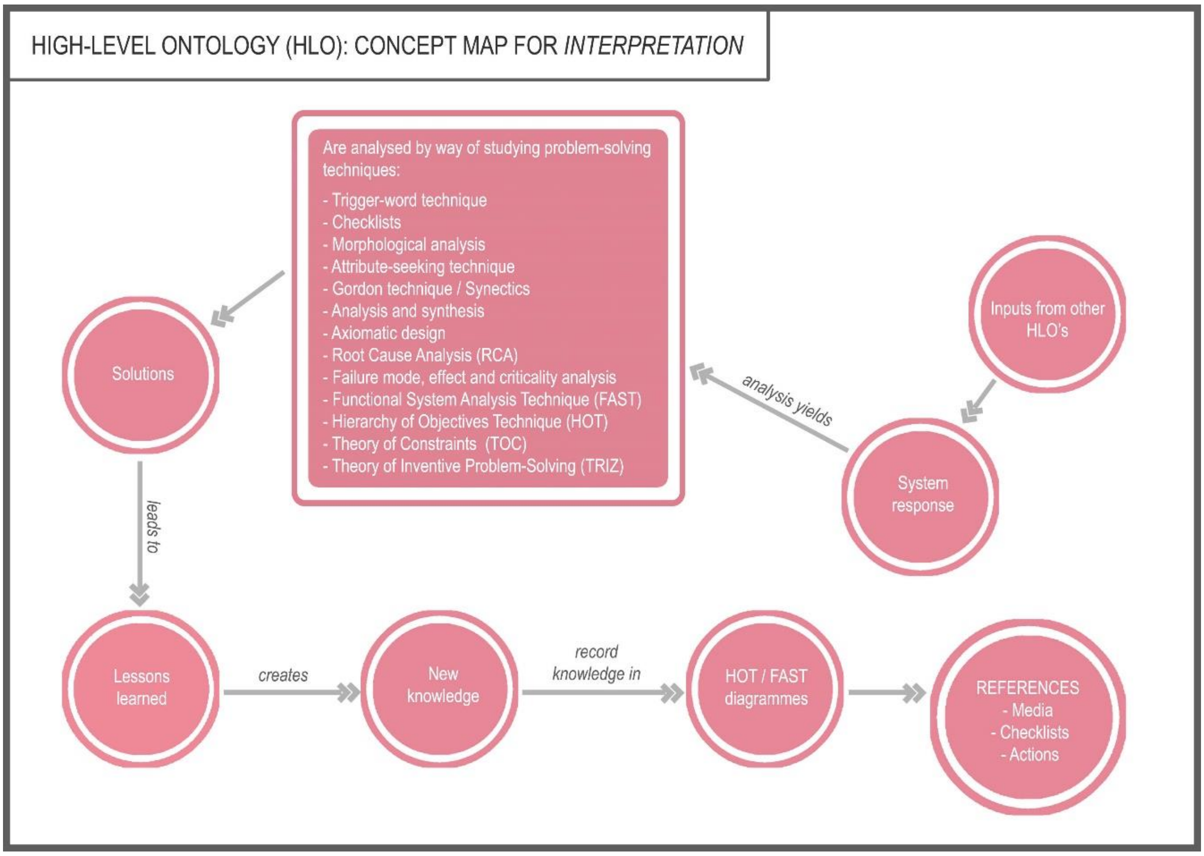

Figure 4.10 High-Level Ontology (HLO): Concept map for interpretation

4.7.10 Lessons learned

When case studies are reported or articles on projects are published, learnings from these are often not explicitly reported. However, the lessons learned are sometimes implied.

The following example is given to illustrate how lessons learned can be obtained from reports.

The example is quoted of a published article regarding remedial work to a steel railway bridge after a derailment took place on the bridge. This is referred to as “The Brakspruit Bridge Project” (Anon., 2012c, pp.23-26). The concluding paragraph of the case study provided a high-level summary and learnings. There are, however, many learnings implied in this article. (Taking into account that the learnings may differ from person to person, depending on the prior knowledge and understanding of the reader.) Following are a few possible lessons learned when studying the article:

(i) Transnet faced serious financial losses whilst a railway line was out of operation. (It seems that no other plan could be made by Transnet to divert rail traffic to other routes.)

ii) Innovative structural design was used by utilising established technology (rather than venturing new technologies in such a critical construction).
iii) Transnet mobilised their in-house team to clear the site of the accident and erected a temporary support structure. (Transnet had capacity to do initial work with in-house resources that saved time when design procurement processes for contractors to perform the new construction works, were in progress.)
iv) Existing mass concrete foundations that were originally used for the erection of the original trusses, were modified and used to accommodate two temporary supports. (Information on historical construction methods was used to the benefit of the new project.)
v) The temporary works were done to minimise the risk of damage or disruption (due to potential floods in the river).

In addition, when analysing the case by using the ontologies for *Investigation* and *Interpretation*, it was noticed that the root causes of the accident were not reported. The question arises, regarding the risk of a potential repeat accident.

When embarking on a new project, engineers could learn from previous projects and through analysis and – referencing to the various techniques for knowledge acquisition and problem-solving – develop designs and construction techniques that would embrace a holistic view that lead to better projects.

The recording of lessons learned flows from the use of the TLOs and HLOs. The lessons learned are recoded and linked to the ontologies to enable discovery and reuse. For example, in the article above, links can be made to the TLO concept of *Design*, *Setting and Context, Investigation, Interpretation, Operation and Maintenance, Sequence of Events and Construction.* Details must be linked to the respective HLOs*.* For example, the concept of "train" will demand recording of attributes in the OAV triplet format (Object-Attribute-Value). The object "train" will have attributes of "number of wagons", with a particular value and "*speed"* with a particular value. When these attributes are investigated and relationships determined with the ontology for *Design,* "*Evaluation of current status*", it may point towards *changes in circumstances* such as a wash-away due to poor drainage conditions, or poor maintenance on the rail. These will then add to the lessons learned.

The above illustrates the value of analysis in terms of the ontologies and the recording of explicit and implied lessons learned.

4.7.11 Educational

Education takes place when an individual's existing knowledge is updated. Knowledge conversion takes place from explicit to tacit through evidence observed and supported by experience. The observing of responses of a system to various events or circumstances serves as inputs that could update one's understanding of a system and thereby expand one’s knowledge. When the logic base deals with prompters, triggers and metaphors, users of the logic base would actively consider searching for possible problems and solutions in a wider field. This approach could, therefore, advance knowledge to other fields where analogies could be identified. The following are needed:

- Expansion of knowledge to widen the field is needed.
- Prompting, triggers and metaphors are to be used.
- Evidence and experience must update knowledge.

The suggested concepts are as follows:

a) System response
b) Evidence
c) Prompters/triggers/metaphors/analogies

These concepts are already part of the TLOs and HLOs and of lessons learned that can be perused for reporting on *Education*.

4.7.12 Referencing

The output of the logic base will report on problems, constraints, solutions and remedial actions, where applicable. Referencing emanates from various activities and analysis in the logic base. Were possible, links to references should be made.

Links can be made to the Internet or intranet or other suitable media to display the learnings or shared knowledge. Any literature, photos, videos, contact mail addresses or websites could be added to enhance knowledge.

4.7.13 Knowledge domains common to all other domains

Certain knowledge domains are essentially common to all other domains. In the sections below, further concepts are listed and briefly discussed. Some of the domains below are already shown as sub-domains in some concept maps. (In other instances, these concepts can be drawn into boxes and added to the sides of the concept maps to indicate its general applicability.) The influencing domains interact with concepts and can modify system behaviour, change attributes and even introduce new related concepts. (This is analogous to the dynamics found in the Cynefin framework where a dynamic movement is modelled towards a line of coherence.)

Each of the domains contain several levels of sub-domains or sub-sub domains. When analysing a case or when embarking on a new project, it will be necessary to identify “candidates” that can influence a particular system. Some concepts will have no influence and can therefore be discarded in the analysis.

The following concepts are supportive of all the HLOs and resort under the Influencing Domain:

Top-Level Concepts: Influencing Domain: High-Level Concepts:

a) System response and controls

The system response and controls are very import elements in the analysis of case studies. Although it is covered under the concept map of “sequence of events” it was deemed expedient to define this concept as a High-Level concept as part of the Influencing Domain. The reason is that for any change of concepts under the Influencing Domain, the system will respond differently. It should be noted that the relationships between concepts at all ontological levels should be checked and analysed.

The way a particular system responds will depend on the culmination of its configuration, all the input received and all the processing capabilities. The system’s response will also be affected by the external factors that can influence the system. For example, a bridge may be regarded as a structural system. The vehicles travelling over the bridge represent the input loading to the bridge. However, changes in the environment affect the performance of the bridge, such as temperature and wind. In a corrosive environment near the sea, a steel construction may experience elevated levels of corrosion and associated deterioration. This may materially affect the performance of the structure and may lead to the failure of the steel structure (Delatte, 2009, pp.70-82).

The system response can also be seen as the effect or the result after initiation/mobilisation in accordance with the operational principles. The sub-systems may respond differently to mobilisation. This has to do with the configuration, influencing factors and the time, space and capacity interfaces. The system response can be measured against performance requirements as follows:

i) The response or behaviour of the system relative to the functional attributes.
ii) The response or behaviour relative to the user requirements.
iii) The response to various influencing domains (environment, human interventions, etc.).
iv) The response to constraints and contradictions.
v) Testing methods and procedures.
vi) Control philosophies, methods and procedures.

The dynamics of the items above must be taken into consideration. When changes take place in any of the above (operating principle, mobilisation, configuration or influencing factors), the system response might change as well. For example, if repeated load cycles are applied to a structural element, fatigue may set in and the structure may crack, break or collapse. Another example is where a clapper in a bell vibrates after impact with the bell. The subsequent vibrations of the clapper resulted in the failure of the clapper (Jones, 1998, p.85). In addition, one has to take into account that the entire system may change its response to changes in time, space and with resource levels.

The concepts chosen for **system response and controls** are as follows:

i) System input parameters
ii) System processing
iii) System output responses (relative to various input parameters and influencing domains)
iv) Observations/measurements
v) Remedial/corrective actions
vi) System problems and constraints

The concept map is similar to that of an adaptive system as discussed in Chapter 2, **Fig 2.27**. The figure shows that an adaptive feedback loop is established via the concept of system problems and constraints. Knowledge and lessons learned provides inputs to the concepts of system problems and constraints where such input can enhance the identification of system problems and constraints. This is depicted in **Figure 4.11**.

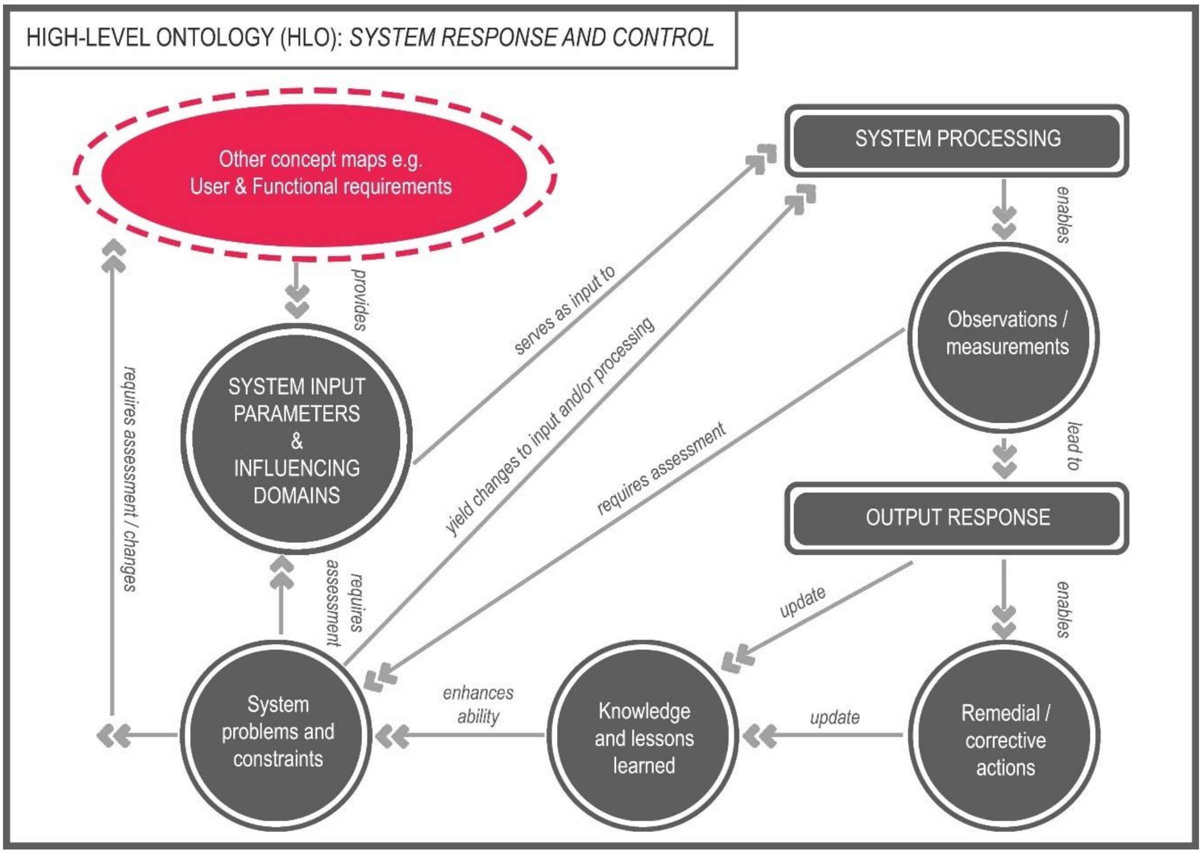

Figure 4.11 High-Level Ontology (HLO): *System response and controls*

b) Environmental aspects

This term refers to the environment within which a system has to perform its intended functions. It mainly refers to external influences exerted on a system and which may influence the behaviour of the system. The term environment represents a broad concept and include, inter alia, the following sub-domains:

- Physical environment
- Chemical environment
- Biological environment (including ecological environment)
- Geographical environment
- Geological aspects
- Societal fabric and values
- Social impact
- Public matters (public opinion, etc.)
- Community impact
- Economic climate

- Political influences
- Cultural influences
- Sustainability (including positive footprint)
- Ethical aspects
- Recognise local conditions

c) Influencing factors

This is a broad category of external factors that also play a role and influences the performance of a system. Under each of the headings below the suggested knowledge sub-domains are listed. There is much overlap with the ontologies, but the list below serves as a checklist for influences. (No separate concept maps will be required for these concepts.)

- **Logistics**

Logistics play an important role in the design, construction/manufacturing and in the operation of assets. This aspect is of particular importance when work is done in remote areas.

Sub-domain knowledge areas are:

  - Inbound logistics of goods and services
  - Outbound logistics of goods and services
  - Storage of goods

- **Ownership of the asset, entity or thing**
  - Full particulars of organisational structure and relative ownerships
  - Details of delegation of authorities to individuals

- **Governance** (including management, oversight reporting structures and roles and responsibilities, and legal appointments)
  - Organisational structures
  - Management roles and responsibilities
  - Reporting structures and methods
  - Legal appointments
  - Delegation of authority

- **Information and communications**
    - Authorised persons and approval of communication
    - Methods and time of communication
    - Details of electronic media (enterprise systems) and procedures
    - Knowledge management protocols
- **Stakeholder management and affairs**
    - List of stakeholders
    - Record of stakeholder meetings and discussions and feedback
    - Management actions relating to stakeholder affairs
- **Processes and methods**
    - Design
    - Specifications
    - Procurement
    - Commissioning
    - Operations
    - Operator's influence
    - User intervention
    - Maintenance
    - Material characteristics
- **Innovation** (stimulation and support for new ideas etc.)
    - Procedures for analysis and search for new ideas
    - Application of TRIZ and other problem-solving tools
- **Relevance** (obsoleteness)
    - Market intelligence
    - Trending
    - Alternative applications
- **Risks** (physical and business risks)

Risk assessment study across all business processes – this will depend on the particular business and area of interest. The following concepts need to be addressed:

  - The identification of unwanted events
  - The identification of hazards
  - Identification of risks – practices or things that can lead to the occurrence of an unwanted event
  - Consequences of unwanted events
  - Mitigatory measures

- **Safety aspects** (harm to people – safety and occupational health)

  - Safety policies and governance
  - Appointments, including roles and responsibilities
  - Safety standards
  - Identification of hazards and compilation of risk registers
  - Risk-management procedures
  - Safety protocols for reporting
  - Safety procedures
  - Recording of incidents
  - Learning from incidents
  - Safety training
  - Risk audits

- **Health**

  - Identification of health hazards
  - Health-preservation policy and standards
  - Health records of personnel
  - Records of health monitoring and trending
  - Records of health-related incidents

- **Reputational impacts**

This will depend on the nature of the business.

- **Goals**

This is a set of statements that could be used to evaluate the performance of an entire system. These can be seen as the idealisation goals, and is included in **Appendix E**.

4.7.14 Multi-dimensional representation

a) Influencing domains

The above common elements add significant complexity to the concept maps. In order to structure the system and to make it easier to visualise, it is suggested that the above domains, which may be common to all others, be structured as a third dimension of layers to all the concept maps. The TLO and every HLOs concept map could be visualised as the first layer or two-dimensional map with the third dimension constituting layers being the common factors.

Summarising, the following are common to all the other elements:

i) System responses, measurement, monitoring and controlling
ii) Environmental
iii) Risks
iv) Interfaces
v) Changes (in time, space and system response)
vi) Stakeholders
vii) Interfaces and integration
viii) Influencing factors
ix) People roles, responsibilities and legal appointments
x) Safety factors
xi) Health
xii) Reputation

b) Changes in time, space, capacity and interfacing

These aspects span across all the domains. Attributes of all or any knowledge domain or system components may change in time and may also act in different spaces. Capacity, incorporating human resources, financial and physical resources can change over time and could have significant influences in many domains. TRIZ recognises the role that time plays in systems by way of the “nine windows” part of problem-solving techniques. In this problem exploration technique, consideration is given to the past, present and future. By way of a nine-block matrix, the time element is placed on the one axis and the other axis displays the elements under consideration. These elements could be the “sub-system”, the “system”, the “super-system” (Mann, 2007a, pp.63-70).

Changes in time, space and capacity will mostly influence the performance of a system. It is necessary to have controls in this regard. It is also essential that there is full integration among all the concepts at all levels and that the interfaces between all domains are managed.

Knowledge sub-domains are:

i) Time/phases and schedule changes (past, present and future).
ii) Capacity regarding human, financial and physical resources (system controls on time and space to cater for changes).
iii) Changes in space.
iv) Interfacing which ensures coordination among all concepts.

This is depicted in the diagram in **Figure 4.12**, where all the ontologies are subject to changes in time, space and capacities. It is also most important to consider the interfacing between all elements of the ontologies.

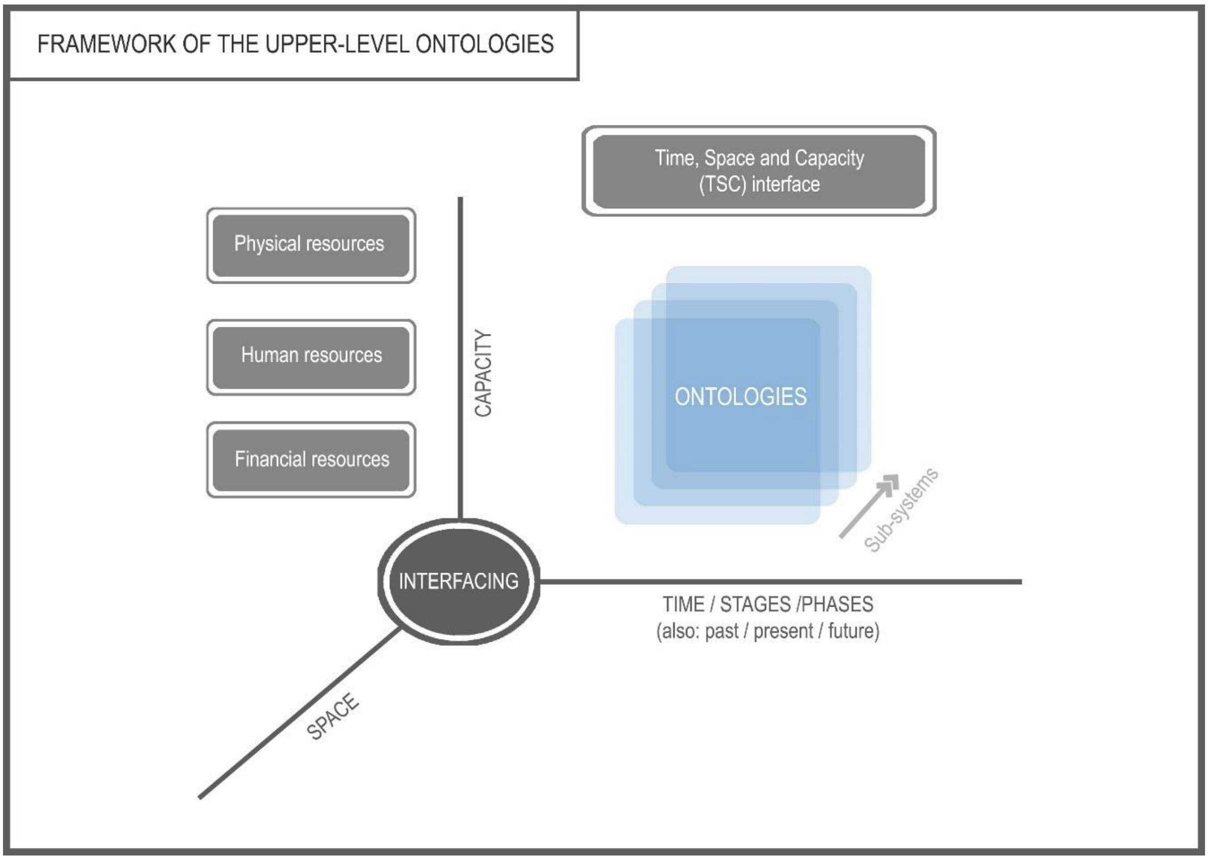

Figure 4.12 Framework of the Upper-Level Ontologies (ULO)

When considering the roles of the influencing domains and that of changes in time, space and resources, a visual representation can be made by a multi-dimensional concept map as shown in **Figure 4.13**.

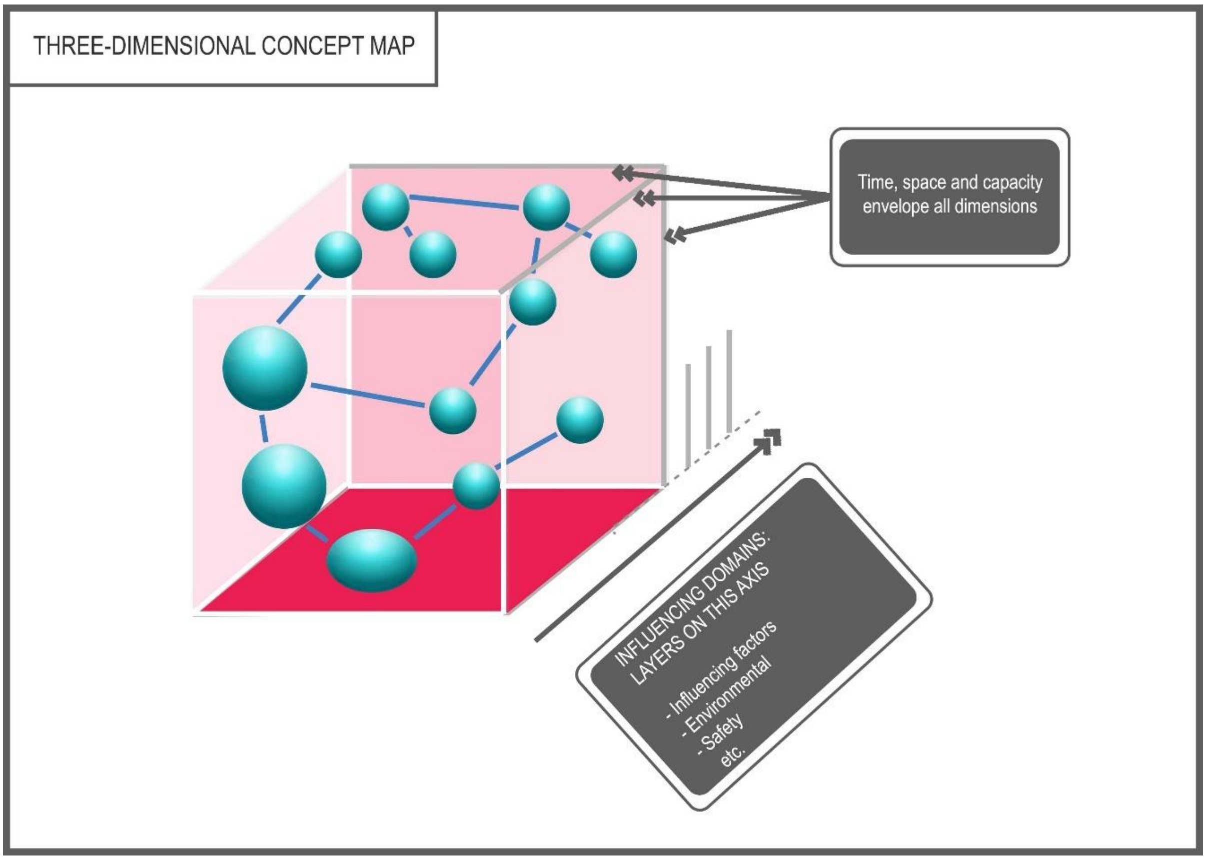

Figure 4.13 Three-dimensional concept map

4.8 RELATIONSHIPS

4.8.1 General discussions on relationships

The ontology of the logic base has been developed in the preceding section. A requirement of an ontology is to interconnect concepts with the relationships among them.

The next step in the design of the logic base is the consideration of relationships among the main knowledge domains, the sub-domains and the sub-sub domains. Even the attributes of components have relationships with attributes of other components within the same or other knowledge domains.

One has to ask the following questions when determining the functional relationships between various elements and between various topics and their attributes.

"Why?", "What?", "On what?", "With what?", "What's stopping?", "When?", "Where?", "How much?", "How many?", "How long?" (duration). When looking even deeper into relationships, one can use the S-Field-technique as applied in TRIZ. Identifying any deficiencies in relationships, or one can consider various solutions to improve or solve a contradiction, constraint or problem.

Dynamic and adaptive processes take place among the various domains. As an example, a specific user requirement may be to have special air conditioning in a computer-server room. This airconditioning system has a relationship with configuration (i.e. the layout of the building) and with design and construction. Furthermore, the regulatory environment also determines that there must be an interface between the airconditioning and the fire protection system. The information and communication systems in a building are highly dependent upon the proper functioning of this airconditioning system, as the computer servers will shut down if the temperature in the room becomes too high. One, therefore, has to look at the influence of time and continuity of service. The relationships between the server's airconditioning system can have relationships with the entire building's airconditioning system, the electronic interface with the computer system and with fire prevention requirements. One can, for instance, eliminate a relationship by designing the server room's airconditioning system totally independent of the rest of the building's system.

The quality of the relationships is highly important in the logic base. Should a particular essential relationship not exist, for example, one can expect a system problem to appear. The system may then call for intervention by establishing or by changing one or more relationships.

In the discussion on knowledge it was mentioned that information with context produces knowledge. The context also includes the relationships among concepts. For example, the relationship between a particular car and the driver is very significant when considering driving on a gravel road, and of little significance when considering a leisure trip along the coast. In the operation of the logic base, learning or experience from other systems' operations are of value. The use of concept maps can assist in visualising and studying relationships. Relationships are not normally reported in published case studies, but rather implied. It is therefore upon analysis of a case or article that relationships are identified and used for analysis. Depending on the type of knowledge being uncovered, the quality of relationships can be studied. In the case of problems solving, contradictions in the relationships are of great value to uncover problems or constraints. In the case where monitoring and controlling are reported relating to the performance of a system, performance parameters can be identified together with their relationships. Some relationships may present particular ineffectiveness and hence responsible for causing particular constraints or problems. Understanding the relationships and the context of the system can assist in replication in similar-behaving systems.

4.8.2 Utilising relationships

A method to study the interrelationships, is to select and pair important or appropriate concepts. (Good judgement and tacit knowledge is necessary to do this.) By pairing the concepts and identifying potential problems or constraints enhances the creation of knowledge. Pairing of concepts is done in several problem-solving methods, such as morphological techniques, attribute-seeking techniques and TRIZ-techniques. Each concept being paired with another, also brings about the pairing of the concept's attributes and values. Pairing is not limited to just two concepts at a time. Each set or pair can lead to a series of possible issues, contradictions or constraints. It can also lead to new ideas. These problems can form new ontologies which can serve to store knowledge.

For example, pairing of “construction time” and “the need for high-quality work” can invoke further concepts that can be studied to ascertain if advantages could be obtained. Construction time can have sub-elements, such as the duration to fix reinforcing and to erect formwork for concreting. The reinforcing bars can have attributes such as bar diameters, lengths and weights with associated values (Object-Attribute-Value or referred to as “O-A-V triplets”). The high-quality work can have attributes such as correct positioning of steel bars and a value describing the exact location and spacing between bars. The steel bars (objects) can have additional attributes, such as the concrete cover to the reinforcing, and correct bar installation and spacing specifications. The specifications can also have appropriate values attached to it. Pairing could be between the attributes, “duration to fix reinforcement” and “correct spacing between reinforcing bars”. Contradictions can be identified in that high quality of fixing may imply elaborate measuring that may be time consuming. One could then think of methods to speed up the placement of reinforcing bars.

More generally, it could also involve other issues such as:

a) Type of construction materials employed (by using more workable materials).
b) Curing processes of concrete or other materials (by adding chemical compounds to accelerate the strength gain).
c) Staff skills (to work more productively).

d) Special tools and equipment (for example, by using conveyors to transport material).

e) Workspace requirements (to re-organise work to create additional working space).

f) Access to the construction site at the required times (for example, to work at night and to provide lighting).

Also of much value, are the definitions and procedures described by TRIZ. In the TRIZ system functional and attribute analyses are carried out to identify contradictions (Mann, 2007a, pp.101-117). In the above example, in a more general sense, one can study the interrelationship between construction time and quality of work. The TRIZ technique would then consider the substance-field relationship between the two entities (Mann, 2007a, pp.245-255). The premise is that a minimum of two substances and a “field” are required for a system to deliver a function. The “field” is defined as any energy present in the system. There are also interactions between substances and between the substances and the field. These interactions define relationships between them. This substance-field relationship is depicted graphically in **Figure 4.14**. Two substances (S1 and S2) are shown as well as the field (F1). In this example of quality and accurate placement of reinforcement, the quality or time can be regarded as separate fields (also interpreted in this as a deliverable). The relationship with the worker can be analysed and can yield the following results:

- It takes too much time to locate the correct reinforcing bar. The relationship between the worker and the steel bar is therefore *insufficient* and needs corrective action.
- The worker cannot position the bar accurately enough. The relationship between the worker and the steel bar is also *harmful* and needs resolution.

The task also has a relationship with the end product. The end product must have a field (attribute) of quality.

From analysis of the substance-field diagram, the relationships between the worker and the steel bar exhibit constraints. Upon further analysis, it becomes evident that the two deliverables contradict each other. If the quality must improve, more time is required; or, if less time is given to fix the reinforcing, the quality gets worse.

Referring to the Contradiction Matrix (Mann, 2007a), the following procedures are followed:

Looking in the headings of the rows and columns, the terms in the matrix with the closest match for “time to fix steel reinforcing” is “productivity and shown in row 39 on the left-hand side”. The term for quality in this instance is best represented by “manufacturing precision” and shown in column 29.

On the left-hand side of the Contradiction Matrix, the parameters that will have "improving features" are shown. In the example, "productivity" is shown in row 39. Manufacturing precision has worsening features as indicated on the matrix and shown in column 29. When pairing row 39 with column 29, reference numbers 18, 26, 28, and 32 are obtained. The numbers refer to the numbers of inventive principles shown on the extreme right of the page alongside the Contradiction Matrix.

The following inventive principles pertain to the reference numbers in this example:

- Inventive principle no. 18: Mechanical vibration
- Inventive principle no. 26: Copying
- Inventive principle no. 28: Mechanics substitution
- Inventive principle no. 32: Colour changes

Out of the above inventive principles, no. 28 seems to be the most plausible. "Mechanics substitution" could be interpreted the same as "mechanising the operation". This solution will restore the relationship between the worker and the steel bar, because mechanisation will improve both productivity and precision. (In the example, time to fix reinforcing and to improve the accuracy of placement.)

Possible other solutions could include the following:

a) Reschedule work to make a construction activity less critical.

b) Accept lower quality work. (This may be quite acceptable if finishing tolerances are relaxed and made less onerous/burdensome.)

The above is illustrated by the representation of the S-Fields as illustrated in the sketches in **Figure 4.14**.

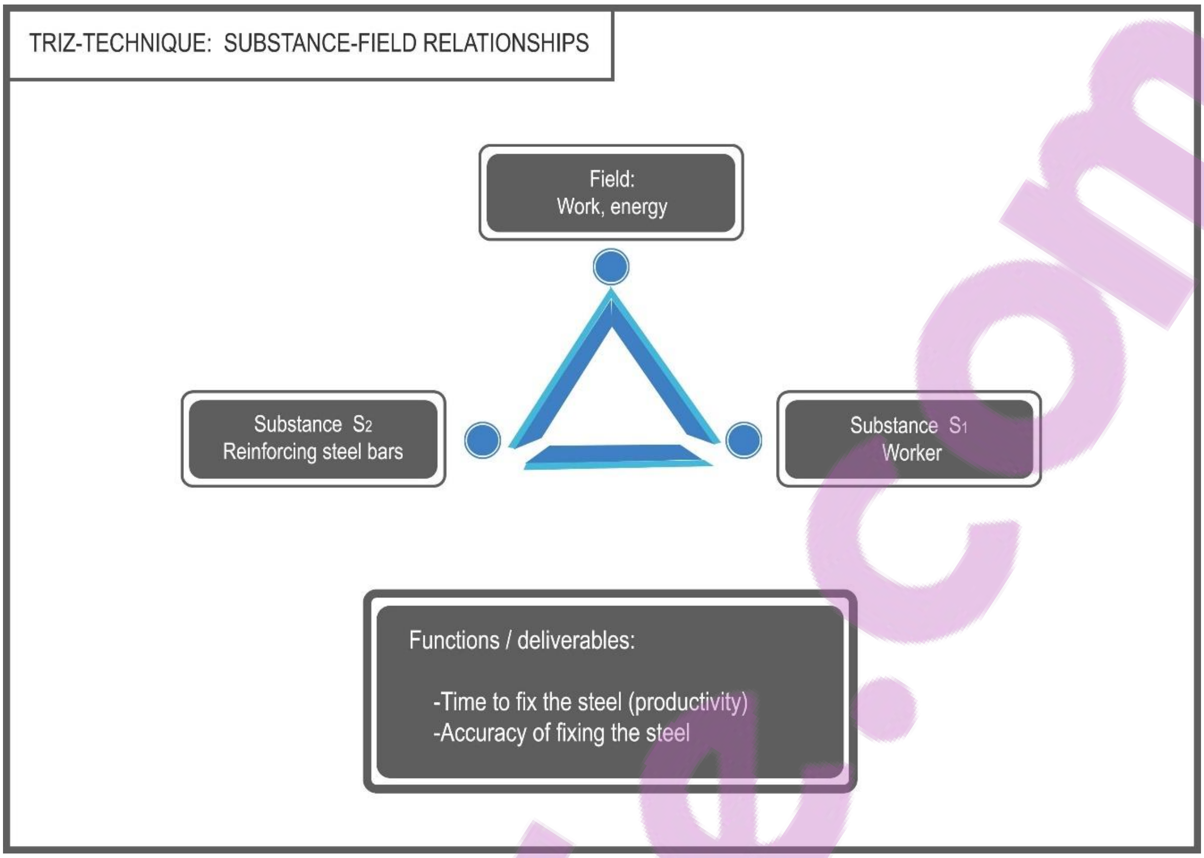

Figure 4.14 TRIZ-technique: Substance-field relationships

In general, the quality or qualities of interactions could be (Mann, 2009, p.246):

- Effective
- Missing
- Insufficient
- Excessive
- Harmful

Mann (2007a, p.246) also explains four types of solutions to problems where any of the above interactions are identified. The suggested solutions are:

- To complete an incomplete S-Field model.
- Modify one or more of the existing S-Field substances.
- Adding new substances.
- Transitioning to a higher or lower hierarchical level.

The above theory is most suitable for the analysis of relationships and for taking corrective actions where required.

It is suggested that the following process takes place in the logic base:

a) To abstract the knowledge contained in a case study and classify it in terms of the ontology or any sub-ontology that may be required.
b) To identify the most important relationships within the main knowledge domains. (There may be a very large number of relationships.)
c) To analyse the relationships by the application of FMECA to simulate failure or to identify constraints. A study of root causes (RCA) should identify the most critical relationships.
d) When certain issues with relationships are established, apply problem-solving techniques to address and solve a particular problem. Various problem-solving techniques are available and should be applied to find solutions to problems.
e) In this regard, it is suggested that the HOT- and/or TRIZ- or TOC-techniques be used to analyse and record solutions to problems.
f) If the relationships are not clear or unknown, application of the Cynefin framework could be followed. It may, for example, involve the introduction of certain controlled variables to test the response of the system to changes. (Refer to aspects of the Cynefin approach.)
g) Once the relationships are clear, the logic followed can be documented for replication.

The structured knowledge obtained from the above process can be retrieved and utilised when new assets are contemplated. In the illustration about the functional relationships in a server room (refer to Section 4.8.1, “General discussions and relationships”), it was discovered that there ought not be any relationship between the airconditioning of a computer server room and the main building's airconditioning system. This discovery constitutes a knowledge unit that could be retrieved.

4.9 THE UPPER-LEVEL ONTOLOGY (ULO)

So far, the TLO was compiled as well as the HLOs. The HLOs are hierarchically a level lower that the TLOs. In practice, in most case studies, only a certain number of concepts and their relationships are sufficient to describe a case. It may be convenient to formulate a combination of selected concepts from the HLOs to act as a simplified, generic map, incorporating all the significant concepts from all the individual HLOs. This combination map is termed an Upper-Level Ontology (ULO). The process is illustrated in **Figure 4.15**.

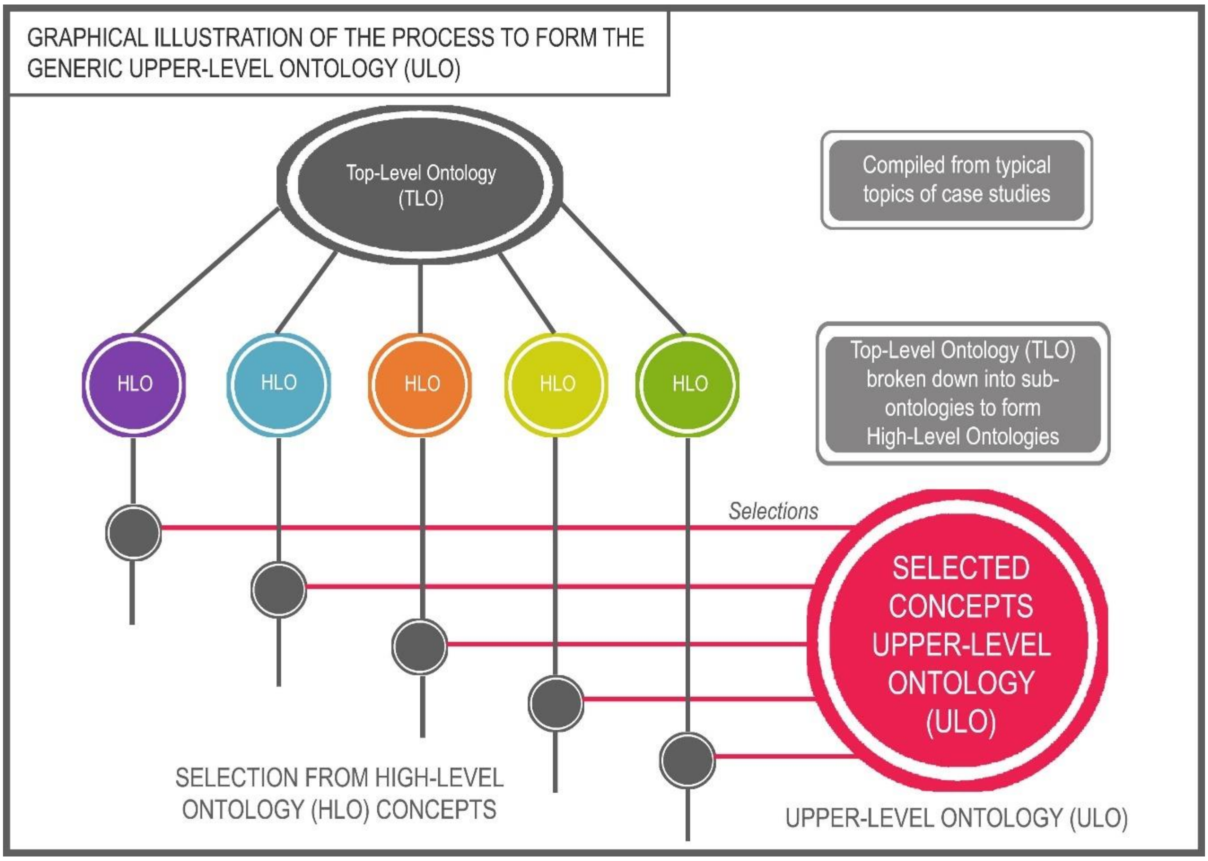

Figure 4.15 The process to form the generic Upper-Level Ontology (ULO)

Note: Not all the HLOs are shown in Figure 4.15. Any selection of a few applicable HLOs or all of the HLOs can be made.

The diagram shows that a selection of applicable and significant concepts can be made from the HLOs. The relationships can be obtained or changed. The resulting choice of concepts can be used to construct an Upper-Level Ontology (ULO). This ULO is still linked and always hierarchically sub-ordinate to the TLO, but hierarchically at the same level as the HLOs.

This could be called a "*generic"* selection, but is not unique, and can be reconstituted to suit specific applications. When a case study has a specific nature, a selection can be made either from the HLOs to form a new ULO, or a selection could be made from the *generic* ULO to act as a template for analysis of cases having a specific character. For example, cases involving the design of a public road will be different from the design of a structural steel building in a mine. When dealing with a specific case study, not all the concepts in the generic ULO may necessarily apply. A judicious selection can be made of the required concepts from the generic

ULO or concepts from the HLO to form a new combination to suit the case. In **Table 4.3**, the selection of topics are illustrated. The left-hand side shows the TLO concepts and the right-hand column shows the selected concepts for the ULO.

Table 4.3 Selection of concepts for an Upper-Level Ontology

TLO CONCEPTS	**SPECIFIC DOMAINS FOR A *GENERIC* UPPER-LEVEL (ULO) ONTOLOGY**
Introduction and scope	• Owner/user requirements • Purpose and scope of work • Functional Requirements (FRs)
Design	• Study/design/conceptualisation • Analysis • Application of discipline technology • Configuration • Drawings • Specifications • Operating principles/methods of operation
Construction	• Work planning and scheduling • Procurement and costing • Management of resources • Logistics • Project execution • Methods and techniques • Systems and controls/quality assurance
Operations and maintenance	• Operational philosophies and strategies
Setting and context	• Location • Roles and responsibilities • Communications
Sequence of events	• Initiation or initiating events • Consequences
Investigations	• Risk analysis, RCA
Interpretation	• Problem-solving techniques • Solutions • New knowledge • HOT/FAST-diagrams

TLO CONCEPTS	**SPECIFIC DOMAINS FOR A *GENERIC* UPPER-LEVEL (ULO) ONTOLOGY**
Lessons learned	• Outcomes • Actions • Consequences
Education/extrapolation	• System response • Evidence • Prompters/triggers/metaphors/analogies
Referencing	• Provide reference to various media

The mapping in **Table 4.3** was used to draw a concept map representing the generic Upper-Level Ontology (ULO). This is graphically represented in **Figure 4.16**.

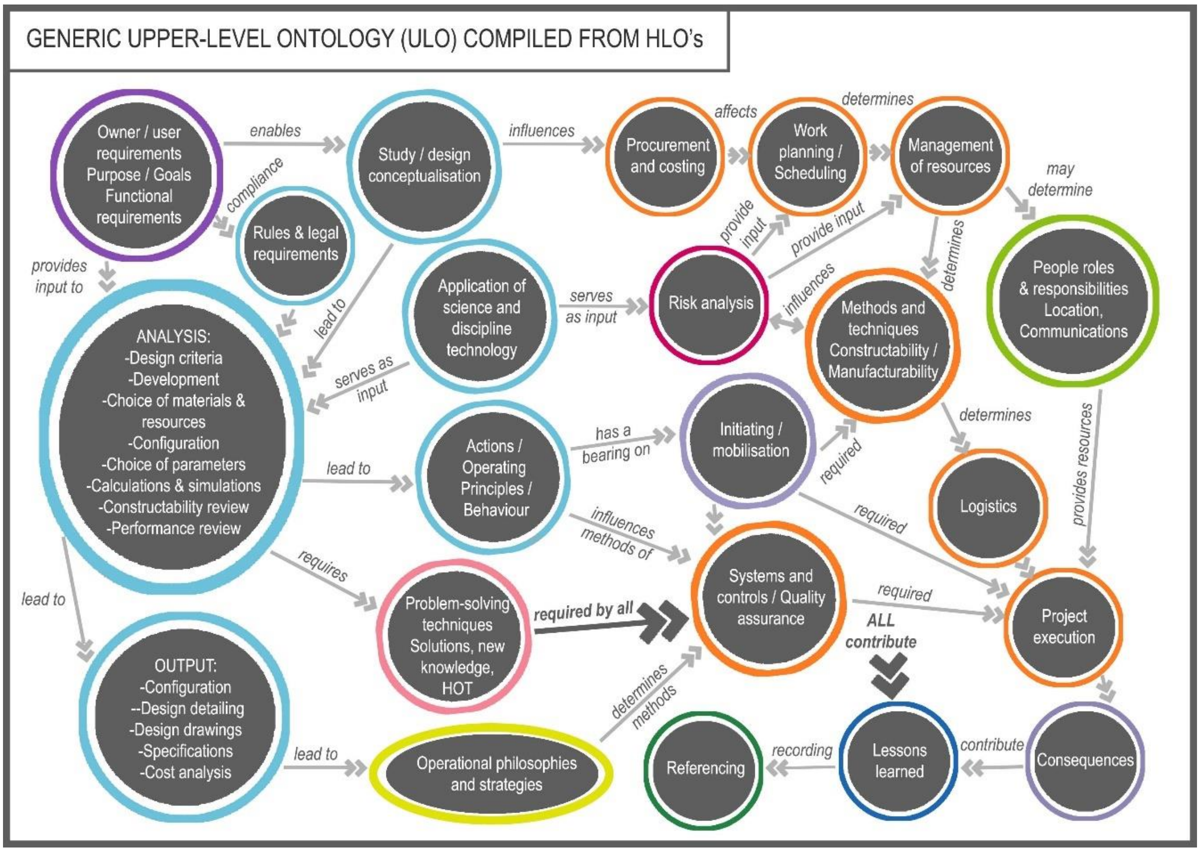

Figure 4.16 Generic Upper-Level Ontology (ULO) compiled from HLOs

The colours in **Figure 4.16** match the colours of the concepts as indicated in each of the HLO ontologies.

4.10 THE CASE-SPECIFIC ONTOLOGY (CSO)

The most granular ontology is the Case-Specific Ontology (CSO). A specific case study has its own selection of concepts. A unique concept map can be compiled to represent a case study. The information to develop the concept map for a case study can be derived from the script of the case study which may include a narrative or story. Work on a new project will provide the definitions of the concepts. This concept map is referred to in this study as a Case-Specific Ontology (CSO). The CSO must be compared or linked to the HLOs or the ULO. By comparing the CSO with the HLOs or ULO, gaps between the ontologies and concepts can be identified and studied. This study will, most likely, suggest that particular gaps are present in the CSO that need to receive attention. (This is analogous to the filling in of missing elements in the cells in the chemical periodic table – refer to discussion in Section 3.9, Chapter 3.)

The concepts in a specific case study can also be studied to identify problems and constraints. These problems and constraints, amongst other things, produce knowledge about the case under consideration. After compiling and analysing a CSO, the linkage to the ULO or HLO need to be confirmed. This will provide a basis of knowledge recovery and reuse. The knowledge obtained from the analysis can be located in output files for easy reading and assimilation by a user. It is important to note that the logic base must contain a narrative of the case study and also the concept maps, analysis and the output files. The intention is that the concept maps be computerised and the output files (reporting module) linked to the TLO. Full traceability must exist from the knowledge units to the TLO. This is also referred to as a "bottom-up" approach. (It is also possible to follow top-down and middle-out approaches (Roussey, 2011, p.30). This will enhance the search process to get to the knowledge units pertaining to specific cases. From the analysis of the cases, output protocols can also be derived to serve as generalised knowledge that practitioners should possess to improve civil engineering projects. This will be discussed in subsequent sections.

This is graphically illustrated by **Figure 4.17**.

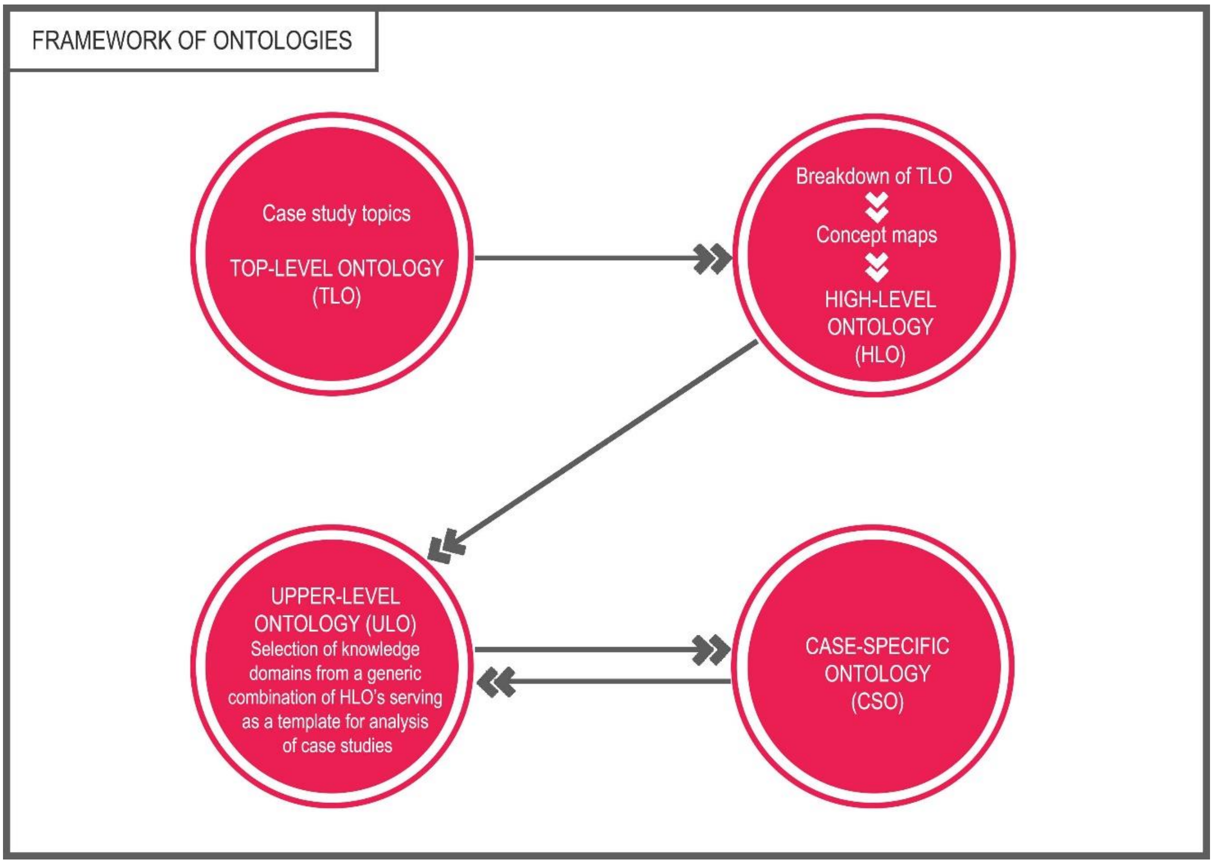

Figure 4.17 Framework of Ontologies

Figure 4.17 shows that the highest level of the ontologies is the Top-Level Ontology (TLO) the concepts in the TLO constitute Top-Level Concepts. Each Top-Level Concept contains High-Level Concepts and when grouped together, form a High-Level ontology (HLO). In order to simplify the Ontologies, an Upper-Level Ontology can be designed that has the same status, hierarchically as a HLO but consist of a grouping of High-Level Concepts to suit specific cases. Dealing with a specific case study, a Case-Specific Ontology (CSO) is drawn up that consists of concepts applicable only to the case at hand. The grouping of these case-specific concepts forms the Case-Specific Ontology. However, in order to follow a holistic systems approach, the CSO has to be mapped to the ULO or to any HLO. The ULO can be linked to the CSO and relationships and gaps identified from any relationship that may be lacking.

4.11 ILLUSTRATIVE EXAMPLE

Example 1: Earthworks

This succinct example is chosen since it already is the end product of an analysis process used for problem-solving and knowledge storage. The purpose of using this example is to demonstrate how the knowledge process followed in a previously compiled process could fit into the ontology as proposed above. Although this example is not a case study *per se*, it serves as an example of how a general case of analysing earthworks operations could be done and how it can be analysed using the ontologies.

4.11.1 H.O.T-technique

An extract from a H.O.T-diagram (Verbeek, 1992, Vol. 2, Appendix L, pp.39-40) is chosen for this example. It is slightly amended for illustrative purposes. (The H.O.T-technique involves stating an objective, followed by a statement of a problem or constraints. These are followed by statements of potential tactics to address the problem and are then followed by potential solutions. The presentation is done by indenting the text when proceeding from one level or step to the next.) (For a discussion of the H.O.T-technique, refer to Chapter 2 of this study; Section 2.7.11.)

In the knowledge domain of "earthworks" in civil engineering, the objective in a H.O.T-analysis is stated as, "Eliminate losses, delays and rework".

One of the problems/constraints identified in the study is: **"To reduce effects due to weather".**

Several tactics are listed and the potential solutions are showed as follows:

a) Consider effects due to rain ***(Tactic)***.
   - i) Programme works to suit the season ***(Solution)***.
     - Do critical earthworks in dry season ***(Solution and action step)***.
   - ii) Do proper planning of the works ***(Solution and action step)***.
     - Combine temporary and permanent drainage works ***(Action step)***.

b) Consider effects due to cold weather ***(Tactic)***.
   - i) Consider effects on personnel.

- Provide heated operator cabins on plant ***(Solution and action step)***.

c) Consider effects due to hot weather ***(Tactic)***.

i) Consider effects on personnel **(Solution)**.

- Provide airconditioned cooling of operator cabins on plant ***(Action step)***.

d) Consider effects due to wind ***(Tactic)***.

i) Reduce dust ***(Solution)***.

- Employ chemical dust palliatives to reduce dust ***(Action step)***.

The solution fields may then be part of a knowledge base where details of dust palliatives, for example, could be found and the experience of people in the industry could be documented.

In the above example, it is now illustrated how the logic base would function.

4.11.2 Analysis in terms of the logic base

The starting point is to draft a concept map for earthworks. **Figure 4.18** shows the Case-Specific Ontology (CSO).

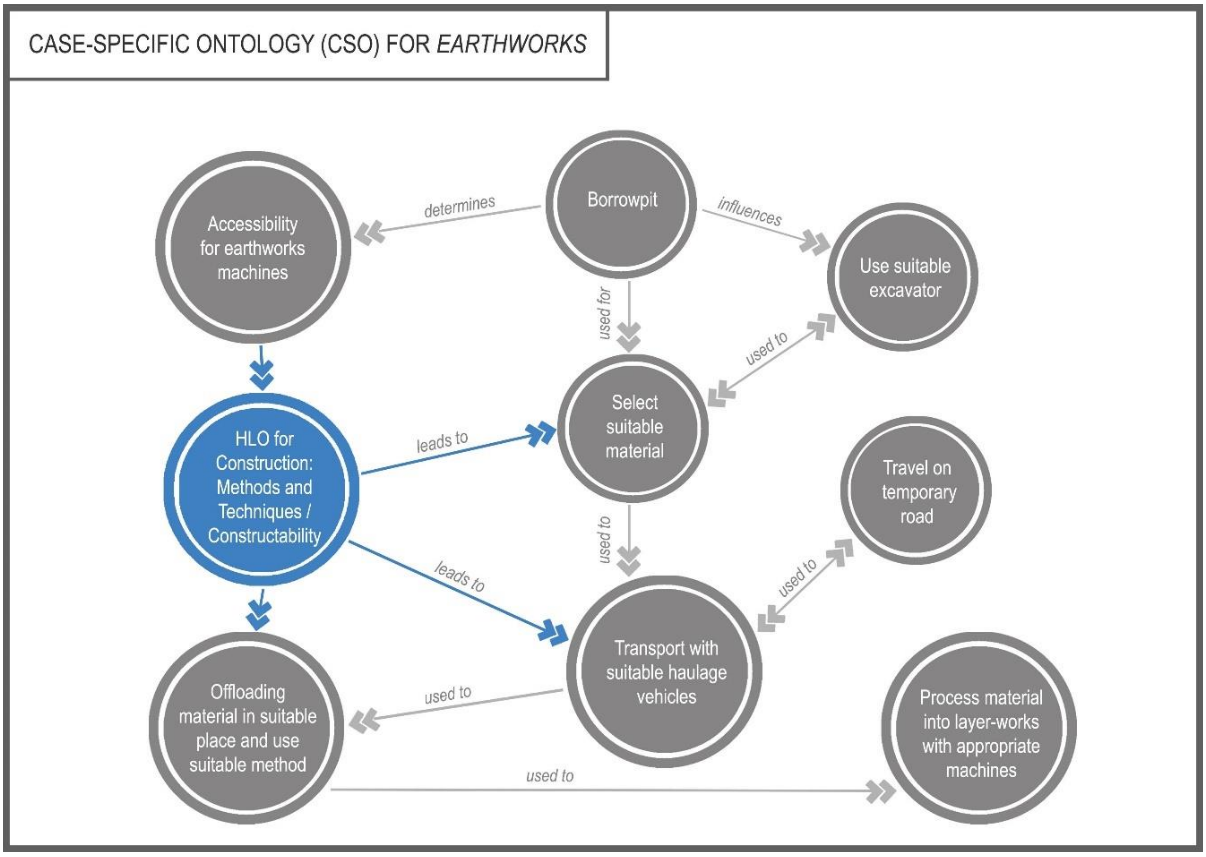

Figure 4.18 The Case-Specific Ontology (CSO) for *Earthworks* example

This Case-Specific Ontology (CSO), however, links to the HLO and hence also to the TLO.

This is illustrated in **Figure 4.19** :

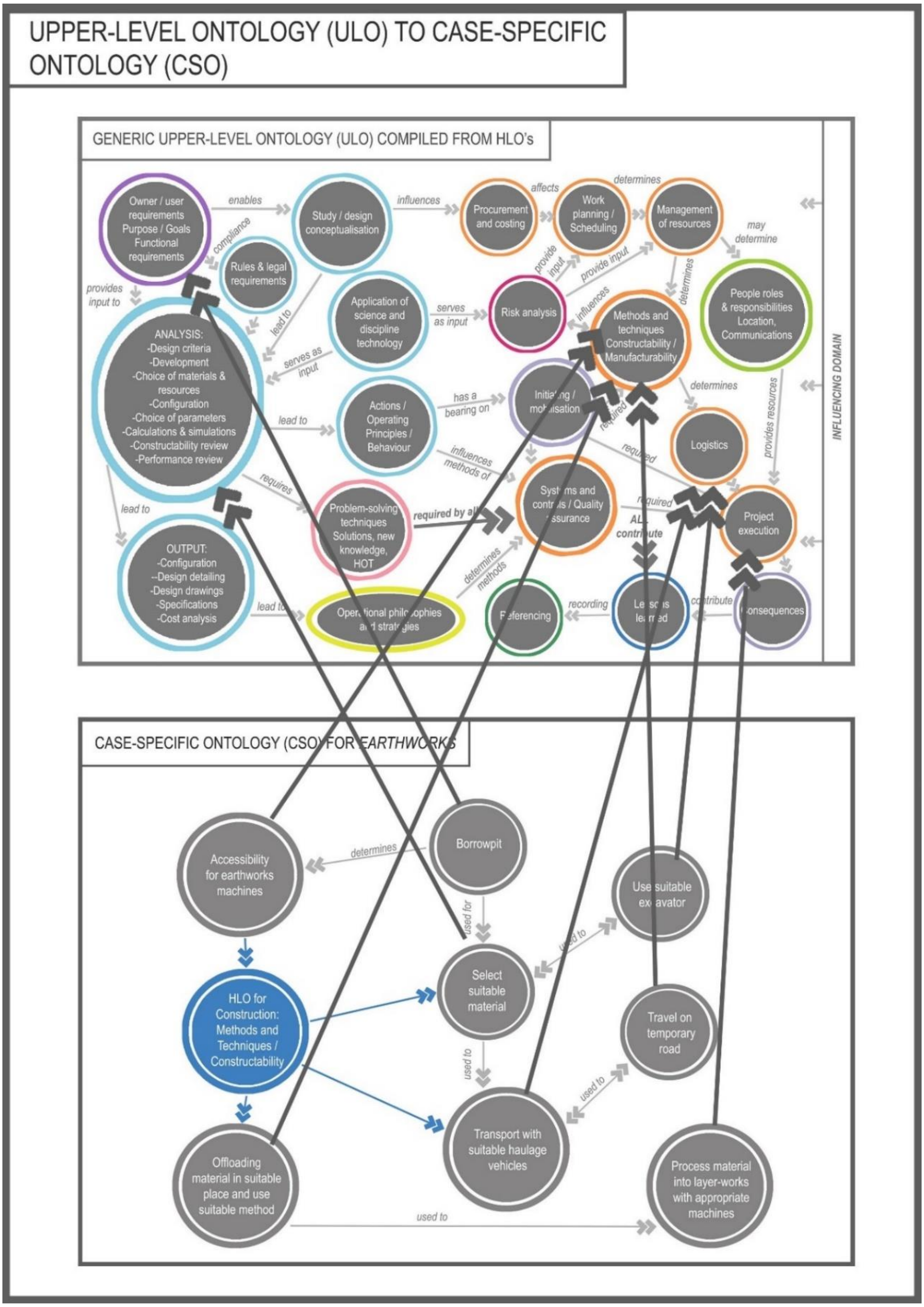

Figure 4.19 Mapping: Case-Specific Ontology (CSO) to Upper-Level Ontology (ULO)

The upper diagram is the same as **Figure 4.16**, the Upper-Level Ontology (ULO). The lower diagram is the same as **Figure 4.18**, the Case-Specific Ontology (CSO). The lines between the lower and the upper diagrams indicate the linkages between the CSO and the HLO (or HLOs). Every concept in the CSO can be linked to a concept or concept group in the generic HLO (or to other HLOs). This enables the linking of knowledge from a specific case to the HLO and hence to the TLO. This provides a means for searching and recovery of knowledge with the view to reuse such knowledge and to identify specific problems or constraints. The logic base provides such links and accumulates and create new knowledge which is fully discoverable.

The juxtaposition of the lower-hierarchy ontologies to the upper levels describes a process that produces many questions and act as seeds to generate knowledge. This process in described below.

a) **Purpose, scope and user requirements:** This can be, for example, to construct a building. A Functional Requirement (FR) may be to construct an earthworks platform in the form of an engineered fill to accommodate the building. The size of the platform should be given by the user. The knowledge units are:

- The construction of an earth platform for a building.
- The extent of the platform (i.e., the size and height thereof).
- Effects of storm water on the earth platform.

(In knowledge representation, it can follow that the object is the platform, the attributes are the sizes and height and slope for drainage of it and the values are the actual size, height and drainage slope. The representation could therefore fit into the O-A-V triplet format.)

b) **Design:** The designer interprets the scope of the work in his design and determines the materials utilisation plan and specification requirements of the earth platform. These are documented, and drawings for construction are prepared.

Knowledge units in this category could be:

- The materials utilisation plan.
- Specifications.
- Drawings.
- Performance of layer work under wet conditions.

c) **Operating principles:** For earthworks, the laws of physics, and more specifically of soil mechanics, are applicable. (For example, the bearing capacity of the fill and settlement characteristics.)

Knowledge units could be as follows:

- The allowable bearing capacity of the soil platform.
- The predicted settlement of the building.
- Dust suppression techniques in dry season.

d) **Configuration, drawings and specifications:** The way the earthworks will be done, what types of soil would be used and what level of finishes will be provided. In addition, one should also fit the earthworks into the bigger picture as part of a development for the construction of buildings.

The knowledge units could be:

- The drawings.
- The specifications for material quality.

e) **Project execution/construction:** This has to do with the procurement, construction techniques and the schedule. (Refer to the HLO for concepts in this regard.)

Knowledge units could be:

- Planned production methods and works schedule (Influenced by seasonal weather conditions). (ULO; **Figure 4.12 –** "time changes".)
- The type of roller to be used for construction, especially during wet conditions.
- The quality-control measures when materials are too wet for compaction.
- Drainage methods (temporary and permanent) .
- Personnel comfort (ULO; **Figure 4.12** – "capacity"; human resources matters; heating or cooling of operator's cabins).

f) **Mechanism of operation, mobilising, processes:** Compacted earth is used to provide the necessary strength to accommodate the forces exerted by the building foundations. These forces will only start to come into being when the building construction commences.

g) **Methods and techniques:** The use of specific compaction technology or special techniques are recorded, such as the use of grid rollers that would perform better in wet conditions than vibratory rollers.

Knowledge units could be:

- Choice of compaction equipment for wet processing of materials.
- Choice of dust suppressants in dry weather.

h) **Mobilisation/initiation:** This refers to the actual removal and placement of fill material. The forces will come onto the earth through the foundations exerting the dead and live loads of the building onto the soil structure. For example, in the case of a warehouse, as shelves in the building are loaded or unloaded, so will the forces on the foundations/earth platform change.

Knowledge units could be:

- Loading conditions during operations in the building.
- Details of vehicles that would be used on the platform.

i) **Operations and maintenance:** The construction process in this instance can be seen as the operations of the company doing the construction. Maintenance is important in the final finishing of the earthworks to line and level, and to ensure proper drainage and stability of edges of fills and slopes.

j) **System and controls:** When performing earthworks operations under wet conditions, it is important to understand and consider the entire construction process. All the activities should be listed and controls put in place to ensure proper system performance. Simplified, it involves the following:

- The selection of material.
- Liberating the material (if rock – it may need blasting).
- Loading the materials.
- Hauling the material to a specific location.
- Off-loading the material.
- Compacting the material.

In wet conditions the above items have to be done in different ways than under dry conditions.

Knowledge units could be:

- Loading material with steel-tracked machine rather than with a rubber-tyred machine. This will reduce the risk of slipping on soil base.

- Material should be stockpiled in well-drained areas rather than spreading it out where it can become wet during rainy weather.

k) Environmental aspects (from Influencing Domain): To enable simplification in this case, one may choose weather conditions only, and more specifically, rainy and cold conditions.

l) Time and space testing: Test the system for changes in time and space.

m) FMECA analysis: The next step is to do a FMECA-analysis on the parameters.

In this case, the following functional relationships have the potential to give problems:

- Haulage: Slippery road surface could cause inability to safely traverse the route.
- Compaction: Rain can increase the moisture content of the material to the extent where compaction cannot be carried out and material will have to dry first.
- Personnel: Truck drivers cannot operate the equipment due to low comfort levels.

n) Application of TRIZ

The first step is to determine relationships and to identify which concepts are contradictory.

The following concepts are in contradiction:

(Note that the word "BUT" connects two contradicting concepts.)

- A truck has to traverse a road to continue with production, BUT the road is too slippery, which renders the operation unsafe.
- Compaction must be done, BUT the material is too wet.
- Personnel has to work, BUT cabins are too cold to comfortably work.

Regarding the first bullet, one can re-word and formulate the contradiction to be, that productivity improves but safety gets worse. Reading from the contradiction matrix (Mann, 2009), the vertical headings on the left-hand side represent the features that improve or gets better, and the horizontal headings represent the features that get worse. In this instance, reading on the left, the feature "productivity" (no. 44) is chosen. Safety gets worse and can be found as feature no. 38 (safety/vulnerability). The following innovative principles are suggested: (Nos. 10, 39, 1 and 18 found in the list of 40 innovative principles printed on the right hand side of the contradiction matrix.) These are no. 10: "preliminary action": no. 39:

"inert atmosphere"; no. 1: "segmentation" and no. 18: "mechanical vibration". Of these solutions, "segmentation" may offer a solution. One can, for instance, apply the principle of segmentation and evaluate the haul road to choose safe sections of road to use for haulage (if such sections are available). "Preliminary action" is also a possibility in that one can prepare the road surface so that it would not be slippery and unsafe during rainy conditions.

The above can be taken up in an amended HOT-technique, whereby the contradictions and innovative principles are used to develop tactics. It is most useful to follow the systematic process provided by the Upper-Level Ontology. (Reference to the ULO enables one to consider as many relationships as possible between the various knowledge domains.) Taking the above example for illustration purposes, the following relationships can also be identified:

- User requirements **and** design.
- Design Parameters (DPs) **and** compliance with regulatory requirements.
- Design **and** construction techniques.
- Resources **and** construction techniques
- Quality controls **and** construction techniques.

The list could be very long, but it is considered expedient to work through as many functional relationships as possible, to ensure that as many as possible contradictions and constraints are identified.

Each of the above relationships could yield several problems or constraints, which could each have a set of solutions. The logic base would, therefore, operate as follows:

- Consider each of the ontological components and study by pairing of the concepts and attributes.
- Define the contradictions and constraints.
- Analyse the contradictions and constraints to search for solutions.
- Present the solutions.

o) Risk analysis

Risk analysis should form part of every investigation. It is recommended to use the so-called "bow-tie" analysis (Hamzah, 2012) in the operation of the logic base.

The process involves the identification of hazards (FMECA can be used for this part). The threats (causes) are then determined that would lead to a top event. An analysis of the consequences of the occurrence of the top event are then carried out and mitigatory measures are then formulated and implemented as required.

In the case of the above example, the following hazards can be identified (from a safety point of view):

(i) Hazards

- Moving plant and machinery (haulage trucks).
- Slippery haul roads.
- Lack of visibility (due to dust in dry periods).

The next question is what the top (unwanted) event would be. In this case it is a road accident. Then follows the search for possible causes of the event. One can consider the following:

ii) Causes of events

- Approaching vehicles can collide as a result of poor visibility due to dust.
- High-speed truck could lose control in a bend.
- Tyres on the vehicle not suitable for operating in wet weather.

iii) Consequences

The consequences of an accident could be as follows:

- Fatal injury of personnel.
- Damage to trucks.
- Production loss.
- Cost of repairs (if possible) to trucks.

iv) Mitigatory steps

- Do not operate trucks in wet weather.
- Construct all-weather surfacing on haul roads.
- Reduce the speed of vehicles.

iv) Construct one-way roads

The above illustrates further considerations when analysing case studies and extrapolating available information.

4.11.3 Summary of logic-base inputs and outputs

If one works through the logic base regarding "effects of rain on earthworks", the logic base would guide the user to choose the appropriate ontology and its attributes. Concepts and relationships will be provided as per the list above. If populated, contradictions and constraints and a list of solutions can be offered. Because the logic base contains generic components (it is not site-specific), the details may apply in general to earthworks.

The logic base represents a process of investigation for the creation of knowledge.

The input information to the logic base is that found in the details of a case study. The output is a set of issues and solutions that could lead users to knowledge.

This is illustrated below:

a) Input:

Topic: "Eliminate losses, delays and rework". A problem/constraints were identified in the study namely: **"To reduce effects due to weather".** (Also from Influencing domain.)

The output of the logic base is as follows:

- Do critical earthworks in the dry season.
- Combine temporary and permanent drainage works.
- Materials specifications and drawings to allow for wet working of materials.
- Materials utilisation in wet weather. Choose material less susceptible or sensitive to moisture increases.
- Allowable bearing capacity of the soil platform may be influenced by wet conditions.
- The predicted settlement of the building. This may influence the design of the fill.
- Quality control in wet weather when materials are too wet for compaction.
- Planed production methods in wet conditions.
- Types of rollers to be used in wet conditions.
- Personnel comfort in hot and cold conditions – provide air conditioners in operators' cabins.
- Selection of most suitable plant to operate in wet weather.
- Loading of trucks with traxcavator, rather than with rubber-tyre loading equipment.
- Stockpile materials rather than spreading it out to reduce risk of material wetting in rain.

- Avoid slippery roads – use sections of roads that are not so slippery when wet.
- Provide all-weather surface to haul roads.
- Reduce the travel speed of haulage vehicles.
- Construct one-way roads for haulage.
- Use chemical dust palliatives to reduce dust and increase visibility in dry times.

b) Output protocols:

These are statements that would be of general use by practitioners and are further elaborated in Chapter 5 of this study.

By way of example, the following protocols can be stated from the discussions above:

- When designing earthworks, all aspects relating to working under wet conditions must be taken into account in the design.
- Special attention needs to be given at an early planning stage to ensure construction activities adequately cater for wet conditions.

The example illustrates the following:

- That the Upper-Level Ontology (ULO) provides a basis for documentation of knowledge. It also prompts the user to systematically consider the concepts in the ULO, but also to consider the concepts in the HLO.
- The CSO is automatically linked to the HLO and the TLO.
- That the ULO is a High-Level process and covers all aspects of the development of assets. (For example, in this case an earthworks platform.)
- That functional analysis is useful to identify contradictions.
- Concept maps can expand the thought processes to cover a wider field.
- That TRIZ can be used to generate solutions.
- That the HOT-technique is a valuable tool to record solutions, but is limited in the analysis of problems and constraints.
- The main purpose of the Upper-Level Ontology (ULO) is to provide a holistic and systematic method for the identification of functional relationships that can be used to identify problems and to search for solutions.
- The logic base is based on the Top-Level Ontology (TLO) and its sub-ordinate HLO and CSO. A generic ULO can be defined that is equivalent in hierarchy to an HLO, and contains a record of the functional relationships that display

contradictions and/or constraints. It also suggests solutions to specific contradictions and/or constraints.

4.12 SUMMARY AND CONCLUSIONS

In this chapter, the ontology is designed for application in the logic base. The characteristic topics of case studies were used as a point of departure. Concept maps were designed and drawn up for each characteristic topic of case studies. These topics were re-defined as constituting a Top-Level Ontology (TLO). A concept map was produced for each concept in the TLO, thereby forming a High-Level Ontology (HLO). A selection was made of key concepts and redefined in an Upper-Level Ontology (ULO), which was then used in the logic base.

An illustrative example was then given to demonstrate how the logic base would function regarding the application of the Upper-Level Ontology (ULO). It was shown that new knowledge can be created from this application and can serve as a useful way to investigate and analyse case studies.

The research questions that are answered in this chapter are the following:

f) What components are required for the logic base?

The following are sub-sub research questions:

i) How can knowledge acquisition, reuse and knowledge creation be translated into components of a logic base?

ii) What are the relationships among the various components and how would the components contribute to the functioning of the logic base?

iii) What criteria are required to provide the functionality of knowledge acquisition, reuse and knowledge creation?

In answer to the first sub-sub research question f (i), the drafting and analysis of concept maps represent the main components of the logic base and the analysis of case studies provide the means for knowledge acquisition and knowledge creation. Once the knowledge is categorised in the CSOs and HLOs, it forms part of the TLO. The TLO can be linked to existing (or newly designed) ontologies for Civil Engineering. This will enable reuse of knowledge.

The answer to sub-sub research question f (ii) lies in the study of relationships between the concepts, constituting the various ontologies. The study of the relationships is a means to uncover problems and constraints. When solving these problems and constraints, new knowledge is created. It also follows from sub-sub research question (i) that it contributes to the reuse of knowledge. The analysis of relationships also provides the opportunity to use knowledge acquisition techniques. These are all essential elements contributing to the functioning of the logic base.

In answer to sub-sub research question f (iii), the criteria are related to the ability to form clear concepts from an engineering case study. It is also necessary to clearly follow an analysis procedure to ensure that a case study is properly analysed. This is the reason for the linking of CSOs to HLOs, which would suggest where gaps or problems exist.

g) What is an appropriate architecture of a logic base to fulfil the Functional Requirements (FRs) for the acquisition, reuse and for the creation of knowledge?

The following sub-sub research questions pertain:

i) What ontology and/or taxonomy can form the basis of the design of a logic base?
ii) How sensitive are the ontologies for different applications?

The answer to sub-sub research question g (i) lies in the procedure to draft concept maps. It was shown in the discussions of this chapter that the typical topics of case studies meet the requirements of an ontology. The ontologies that were subsequently designed provide the basis for knowledge acquisition, reuse and for knowledge creation. These ontologies and the analysis of the associated concepts form the basis of the logic base.

Research question g (ii) can be answered by considering the different ontologies. The definition and custom design of the CSO render the ontologies extremely flexible and capable of handling a large variety of applications.

The discussions on the sub-sub research questions, answer the sub-research questions (f) and (g), regarding the components and the architecture. The architecture is defined by the ontologies, the analysis of relationships and by the applications of problem-solving techniques as illustrated in the example given on the analysis of earthworks.
(A complete summary of all the research questions is given in **Appendix I**.)
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In the following chapter the application of the logic base is researched and further developed by analysing several case studies in detail.

CHAPTER 5: EXPANSION OF CONCEPT MAPS

5.1 INTRODUCTION

In Chapter 4 the knowledge base was designed. The design took place by referring to the typical topics, and approximate hierarchical order followed in the structuring of case studies. Consideration was given to the various desired attributes of a logic base. Most important attributes are classification and hierarchy (refer to Chapter 4, Section 4.4). Through the use of concept maps, knowledge domains were defined and put in the form of hierarchical order to constitute ontologies. Concept statements represent the starting points of ontologies for the applicable knowledge domains (Novak and Caňas, 2008). Concept statements can be developed into sub-statements, objects, verbs, actions or activities. Attributes with certain values can also be defined. (For example, Object-Attribute-Value (O-A-V) triplets are discussed in Chapter 2, Section 2.10.) The first hierarchical level of concept maps was designed from the topics of case studies and is termed the Top-Level Ontology (TLO). Each concept in the Top-Level Ontology was expanded into a sub-ontology, termed the High-Level Ontology (HLO). To simplify the structure of ontologies, allowance is made for the selection of concepts from the HLOs and combined to form an Upper-Level Ontology (ULO). ULOs can be compiled to suit user needs. This ULO can be used as a reference ontology to assist with the analysis of case studies. When analysing any particular case study or another source of knowledge, a Case-Specific Ontology (CSO) can be compiled. This CSO must then be linked to the ULO or HLO, which, by definition is part of the TLO. ULO is not a unique grouping of concepts and individual users may wish to choose other groupings of concepts from the HLOs. For illustrative purposes, a generic ULO was developed and shown in Chapter 4 (**Figure 4.16**). The choice of concepts to form a ULO is determined by the intended end-use of the ontology. For instance, the end use of the ULO may be to investigate the reasons for structural failures. Concepts most appropriate to such types of investigations may then be chosen to suit the proposed end use. End-use statements are also referred to as competency questions (Noy and McGuinness, 2001) and would typically ask questions relating to the events preceding an actual incident. (In general terms, end-use statements may be seen as questions relating to the system's performance or characteristics.) Also, if for example, one wishes to represent certain learnings from the solutions of specific problems presented in a case study, one should select the concepts from the HLO that would play significant roles in the solution of the particular problem(s). The ontologies described above serve as tools to systematise thinking patterns and to facilitate further analysis. By studying the differences between the ULO or HLO and the CSO, one can determine where gaps in the understanding of a case exist, where essential concepts might be missing or lacking and what relationships emanate from the analysis process. From this analysis, various issues, problems and constraints can be identified and various problem-solving techniques can be used to resolve these.

Representation of knowledge by way of concept maps gives the opportunity to analyse relationships between various concepts, sub-concepts, objects, attributes and values. These relationships would best define and describe problems and constraints that were found in case studies. Furthermore, deeper insight can be obtained that would lead to the potential development of new knowledge.

This process is discussed in the sections below.

5.2 DISCUSSION AND EXPANSION OF CONCEPT MAPS

5.2.1 Problem-identification process

In Chapter 2, the role of problem-solving was discussed. The learning processes and the creation of new knowledge are mostly based on problem-solving. The main challenge, however, is to firstly identify that there is indeed a problem and secondly, that the correct problem is addressed most appropriately. “People come to believe that a problem exists after seeing evidence to the effect” (Smith, 1998, p.48). “Problem identification is a prerequisite for problem-solving […] Early identification can prevent potential problems from happening and enable exploitation of opportunities” (Smith, 1998, p.49). This emphasises the need and the value of applying problem-solving techniques as early as possible in a development process.

Problem identification has been defined (Smith, 1998) as the process by which someone comes to believe that a problem does or will exist. Because of a large variety of reasons why problems exist, they come to be discovered via different paths. Virtually all problems provide evidence of their existence. Concept maps, and in particular, Case-Specific Concept maps, or Case-Specific Ontology (CSO) may provide the “paths” for problem discovery. One way of identifying problems is to study the relationships between elements. The focus on the relationship between elements is found in many problem-solving techniques. Refer in particular to TRIZ (Theory of Inventive Problem Solving), and TOC (Theory of Constraints), which are primarily based on the study of relationships between entities. These two theories are very well established in the industry and of a most fundamental nature, and suitable to use for problem identification in this study.

5.2.2 Relationships

a) Relationships in various problem-solving techniques

Relationships between entities (of various nature) play important roles in several knowledge-acquisition and problem-solving techniques. Some examples of problem-solving techniques based on the study of relationships are given below. (These were also discussed in Chapter 2 of this study.)

- Cynefin framework (Snowden, 2013d)
- Morphological analysis (Zwicky, 1948)
- Attribute-seeking technique (Govindaraju and Mital, 2008)
- Analysis and synthesis (Ritchey, 1991)
- Root-Cause Analysis (Rooney and Van den Heuvel, 2004)
- FMECA (Luthra, 1991)
- TRIZ (Mann, 2002)
- TOC (Goldratt, 1997; Scheinkopf, 1999)
- FAST (Grönqvist, Male and Kelly, 2006)
- HOT (Youker, 1998)

The above problem-solving techniques have different approaches to the relationships between elements or entities; however, cause-effect types of relationships are common to all and relationship types are not limited to cause-and-effect relationships. In **Table 5.1** a summary is given of the important aspects about the above relationships.

Table 5.1 Summary of relationship types in various problem-solving techniques

Technique	Treatment of relationships
Cynefin	A series of two-dimensional matrices, each consisting of 3 x 3 blocks, are used. The relationships between parameters on each of the sides of the matrices define the state of awareness. The relationships between the pairs of parameters should be managed to follow a line of "coherence", which signifies the movement away from chaos towards situations with more order. This approach is mainly used in managing complexity.
Morphological analysis	Parameters or attributes are entered into a multi-dimensional matrix and the relationships, however trivial or seemingly irrelevant, are studied. The effects of these relationships in finding solutions are determined by inspection, selection, logic or judgement. One then focuses on the relationships that would best contribute to the solutions of problems.
Attribute-seeking technique	The method relates to morphological analysis. Attributes of an object or system serve as inputs to the morphological analysis and the same procedure is followed as in morphological analysis.
Synthesis and analysis	The mutual interaction between attributes or parts is studied, as well its responses to external stimuli. Cause-and-effects are studied.
Root-Cause Analysis (RCA)	Multiple factors are considered. Normally the causes of some unwanted events are studied. This represents a cause-and-effect study.
FMECA	Each component of a system or each functional aspect is evaluated for its effects on other related components and on the system as a whole. The risks and consequences of each possible failure mode are evaluated. It is essentially a cause-and-effect study.
TRIZ	This method relies strongly on the study of different types of relationships. The types of relationship then lead to the identification and analysis of problems. A number of inventive problem-solving techniques are then used to guide the analyst to plausible inventive solutions.
TOC	TOC focuses primarily on cause-and-effect relationships and takes into account the types or qualities of such relationships. System constraints are identified and resolved to improve the performance of an entire system.
FAST/HOT	These methods are very similar in nature. Once a problem is identified, tactics are devised to find solutions. The method entails consideration of goals and objectives. Essentially cause-and-effect relationships are tested to yield the desired solutions to specific problems or constraints.

Table 5.1 reinforces the contention that relationships between parameters (also referred to as entities, elements, or functions) and attributes are of great importance in problem-

solving. Therefore, a study of relationships is considered essential for the functioning of the logic base. When considering the various techniques, the following are observed:

- Relationships depicting cause-and-effects are the most prevalent and important aspect in most problem-solving techniques.
- Relationships, other than cause-and-effect relationships, also need consideration.
- The quality of relationships should also be studied.

The various concept maps shown in Chapter 4 display relationships between concepts. A variety of relationships can exist and are not necessarily limited to cause and effect relationships.

Morphological and attribute seeking techniques provide the basis for identification of relationships. By compiling a multi-dimensional matrix from the HLO, covering all the domains identified in case studies, one can capture most of the possible parameters/entities found in case studies. An example of a relationship matrix is shown in **Appendix G**. All the concepts comprising the HLO are listed in the columns and rows of a spreadsheet. This enables one to pair all the concepts in search of relationships that can be paired and evaluated. The evaluation of the relationships against a set of criteria leads the user to the identification of meaningful relationships that may assist in the identification of problems and constraints. The main purpose is to prompt the user to identify relationships between concepts as they appear in the HLO. In a paired cell, more than one set of problems and constraints can be identified. It all depends on the role of influencing domains. Once a problem was identified and solutions obtained, reference can be made to the cell where the pairing was found to indicate a problem or constraint. References can also be linked to such cell. After solving a problem, the knowledge used to solve the problem can be linked to the specific cell. The cell can also be used to link learnings and references for subsequent reuse.

In the sections below, the relationships found in TRIZ and TOC are briefly discussed.

(b) TRIZ relationships

TRIZ has three related methodologies in the application of problem-solving. These are:

(i) Perception mapping

This TRIZ tool "use the way the human brain works to develop lists of our perceptions of certain situations. [...] They offer a brain-compatible means of mapping complexity. [...] Perception maps can be used to analyse situations as they are or propose solutions to identify what you would like them to be" (Mann, 2007b, p.150). There are four basic stages in doing perception mapping. The first stage entails recording of perceptions about a given situation. In the second stage the question is asked: "What does this lead to for each perception under consideration?" A diagram is then compiled showing an arrow from a perception under consideration to the next perception that represents the most likely perception leading to the first. Each perception can have only one arrow pointing from it. The third stage is to examine all the perceptions and to try and identify contradictory or conflicting perceptions and relationships. The fourth stage involves the interpretation of the resulting perception map. Some perceptions may have several arrows leading to it, and these perceptions are then called collector points. The situation can also be that perception A leads to B, and B leads to A, which then forms a loop. Such a loop may contain two or even many perceptions. Any group or succession of perceptions that form a chain between two conflicting perceptions should be noted. These represent central areas or issues to focus on to improve the system's operations. When considering the "lead to" relationships, one can also distinguish between some perceptions that "could", "should" and "will always" lead to some other perception (Mann, 2002, p.155).

(ii) S-Field Analysis

To successfully deliver a function, a minimum of two substances and a field are required. The word "field" can mean any form of energy present in a system. A comprehensive list of fields is presented by Mann (2007a, pp.248-249). TRIZ is aimed at innovative problem-solving and the relationships between "things" and the "fields" between two concepts are investigated. The "S-Field" models are considered from a systems point of view. "The foundation of which this tool is constructed derives from the uncovering of a test of what makes a system viable – and therefore, able to successfully perform a function." A minimum of two substances (or "things") and a field are required (Mann, 2007a, pp.245-255). ("Things" can also be understood to be concepts.) TRIZ provides a definitive list of such fields. (Refer to *list of fields* in Mann, 2002, pp.248, 249.) The lines connecting the things represent the type of interaction taking place between the different pairs of things. The types of interactions could be classified as follows:

- Effective
- Missing
- Insufficient
- Excessive
- Harmful

Apart from a special class of measurement problems, all the inventive standards used in analysing a particular form of a S-Field model fall into four types. These are:

- Solve the problem by completing an incomplete S-Field model;
- solve the problem by modifying one or more of the existing substances or fields;
- Solve the problem by adding new substances, fields or combinations thereof; or
- solve the problem by transitioning it to a higher or lower hierarchical level.

(Mann, 2002, p.246.)

(iii) Function and attribute analysis

Part of the TRIZ system of innovative problem-solving involves function and attribute analysis. It recognises the importance of function and functionality in the design of systems. In TRIZ this is regarded as one of the three essential elements of the problem-definition process. Function and attribute analysis, in summary, involves the following (Mann, 2002, p.101):

- Identification of components within a system.
- The definition of the functional relationships that exist between each pair of components.

- Identify the attributes of system components.
- Recognition of relationships occurring between components and their attributes.
- Recognise time-based elements of the problem and how a functional model behaves over time.
- Recognise space-related interactions.
- Recognise the interface between systems (interaction with the bigger picture).

When considering the time element, TRIZ makes use the so-called "nine-windows" model. The model is best illustrated by a matrix, as shown in **Figure 5.1**.

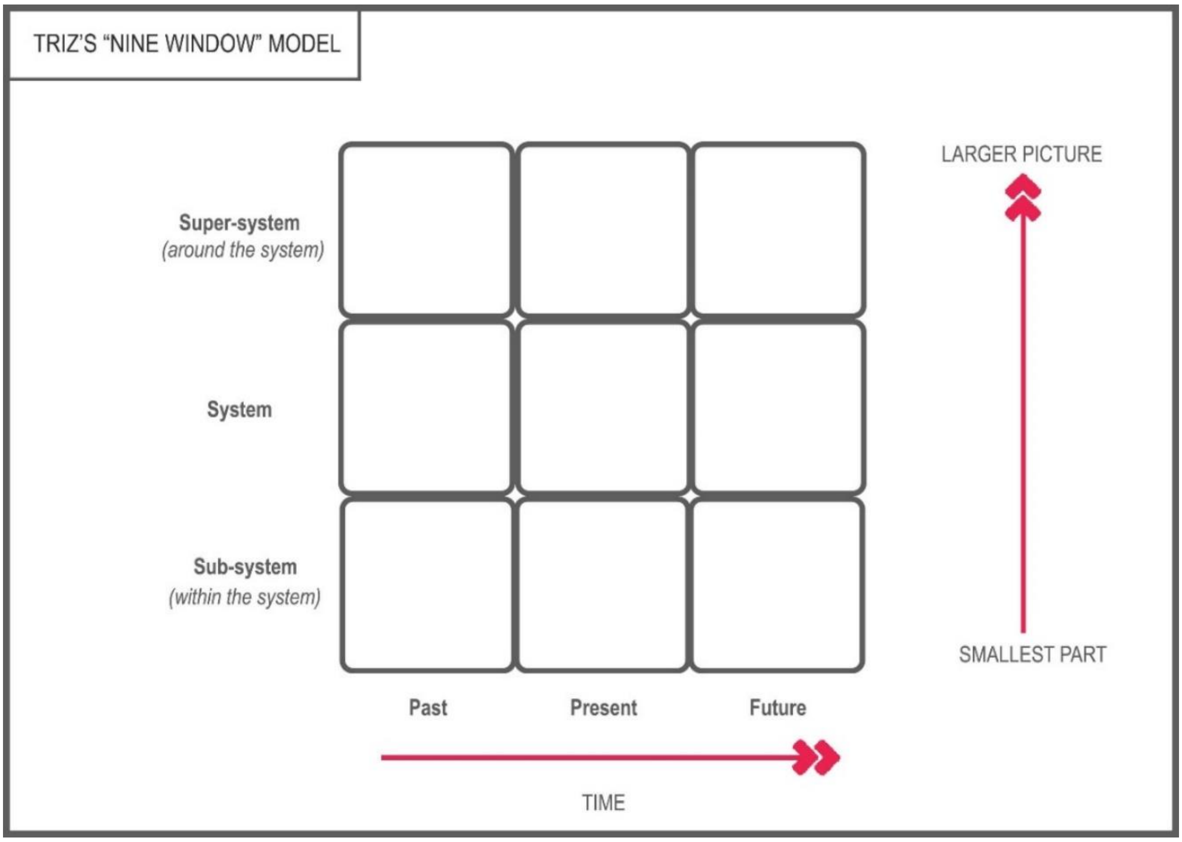

Figure 5.1 TRIZ's "nine windows" model

The system's response is tested in each of the nine windows. Each block in the figure represents a different combination of the system and time elements. When considering the system's responses to each block, problems and constraints can be identified.

To analyse a particular system, the following should be done to all the functional relationships in the system (Mann, 2007b, p.107).

i) Start by recording all of the present functions. (For example, adding cement to a concrete mix.)

ii) Ask the question, “Would I like more of this function?”

iii) “Would I like less of this function?”

In following the above process, one identifies both positive and negative relationships. One does something positive, but it also might have negative effects or consequences. For example, if one adds more cement to the concrete mix, the strength may increase (positive relationship), but to keep on adding more and more cement, increases the cost of the concrete mix as a negative consequence.

The qualities of relationships (or interactions) are of importance. TRIZ refer to these as “types” of relationships. In this study reference is made to both the types and qualities of relationships. For example, referring to paragraph (c) above, “effective” can have particular levels of effectiveness. A relationship can be graded as ineffective, reasonably effective and highly effective. The same holds for harmful relationships. Other relationships, however, clearly can only exist or not, such as “missing” and “sufficient”.

Often functional relationships occur between components and attributes rather than component and component. “The user needs to be able to connect functional relationships either from or to any combination of components and attributes. As such, the method is intended to not only provide more flexibility of operation but also to allow fundamentally better access to problem root causes” (Mann, 2002, p.102). Functional and Attribute Analysis (FAA) also advocates modelling regarding space, time and interface issues. Functional diagrams are drawn hierarchically, starting with the “Main Useful Function” (MUF) at the top, and lower down, the lower, subordinate functions that serve the MUF.

Where complex systems are analysed, it could be very difficult to keep track of the pairs of components that have been analysed. For ease of analysis, a relationship matrix is compiled with the attributes/components listed on the horizontal and vertical axes. The pairing of relationships is also entered in the cells of the matrix. This is illustrated in **Table 5.2**.

Table 5.2 Relationship matrix

From / to	Component A	Component B	Component C	Component D
Component A	**X**	**X**	**X**	**X**
Component B	*supports*	**X**	**X**	**X**
Component C	*links to*	*moves*	**X**	**X**
Component D	**X**	**X**	*heats up*	**X**

In **Table 5.2**, the X's indicate that there is no relationship between the pairs, for example, component B and component C have no relationship. However, components B and A have a relationship, where component B supports component A.

TRIZ focuses on the identification of contradictions between relationships and the resolution of these, using inventive solutions. Considerations are given to both the things (substances) and the fields between them.

5.3 The Theory of Constraints (TOC)

The main purpose of TOC is to improve the functioning of a system to achieve particular goals. This is done through the identification of constraints in a system and taking appropriate actions to improve its performance. For example, if the goal is to improve profits, it can be achieved by increasing throughput, reducing inventory and operating expenses. TOC developed strategies to manage and achieve systems' goals. The first step in TOC is to identify the system constraints. This process of identifying system constraints and dealing with it is also of particular interest in this study. One of the ways to identify system constraints is to identify key system components or entities, as well as all the relationships between them. (In this study, the term "entity" is regarded as having the same meaning as concepts.) Entities are described as single elements of a system and are expressed by complete statements. TOC studies the relationships between entities by employing so-called, “sufficient-cause diagrams”. (This is different from the cause and effect diagrams of the so-called Ishikawa or fishbone diagrams that are popular for diagnosing production problems.) The TOC defines the term “sufficient-cause diagram method” which is used to map out the entities and their relationships to enable understanding of assumptions underlying the relationships. TOC critically questions the existence of entities, challenges possible assumptions in the cause-and-effect relationships and critically tests the participation of entities in producing certain causes and effects.

a) Sufficient cause

Sufficient cause is defined as the thinking process whereby one simply assumes that something exists because something else exists, i.e., something is the inevitable result of the mere existence of something else. Sufficient-cause studies require thinking processes which are aptly described by Scheinkopf (1999, p.32) by the following: “When you are speculating causes for effects, or effects of causes, you are actively using sufficient cause thinking. The TOC Thinking Processes add a twist, by challenging us to ask *why*? *Why* do we believe that something causes something else? *Why* do we believe that an effect is caused by that which we believe causes it?” TOC also asks the question, “Why?” The question really is, *why* does one believe that something causes something else, or *why* does one believe that the effect is caused by that which we believe causes it? One may also ask the question, “what?” to test hypothesised assumptions. For example, *what* if an entity exists, would force one to believe that this or that, or the other statement or condition are in fact inevitable or true?”

b) Legitimate reservation: Level 1 reservations

Legitimate reservation is essentially a method to check if the cause-and-effect relationship is in fact valid. Any claim of cause and effect should be able to pass three tests:

- “Verification of what we say exists does exist” (entity existence).
- “Validation of the relationships between causes and their effects” (causality existence).
- “Agreement that what we say reflects what we mean to the people we are attempting to communicate with including ourselves” (clarity).

(Scheinkopf, 1999, p.48.)

Scheinkopf (1999, p.32) remarks that "The TOC Thinking Processes provide a methodology for testing our claims with a set of tools called 'Categories of Legitimate Reservation (CLR)'. These tools blend the scientific method with the powerful intuition we gain through our life experiences to provide easier, yet systematic approach to uncover, verbalize, challenge and replace our assumptions while using sufficient cause thinking." This reflects on the role that tacit knowledge plays in the analysis relationships and in resolving problems.

c) Legitimate reservation: Level 2 reservations

Three further questions are asked if any of the preceding Level 1 reservations remain unanswered. These are:

Additional causes. This asks one to "further examine causality existence by looking for additional independent causes for a given effect" (has this effect got only one possible cause?).

Cause insufficiency. This "examines causality existence by looking for missing dependent elements of a cause" (must anything else exist in conjunction with the speculated cause for the effect to exist?).

Predicted effect is used to examine either causality or entity existence by considering effect-cause-effect methods" (for a given effect, speculate its cause).

(Scheinkopf, 1999, pp.45-53.)

d) Necessary-condition thinking

Necessary-condition thinking is a thought pattern when one thinks in terms of requirements. Something must exist or be allowed to exist before one can achieve something else. "The terms such as *must*, *must not*, *cannot*, *need* and *have* are indicators of necessary-condition thinking. Necessary conditions are rules, policies, or laws that provide the limitations or boundaries within which we believe we are allowed to pursue goals and objectives."

When one sees any necessary condition as a constraint, one can do three things to change:

- "Diagram the necessary condition relationship
- Surface the underlying assumptions
- Brainstorm alternatives."

(Scheinkopf, 1999, pp.69,71.)

When one finds it difficult to come up with alternatives, one can use other problem-solving methods such as analogies relating to experience from other fields, which can inform thinking processes.

e) Current-reality tree

This is a methodology followed by the TOC to establish core causes in complex systems. The term “core cause” is defined as a common cause of many different effects. The current-reality tree is a method used to pinpoint the core cause(s). The following six major steps are used in the analysis:

- “Determine the scope of the analysis.” (In a complex system, one should limit the scope by considering various key elements and by involving supporting disciplines.)
- “List between 5 and 10 pertinent entities.”
- “Diagram the effect-cause-effect relationships that exist among the pertinent entities.”
- “Review and revise for clarity and completeness.”
- “Apply the ‘So what’- test.”
- “Identify the core cause(s).”

(Scheinkopf, 1999, pp.143-144.)

f) Evaporating clouds

This is said to be the most often used thinking processes in TOC. The tool called the evaporating cloud is used for conflict resolution. Scheinkopf (1999, p.171) remarked that “I have not found a problem yet that cannot be described as a conflict, in the form of an evaporating cloud. Further, I have not found a problem yet that is impossible to solve.” The cause-effect diagram in **Figure 5.2** explains the thinking:

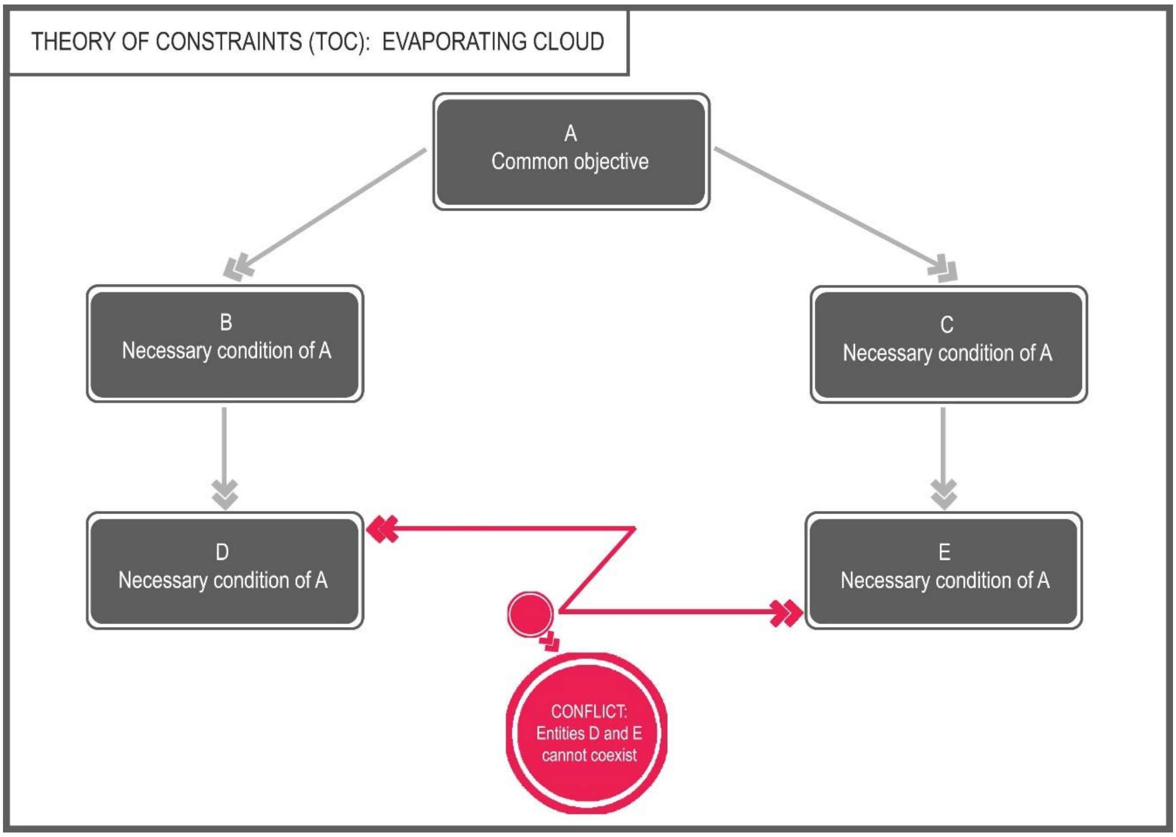

Figure 5.2 Theory of Constraints (TOC): Evaporating cloud

(Adapted from: Scheinkopf, 1999, p.172).

From **Figure 5.2,** the essence is that there are conflicting entities D and E in the sense that they cannot coexist. Both are necessary conditions for entities B and C respectively, and necessary for the common objective to exist. “Once a way is found to invalidate just one of these relationships, the conflict is resolved, and the cloud is evaporated” (Scheinkopf, 1999, p.172). The following questions can be applied to surface assumptions:

- Why can the entities not coexist?
- Why is there any overlap between entities?
- Are the entities mutually exclusive?
- Is the assumption that is being analysed, part of the conflict’s system (situation)?
- Is the assumption valid in the conflict’s system?

Provision of a detailed exposition of TOC is not intended in this study. The main purpose of considering some of the aspects of the TOC is to obtain insight into the current practice of problem-solving and to research methods for incorporating into the logic base for the enhancement of engineering knowledge.

The resolution of conflict in TOC compares well with that of resolution of contradictions in TRIZ. Standard solutions are provided by TRIZ to resolve contradictions emanating from research on a large number of patents. The contradiction matrices for technical and for business solutions (Mann, 2002 and 2007b; respectively) serve as valuable guides for users to arrive at solutions. TOC leaves the resolution of conflict to each user. By following TOC's suggested methodologies as outlined above, users should be able to identify the most significant conflicts and find methods to resolve such conflicts.

In order to understand the differences between TRIZ and TOC, **Table 5.3** is compiled as a summary:

Table 5.3 Comparison between TRIZ- and TOC-techniques

Comparative feature	**Description of feature**
Cause-effect.	• An effect exists because one or more things caused it to exist. • Common to both TRIZ and TOC.
Entity existence.	• Questions the very existence of the entity itself. • Common to both TRIZ and TOC.
Causality existence.	• Questions the existence of a cause-effect relationship. • Common to both TRIZ and TOC.
Additional cause.	• Questions if the hypothesised cause is the only cause for the resulting effect. • Common to both TRIZ and TOC.
Insufficient cause.	• The question is: is there something else that must exist in conjunction with the speculated cause for the effect to exist as a result? TOC covers this, TRIZ also, regarding its consideration of S-Fields. • Does that 'something' exist in the reality of the system or situation one is examining?

Comparative feature	Description of feature
Predicted effect.	• This is common to both TRIZ and TOC. In TOC, an entity (cause) is injected to drive a certain effect. In both TRIZ and TOC insufficient causes suggest the addition of causes to deliver the desired effect.
Necessary-condition thinking.	• TRIZ refers to completing incomplete S-fields.
	• TOC analysis effect-cause-effect relationships with some relationships as necessary conditions.
Undesired effects or consequences.	• TRIZ refers to harmful relationships.
	• TOC covers undesirable effects in current and future reality trees.
Future reality.	• TRIZ covers this with the "nine-windows" approach and with the ideal final result concept
	• TOC defines future reality with the concept of "to what to change".
Injection.	• TRIZ solves problems in S-Fields by adding new substances, fields or combinations thereof to improve the functioning of a system.
	• In TOC, these are entities (ideas) that do not exist in the current reality. Once an idea is injected (a new cause), the predicted effects should emerge as a result.
Add reinforcing loops.	• TRIZ deals with loops in perception mapping.
	• In TOC's future reality trees, it defines the key means by which the system will sustain itself in ways that it will keep getting better.
Process to do improvements.	• TRIZ's approach is to identify contradictions and to use standard solutions as guidelines to find innovative solutions.
	• TOC drive is virtually the same through the "evaporating cloud" and cause-and-effect mapping to resolve constraints.
Contradictions.	• TRIZ deals with contradictions and suggest standard solutions.
	• TOC refers to the process of conflict resolution through the method of the evaporating cloud.

The comparative features stated in the first column of **Table 5.3** are taken from TOC.

The purpose of the two methods is virtually the same, with TOCs focusing on process improvements and TRIZ on inventive problem-solving.

5.4 Diagnostics

A useful addition to the discussion on cause-and-effects is found in the field of diagnostics. Diagnostics is a study or investigation of any system to establish reasons why a system does not perform satisfactorily. Troubleshooters track down faults on equipment and physicians diagnose a patient’s condition to prescribe a treatment. Scientists seek for causes to determine how one variable affects another. “Practically speaking, a cause is whatever is responsible for some or produces some effect. A single cause can have multiple effects” (Smith, 1998, p.98). An important aspect of causes and effects are the conditions. A condition is an enablement needed for the effect to occur. Smith (1998, p.99) identifies a number of types of causes:

a) **Generative causality**. This refers to the most common daily affairs. An example would be that, “The nail caused a flat tire”.

b) **Purposive causality** points to the goal or purpose of an action. An example would be that, “Joe stayed at work because he wanted to finish the report”.

c) **Functional causality** is used in science and refers to an explanatory law or principle such as “The period of a pendulum is a function of its length”.

d) **Precipitating causes.** This “is the factor that sets of an effect”. These are usually close to their effects, physically or temporally.

e) **Underlying causes.** These are more remotely responsible for the effect’s occurrence.

f) **Root causes.** These are defined as “the most basic reason for an undesirable condition or problem which, if eliminated or corrected, would have prevented it from existing or occurring”.

g) **Common causes.** Normal variation is attributed to normal causes and usually have insignificant effects.

h) **Special cause.** These causes must be identified and corrected as these may have significant effects.

An important part of diagnostics is the generation of hypotheses. The primary source for the generation of hypotheses is "experiential knowledge" (Smith, 1998, p.103). Experts may simply recognise what is going on and the cause comes to mind by association with observes symptoms. Depending on how strong a hypothesis is supported by evidence and experience one may decide to test the hypothesis. Hypotheses testing involves producing new information bearing on the validity of the hypothesis. Experimentation is the classic way of testing hypotheses. Hypotheses testing can also be done by comparing how a system works under different conditions.

5.5 Types of relationships

A specific case study comprises a selection of concepts. The identification of concepts will depend on the goal and perspective of the person analysing the case. Furthermore, it would also depend upon the reason or purpose for analysing a case. Once a concept map has been drawn up, one needs to study all the important relationships between concepts/components, their attributes and values. Every relationship reveals some additional knowledge, not necessarily only causes and effects. Apart from the relationships that appeared in the literature about TRIZ, TOC and diagnostics, the following summaryare given and additional relationships are added as indicated in **Table 5.4**.

Table 5.4 Types of relationships

Description of relationship types	Description of relationship	Comments
Cause-effect	Effective/missing /inefficient/ excessive/harmful.	Useful for interpretation of system components and the functioning of a system.
Part of/belongs to	Component-attribute relationships.	These are crucial for a complete understanding of system's operations.

Description of relationship types	Description of relationship	Comments
Leads to	Could, should or will always.	Describes variables and uncertainties in the operation of a system.
Follows on / after	One element follows after the other or is preceded by.	Could also be represented by precedence networks such as PERT (Programme Evaluation Review Technique).
Associated with	Represents indirect relationships.	Provides cues for knowledge of other systems.
And	Self-explanatory.	
Or	Self-explanatory.	
Both required	Self-explanatory.	
If-then	Conditional relationships.	Provides alternative solutions to system's functions.
Means-end	Provides more information about a system.	This suggests something about resources to achieve certain results.
Temporal	Time-dependent relationships.	Time variables can change system components and functioning.
Influences	This relates to external factors that have a direct or indirect bearing on the system's functions.	This considers the systems performance with respect to changes in the external environment.
Coupled/uncoupled /connected/independent /dependent	This relates to terms used in axiomatic design where design elements relate to each other and design relates to system's performance.	When making changes to any system, dependencies must be taken into account to be able to evaluate outcomes of system performance.
Operating on/performing an action on or with something.	Something to be done to, with or on something.	Such as mixing the concrete, installing a piece of steel or holding a hammer.
Impact on	When something happens or changes, it has a knock-on effect on other elements.	A change in design during construction can have a

Description of relationship types	Description of relationship	Comments
		serious impact on progress and costs.
Coordinate	Interfaces between elements in a system need to be carefully considered and managed.	Synchronising of functions and activities is always required for proper functioning of a system.
Communicate and translate	When information needs to be passed on to someone else, not only must the information be appropriately communicated, but the receiver of the information must interpret the information and translate it into appropriate actions.	An example could be when a design change is required and communicated to a building contractor. The design change must be integrated (translated) into the building construction techniques and methods as applied by the contractor. This may, in turn, initiate further changes or initiate unwanted impacts on the construction schedule and costs.
Necessary condition	One entity is linked to another in such a way that one entity cannot exist without the other being present.	An example is that a machine cannot function unless energy is supplied. The function of the machine is conditional to a source of energy being connected and supplying energy to the machine.
If/when – What relationship	The argument is when or if something is needed, what is needed or must be done to support to satisfy the if or when.	An example is that, if or when environmental approval is required, a detailed ecological assessment (“what”) needs to be done.
Associations	When external references are made.	Reference to a library file pertaining to an item.
Discrete	Exact mathematical.	Mathematical formulae describe relationships to very high degrees of accuracy.

Description of relationship types	Description of relationship	Comments
		Only insignificant terms of lower orders are ignored.
Empirical	Relationships are derived from observations.	Relationships are the result of field observations and studies.
Correlations	Statistical correlation, such as derived from regression analysis.	Correlations between parameters with particular correlation coefficients.

When analysing case studies, knowledge can best be obtained and enhanced by application of further analysis of the contents. Perception mapping and analysis provide the means to analyse any case study. The provision of HLOs serves as templates for prompting a user for knowledge in various areas. There may be certain concepts or elements in a system that are problematic in themselves. TOC could then identify weaknesses and would argue for the elimination of weak elements and changes in the system design to suit.

5.6 Synthesis of relationships

The foregoing sections dealt with relationships as found in the techniques applied by TRIZ, TOC and diagnostics.

Each of the techniques aims to improve systems or to provide innovative solutions to system problems. The approaches are somewhat different for each. However, there are also much in common. To design the functioning of a logic base, it is considered expedient to do a selection of techniques from the available technologies and develop it to suit the purposes of the logic base.

a) Concept existence

This should be tested by the following:

- Validity of the concept

- Coexistence
- Overlap
- Mutual exclusivity
- More of something?
- Less of something?
- Is there sufficient cause?
- Can the effects be predicted?

Test by asking if one would like more of it or less of it.

b) Assumptions must be uncovered and challenged:

- Participation of assumption in conflict relationship.
- Validity and applicability of assumptions.

c) Relationships can be of different types:

- Determine the type of relationship.
- Does it have a positive result?
- Does it have a negative result?
- Determine the validity of the relationship.
- Determine the quality and grade of the relationships.

(Compliant, effective, missing, insufficient, excessive or harmful)

In all the above, determine the system's response to time, space, capacity and interfaces with other systems (sub-systems and larger systems). In addition, the effects of the influencing domains must the considered.

One has to guard against over-complication of the study of relationships. In this study it is intended to be a means of simulating a pattern of thinking and which supports an ontology rather than to enter into a detailed analysis process. If such a process is required, however, the methodologies are available to do so.

5.7 TECHNICAL ONTOLOGY

5.7.1 Ontology structure

The definition and types of concepts used thus far in this study were wide and without any restrictions. The types of concept statements can be:

a) Entities
b) Objects
c) Aspects
d) Items
e) Actions
f) Considerations
g) Applications
h) Realisations
i) Components
j) Matters to be taken into account

When analysing case studies or when doing any design and analysis, it is important to phrase the concept statements to reveal the correct relationships.

Engineering cases often have a discipline-analytical content and concept statements contain discipline-specific content. Knowledge representation can be augmented by structuring technical ontologies. In the following section a conceptual design of a Technical Ontology (TO) is illustrated. (This requires further research and is not fully investigated and expanded in this study.) In the engineering environment, both qualitative and quantitative elements need to be considered. The TO provides a means to cater for the analysis of both. The TO can hierarchically be at the same level as the CSO, or alternatively, be at a lower level. The TO is primarily designed to cater for concepts that have qualitative relationships and the functional analysis (that will be dealt with later) deal with the quantitative relationships (but not limited to).

When dealing with science and technology, in particular with engineering, concepts reflecting the knowledge domains in physics can be used as a basis for the design of ontologies. Each field of engineering has its own (in some cases overlapping) knowledge domains. The same holds for the various disciplines in each engineering field that also have their own knowledge domains.

One possible approach is to argue that all engineering is primarily based on natural sciences and physical sciences. However, other sciences such as financial and legal sciences are also involved. Each field of engineering comprises a particular selection of concepts that belong to natural and physical domains. In each engineering field, such as civil, mining engineering, mechanical, electrical, etc., there are several disciplines and sub-disciplines. For example, main sub-disciplines in civil engineering are structural, geotechnical, water, transportation, mining engineering, etc. Each sub-discipline has further sub-disciplines (sub-sub-disciplines in terms of civil engineering). By way of example, such sub-disciplines are for structural engineering, high-rise buildings, bridges, industrial structures, etc. For geotechnical engineering, sub-discipline can be earth structures, tailings storage facilities, road pavements, etc. For transportation, sub-disciplines could be airports, highways, railways, etc. These sub-disciplines can be further sub-divided to structure a taxonomy of concepts that can cover all aspects of civil engineering (and for all the engineering fields).

However, the purpose of the Technical Ontology (TO) is to consider relationships and to solve problems. All the engineering-analytical studies eventually reduce to technical elements or parameters that have specific relationships. For example, in **structural engineering**, the following taxonomy can apply:

Industrial structures >> steel structures >> beams and columns >> loading conditions >> stresses in members. The stresses in the members are concepts and termed “elements” that can only be specified further by particular attributes (such as tensile stress) and values (say, e.g., an applied force of 200kN).

In **geotechnical engineering** the following taxonomy can apply:

Retaining structure >> soil backfill >> effective stress >> lateral earth pressure. The lateral earth pressure is a concept or element that can have attributes (active or passive pressure) and value (say active pressure equals 400kPa).

In **transportation** the taxonomy could be:

Roads >> geometry >> vertical curve >> curvature. The vertical curvature is an element that can be specified by a coefficient, “k”, that defines the curvature that has attributes for crest vertical curves and for sag vertical curves with corresponding values.

In each example there are several concepts that interact and play important roles in the determination of the attribute values. In the example of the road curvature, the curve must satisfy criteria for safety, comfort, appearance, drainage conditions as well as criteria regarding the design speed. (These concepts are mainly of a quantitative nature, but do contain qualitative concepts, such as the "appearance, comfort and drainage conditions".) An ontology can be designed to incorporate all the concepts that have a direct bearing on the values of the attributes. Furthermore, the Technical Ontology (TO) does not stand on its own, but is part of the same Top-Level Ontology (TLO) as already described before. That means that the opportunity exists to study the relationships between concepts and technical elements of both a qualitative and quantitative nature in the TO and tie these concepts to the CSO, HLOs, and TLO.

The conceptual design of the overall ontology is depicted in Figure 5.3.

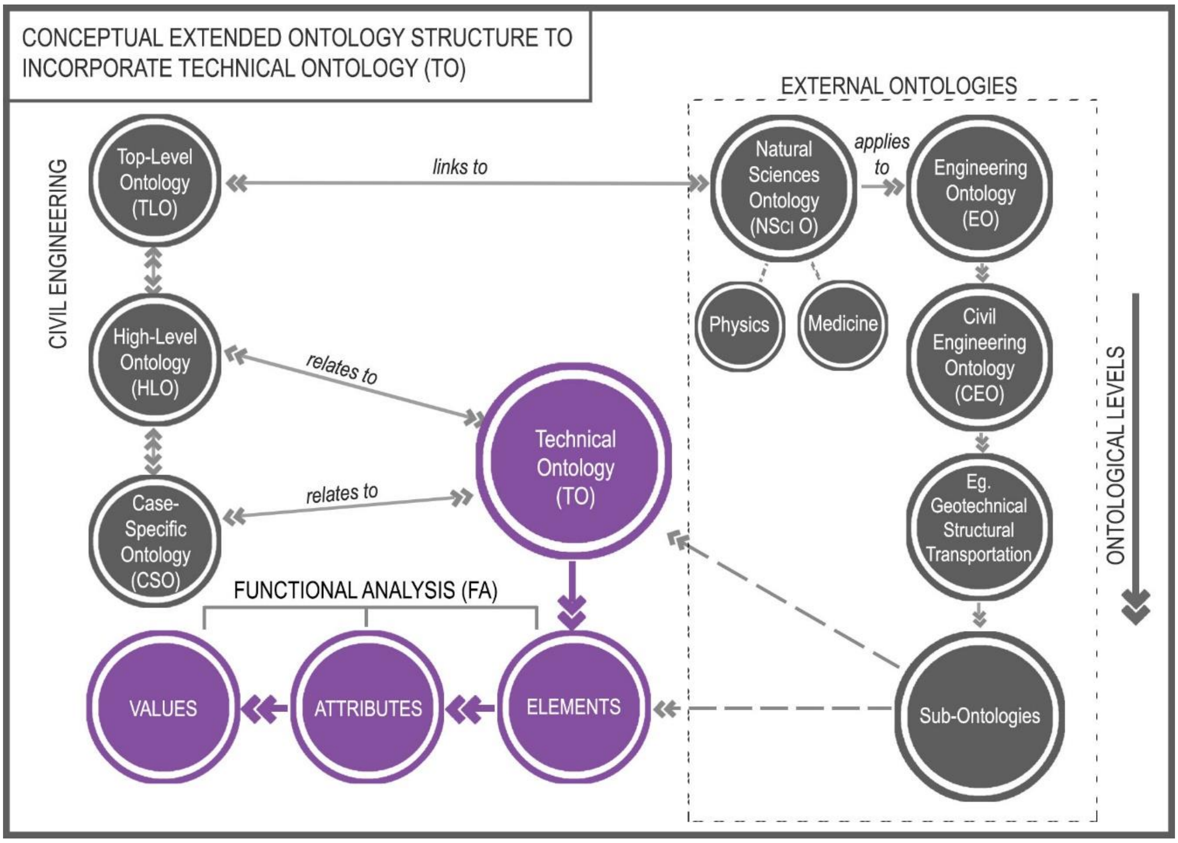

Figure 5.3 Structure to incorporate the Technical Ontology (TO)

The dark-circled concepts indicated in **Figure 5.3** are of immediate importance in this study and are used when conducting Functional Requirement (FR) analysis.

5.7.2 Technical relationships

In the technical environment when relationships between technical parameters or concepts are studied, the "technical" relationships are mostly of the following types: (Mostly computational or quantitative, but not limited to these as qualitative relationships may also play a role.)

a) Discrete mathematical relationships
b) Empirically derived relationships
c) Statistically derived correlations to some degree of accuracy or confidence
d) Logic relationships (and, if, or, and conditional relationships)

In engineering case studies, especially when empirical or statistical studies are done, particular elements, their attributes, values and relationships are often reported. Concepts can be compiled in concept maps as before. The relationships between the concepts can follow any of the four types listed above. At the sub-concepts and element levels, the relationships will be represented mainly in computational format by way of by expressions, equations and formulae, or by way of some or another rule. A very simple example of a discrete relationship or equation is:

Element A (Volume) = Element B (Area) x Element C (height)

Or, that Element C (height) = Element A (Volume) / Element B (Area).

The individual concepts in the Discipline Ontology (DO) can be paired with concepts at the same hierarchical level. This pairing is probably most productive at the discipline-concept level (such as structural, geotechnical, water, etc.), but mainly within the same discipline. However, cross-discipline and cross-engineering fields may also be important. (This is evidenced in practice when electrical engineers do not take structural loading into account when specifying an upgrade of motor size in an industrial plant. The upgraded motor can be much heavier than the original with the result that the permissible structural load is exceeded.)

For instance, in the ontology for structures, the relationship between the elements "stress" and "corrosion" are empirically related. As stated by Kearsley and Joyce (2014, p.29) "Severe corrosion may lead to reductions in the load-carrying capacity of structural members." This finding was the result of experimental work and was reported in a case study.

Another example is in geotechnical engineering. If one pairs concepts such as “loading” with “compressibility”, the result is that loading will induce compression and settlement. Mathematical expressions are available with empirically derived coefficients to calculate the amounts and rates of compression or settlement.

In engineering, it is crucial to:

- Recognise all the comprising concepts and elements, i.e., that “volume” comprises two concepts; “area” and “height”. In some complex engineering situations, there can be many concepts that form part of the equation (refer to a collection of technical formulae; Gieck and Gieck, 1990). The identification of relationships can be done by pairing relationships in the sub-discipline ontologies and across engineering fields. The pairing has to be between technical concepts, elements and the non-technical concepts.

- Recognise that there is a direct multiplication operation that connects *area* and *height* to yield *volume*, or that there is an inverse relationship between *height* and *area*, i.e., as the value of *area* increases, the *height* will decrease if the *volume* stays constant. Some of the relationships or expressions can become very complex with many elements and many mathematical or statistical operators. Multi-dimensional graphs depicting the relationships between the elements, are often compiled to enable the determination of values. Numerical modelling and simulations are most often used to determine the performance of systems.

- Recognise that some relationships have boundary conditions and limitations where relationships cease to exist or become unclear.

- Recognise that some relationships are case-specific and therefore circumstance-specific and cannot be generalised for universal application.

- Recognise that both quantitiatve and qualitative relationships may exist.

The above technical concepts or elements form part of appropriate HLOs or of a CSO. The concepts are often related to “external” concepts. For example, the element “area” can be related to the HLO of “scope” where the area of a facility is limited to particular dimensions or where the *height* or *depth* dimension can change over time. The elements cannot be seen in isolation. In civil engineering, for example in community projects, much of what is done is influenced by community requirements that are mainly qualitative in nature (Anon., 2012d).

There are instances in civil engineering where many concepts that influence the performance of a system. The concepts comprising the system all contribute in a direct or indirect way to the performance of the system. An example is the performance of a road pavement. Sub-concepts contributing to the performance of the road (say amount of surface cracking on an asphalt road) may comprise the following elements:

- The traffic loading
- Depth of constructed pavement structure
- The densities of the pavement layers
- Shear strength of subgrade material
- Fatigue resistance of subgrade materials
- Thickness of individual layers in the road pavement
- Shear strength of each pavement layer
- Stress-strain properties of each pavement layer
- Fatigue resistance of each pavement layer
- The width of pavement layers
- The moisture regimes in each pavement layer
- Drainage conditions of the road formation
- Drainage conditions of the road surface
- Creep resistance of each pavement layer
- The stability of the asphalt layer
- The void ratio of the asphalt layer
- Bitumen type and content in asphalt layer
- The grading and types of aggregate in asphalt layer
- The amount of stabilising agent in sub-base course

The above list of sub-concepts is not exhaustive. However, all the above elements contribute, to more or lesser degrees, to the performance of the road and not all the elements are quantitatively interrelated. (Reference is also made to Chapter 10 of the *South African Pavement Engineering Manual,* 2014.)

The above elements can be put in a TO sub-concept ontology; say, “Road pavement riding quality” ontology that links to the HLOs of *Design and of Construction* or to concepts in the generic ULO.

5.7.3 Functional Requirements (FRs)

The TO and its sub-ontologies eventually lead to elements, their attributes and values, i.e., the specification of participating elements in a system. These participating elements determine the performance of a system. The incorrect specification of elements, for example, the value of an attribute can cause an entire system to fail. For example, if the sizes and positions of reinforcing bars in a reinforced concrete structure are incorrectly specified, an otherwise well-designed structure may collapse. As an aid to specifications, functional relationships can be studied and used. The suggested formats to follow are the Element (Object)-Attribute-Value or Function-Behaviour-State (refer to Chapter 4).

In civil engineering, the proper performance of facilities, such as roads, bridges, structures, pipelines, canals, traffic flow, etc. constitute the end goal. Part of engineering knowledge is to understand what concepts and elements are part of, and contribute to the performance of a facility, and what the performance requirements are. This can be done by conducting a functional-relationship analysis whereby the performance goals of a whole system are defined (specified), as well as the performance goals (specifications) of contributing elements. This has to be done in conjunction with the other analysis techniques in the logic base. The performance goals can be defined as the “Demand” and the elements, behaviour (or characteristics) and status or values as the “Supply”. The system’s performance is expressed as the Main Useful Function (MUF). In order to achieve the MUF, several sub-demands may contribute to meeting the MUF. These sub-demands are referred to as the Upper-Level Functional Requirements (ULFRs). There can be second, sub-ordinate levels of FRs, referred to as the Lower-Level Functional Requirements (LLFRs). FRs constitute specifications of the participating elements. Each LLFR contribute to an associated ULFR. This can be expressed conceptually as follows:

MUF = proportional to the contribution of the ULFR or “Demands”.

ULFR = proportional to the contributions of (LLFR1, LLFR2, LLFR3 etc., ... LLFRn).

The ULFR can be defined as the dependent variable and each LLFR as independent variables or “supply”. In the above example, the element “Volume”, represents a dependent variable or a MUF (or ULFR). The value of "Volume" will be determined by the "supply" or independent variables, "Area" and "Height", which are the LLFRs. These LLFRs, in this example are quantitatively related by multiplication. If by "external" circumstances, such as the height of a container is limited to a specific dimension or by a handling issue, qualitative concepts (expressed as LLFRs) start to play a role in the determination of the ULFR of "Volume". Qualitative concepts can be accommodated in a TO, whilst the quantitative concepts can best be placed into the FA.

As mentioned before, there are often no clear relationship between some of the concepts. It is not required that any mathematical, empirical, statistical or logic relationship exists between the concepts and/or elements for which specifications are given.

Many case studies are limited to the investigation of relationships among various elements or only some of the elements.

In the following section the technique of Functional Relationship analysis is discussed.

5.7.4 Functional analysis technique

In the following sections, reference is made to Mann (2007a); Scheinkopf (1999) and Suh (2001) and adapted for use in this study.

In this study, the term Upper-Level Functional Requirements (ULFRs) refers to the Main Useful Function (MUF), or ultimate goal, or demand of a design or systems performance. The sub-goals are referred to as Lower-Level Functional Requirements (LLFRs). The sum of the contributions of the LLFR cumulates to satisfy the ULFR. This is best illustrated by way of the examples below:

An example can be the fatigue life of any structural element which is dependent on the stress range and the corresponding number of stress cycles taking place within that stress range. Fatigue life or fatigue resistance can represent the main useful function (MUF) or the ***Upper-Level Functional Requirement*** **ULFR** (if there is only one ULFR). The ULFR is also referred to as the *demand* that must be met. This demand can further state that the material (steel) must withstand particular maximum levels of stress (**Lower-Level Functional Requirement LLFR**), as well as withstanding a certain number of repetitive stress cycles (a further Lower-Level Functional Requirement LLFR). There are therefore two LLFRs. These LLFRs are then referred to as LLFR1 and LLFR2. Each Functional Requirement (FR) contributes to the ULFR and either has a specified value or must be within a particular range of values to be able to meet the ULFR. When looking at how the FR or demand will be met, one can consider the contributions of the various components.

As another example, consider a bolted connection between a steel beam and a column. The components are typically the fixing brackets with holes drilled through them as well as a number of bolts and nuts to secure the elements. If the connection is meant to be a pinned connection, the MUF is to transfer forces without developing any bending moment. If there is only one ULFR, the MUF and the ULFR are the same. The ULFR can be met if a two-bolt connection, configured to be, for example, in a horizontal line is supplied. This represents a single LLFR (LLFR1). If a second LLFR (LLFR2) is added by installing friction-grip bolts, the ULFR will be met by a combination of shear stress in the bolts as well as by friction between the two mating surfaces. Thus, both LLFR1 and LLFR2 will contribute to achieve the value (or demand) of the ULFR. If, in addition, moments must be transferred, the MUF will now be to transfer shear forces and moments. A new ULFR is then added. The first being ULFR1 for shear forces and the second, ULFR2 for bending moments. These ULFRs represent the “demands” and both need to be fully satisfied to meet the MUF. In this example, a minimum of four bolts may be required. The following LLFR are of interest:

- The types of bolts.
- The effective diameters of the bolts.
- The geometrical configuration of the bolts.
- The torque applied to the nuts.
- The tolerance of the diameter or the bolt holes.
- The installation procedure.
- The corrosion protection methods and procedures.
- The constructability (for example, is there enough working space to install the botls?).

Each of the above items can be regarded as a LLFR.

There may be a specific relationship between the ULFRs and the LLFRs. In this case the relationship can be called a “necessary condition”. A ULFR may have a design parameter

(DP). This DP may be derived from a structural analysis that determines the conditions or demands that are required at a specific steel connection. Certain LLFRs may have particular limitations, such as limit values laid down by design codes. or DP has a *Function-Behaviour-State* ontology. (Refer to Chapter 4.)

When considering the example of the road pavement, the MUF may be to have road to meet an acceptable standard defined by a useful life and by acceptable maintenance costs. Functional Requirements (demand) may be acceptable surface conditions and riding quality, i.e., two Functional Requirements (ULFRs). When considering how the demands will be met, one has to consider several parameters or elements such as the Atterberg Limits (plasticity index, liquid limits, particle-size distribution and compaction) and the thicknesses of the pavement layers (at least six elements). There may be many more elements. For each of the elements there are usually specific requirements. These are termed Lower-Level Functional Requirements (LLFRs). It is crucially important for civil engineers to consider all the FRs, as well as all the possible elements that may contribute towards meeting the various FRs under different circumstances, such as climatic conditions, changes in traffic, lack of maintenance, etc. The more experienced engineers are, the more confidence they would have that the best choice could be made of the contributing parameters and their values. It must be emphasised that the relationships between all concepts and elements must be studied to ensure that contradictions and constraints are resolved.

As engineers become more experienced and knowledgeable in particular engineering applications, they often make some refinements, corrections or adaptations to the expressions, such as the judicious adjustment of constants contained in equations. When parameters are plotted graphically, adjustments are often made to curves or parts of curves to better suit observed performance. It is therefore considered expedient to have an ontological element where such, expressions, formulae or relationships can reside and be adjusted in accordance with experience. For example, engineers' experience with the application of the fatigue life relationships can then be recorded together with the case studies which led to such experience. (Action research can play a valuable role in this regard.) An example is the application of the well-known "Manning's formula" for water flow in an open channel. The value of Manning's roughness coefficient or "n-value" is subject to interpretation and experience. Manning's formula has other independent variables which are defined as attributes of channel flow. These are the area of the channel, the wetted perimeter and the slope of the channel. The ratio of area to wetted perimeter relates not only to the discharge volume in the channel, but also has, for example, a bearing on the economy and ease of construction. Experience in the application of this relationship and the economy of using different materials and construction techniques provide valuable experience for reuse of such knowledge.

Another technical example is in geotechnical engineering where one wishes, for example, to design a large earth embankment for road construction. The design of the embankment may call for certain FRs. A FR could be that the earth fill must not settle by more than 50mm after construction, otherwise the fill and the structural layers in the pavement structure might crack and loose its useful function (ULFR). Designing for this FR involves a number of parameters, such as, inter alia, the underlying geology where the fill is to be constructed, as well as the settlement and strength elements of the sub-soil. The moisture regime and material characteristics, as well as the strength and mechanisms of collapse settlement need to be known for the earth fill and the underlying materials. To achieve the main useful function or Upper-Level Functional Requirement (ULFR) each element will have its own limits or behavioural characteristics that can be regarded as subordinate Functional Requirements (LLFRs). The cumulative effect of the behaviour of the subordinate (LLFR) elements would yield the required ULFR. In the case of an earth embankment, for instance, the construction rate of the embankment will be determined by the types of foundation soils and its properties (or attributes). For instance, if thick, soft clay layers are present in the underlying soil, the stress-strain properties (the stress-strain or load-void ratio behaviour and the time-settlement curves) will determine the rate at which the fill may safely be constructed.

The experience of engineers in this regard need to be captured, as well as the underlying thought processes. An ontology which depicts the participating elements and their specifications would provide the means to do so. In addition, all the LLFR elements contribute to the ULFR. Where relationships exist between elements, such relationships must be shown.

The proposed format of the FR ontology is as follows:

Table 5.5 Functional Requirement (FR) Matrix

(Generic layout of matrix with generic matrix and two examples)

Main Useful Function (MUF)		
	Upper-Level Functional Requirements (ULFRs)	
LLFR (Generic matrix	**Requirement 1 ULFR1**	**Requirement 2 ULFR2**
Lower-Level Functional Requirements (LLFR)	**Elements, Attributes and Values**	**Elements, Attributes and Values**
LLFR1	Attribute 1	Attribute 1
LLFR2	Attribute 2	Attribute 2
LLFR3	Attribute 3	Attribute 3
Example 1		
Open-channel flow	**Discharge volume (Manning) (ULFR)**	**(No ULFR2 defined in this case)**
LLFR1	Manning's n-value	
LLFR2	Area-/wetted-perimeter ratio	
Example 2		
Earth embankment	**Attribute/state**	**Attribute/state**
	ULFR1: Limited settlement	**ULFR2: Shear strength of fill material**
LLFR1		Thickness of clay layer
LLFR2	e-log P curves	
LLFR3	Time-settlement curves	
LLFR4	Secant modulus	Secant modulus
LLFR5	Stress-strain curves	Stress-strain curves
LLFR6	Collapse settlement curves	
LLFR7	Over-consolidation ratio	

Flexibility should be incorporated in the FR matrix to define each FR and its attributes as the need arises.

5.7.5 Illustrative example – structural engineering

In order to illustrate the foregoing, consider the example of simple steel beam, spanning between two supports. The length of the clear span is directly related to (or is a function of) the loading conditions and the properties (attributes) of the steel member – such as the geometry, the moment of inertia and the stress distribution in the steel section at various points. The MUF will be satisfied if both the requirements for span and load conditions are satisfied. The following ULFRs therefore apply:

- The span of the beam between the supports, representing the ULFR1.
- The superimposed loading, such as the dead and live loads, load directions and variations of loads on the beam form a set of further Upper-Level Functional requirements ULFR2, ULFR3, ULFR4, etc.
- The LLFRs are the various factors and elements that provide structural resistance to meet the ULFRs.

The above represent concepts with relationships between them and shown in **Figure 5.4**. The Technical Ontology leads one to the relationship matrix or FA as shown in **Table 5.6**. The table shows the ULFR represents the user and functional requirements of the beam. LFFRs represents the elements that contribute, through their technical relationships to the overall ULFR.

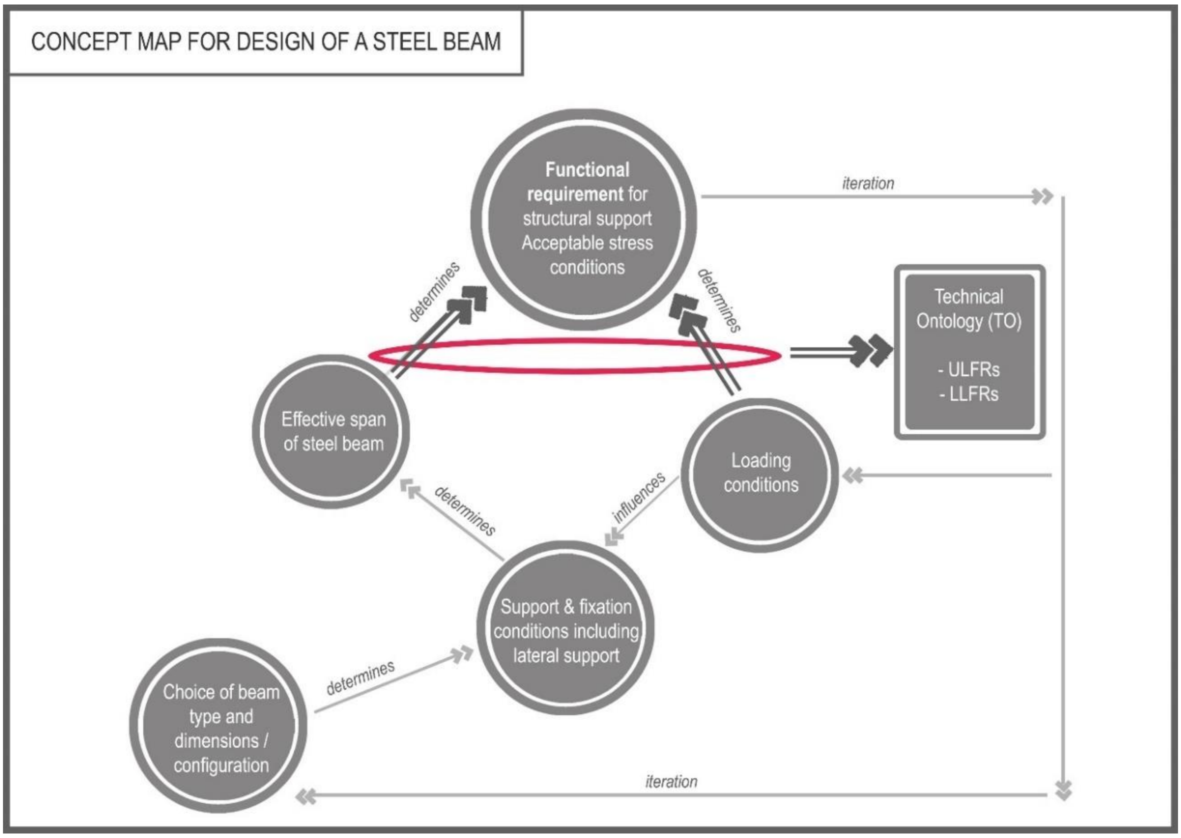

Figure 5.4 CSO Concept map for design of a steel beam

The relationships between the concepts are as indicated in **Figure 5.4.** It should be noted that there can be relationships between elements that are specified in the ULFR, as well as between elements of the ULFR and LLFR. There can also by relationships between elements of the LLFR and their attributes.

Each concept can have sub-concepts, elements, attributes and values, or function, sub-function-behaviour-state ontologies. For example, the element with a specified ULFR “loading condition” can have an element, such as a fixed superimposed point-load with attributes “position” and “direction” and values of the distance from (say) the left-hand side and acting in a vertical direction. These form input information for the design of the beam. The values of “span”, “loading” and “support” conditions as well as “lateral support” are linked by equations to the stress conditions in the beam. Design criteria and code requirements are used to determine if stress conditions are acceptable.

The concept map in **Figure 5.4** does not stand on its own. It represents a CSO and is linked to the HLO for design as indicated in **Figure 4.4**.

When considering the various relationships, a relationship matrix can be compiled as follows:

Table 5.6 Relationship matrix for design of steel beam

MAIN USEFUL FUNCTION (MUF) **A beam that can span the required distance and carry the various loads and meet the ultimate and serviceability limit states requirements.**		
	ULFR1 **Functional Requirement: Load resistance (Stress conditions)**	**ULFR2** **Span of beam**
LLFR	**Element**	**Element**
LLFR1	Effective span	Configuration
LLFR2	Fixation at supports	
LLFR3	Lateral support of top flange	

The contributing LLFR are shown in Table 5.10. Concepts/parameters can be given for each of the above concepts and relationships are as follows:

- **Effective span:**
  Fixation at ends, lateral support.
- **Load characteristics:**
  Dead loads, live loads, cyclic loading, frequency, amplitude, horizontal forces, axial forces, vertical forces, lateral loads and load combinations.
- **Fixation at supports:**
  Welded connections, bolted connections (moment, friction and/or pinned connections).
- **Lateral supports:**
  Continuous, intermittent, occasional.
- **Stress conditions:**
  Beam's configuration, geometry, stiffness, moment of inertia, sectional modulus, centroidal axis, neutral axis, steel type, stiffness (Young's modulus) yield stress, self-weight, type of section (rolled or welded girder), fatigue resistance and corrosion resistance.

Relationships between attributes can, for example, be the geometry of the beam that will determine the self-weight, moment of inertia, the centroid of the section and the location of the neutral axis.

In a more general sense the relationships are more complex. In **Figure 5.5** a multi-dimensional concept map is presented for structural engineering.

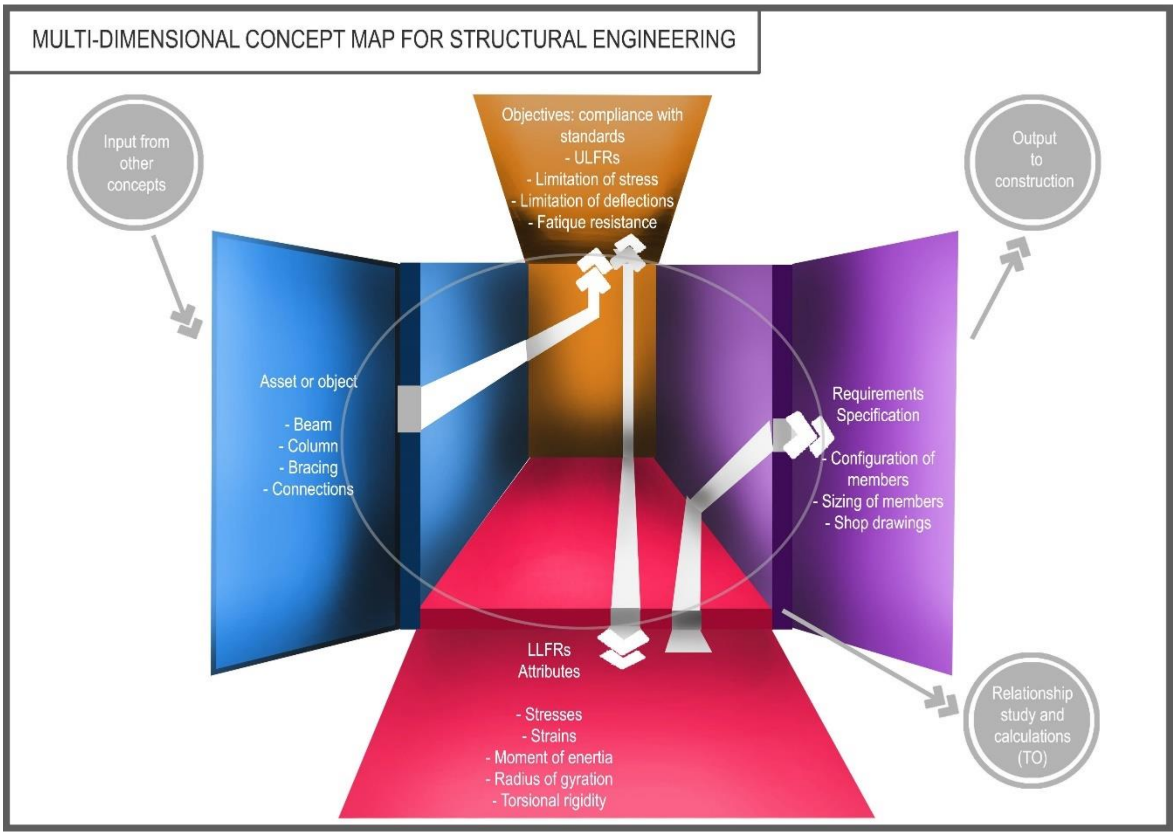

Figure 5.5 Multi-dimensional concept map for structural engineering

The arrows show that one starts off on the left-hand side with the beam (simplified functionality) to be designed. The objective of the beam (i.e., to span a certain distance under particular loading conditions) is determined and the design criteria are formulated. There may, for instance, be cyclic loading acting on the beam which would mean that one of the design criteria would be to design for the required fatigue life and would, for instance, limit the tensile stress in the beam to a predetermined limit. One would then make a trail choice of a steel member and study its attributes relating to its load-carrying resistance. After a few iterations, a choice of a particular steel member can be made. The next step would be to specify the desired attributes for construction purposes.

The concepts involved are as follows (all concepts will have attributes and values):

- Loading
- Span
- Geometry
- Fixation

Table 5.7 Example of pairing of elements

	Loading	Span	Geometry	Fixation
Loading		1	2	3
Span	1		4	5
Geometry	2	4		6
Fixation	3	5	6	

The paring produces 6 relationships:

Relationship 1: Loading vs span: For constant stress in the beam, the higher the loading, the shorter the span must be (inverse mathematical relationship).

Relationship 2: Loading vs geometry: For constant stress and span, the geometry must improve the moment resistance (for example). The moment of inertia must increase. (There is, in the case of a rectangular section, a 3rd power relationship between beam depth and the moment of inertia.)

Relationship 3: Loading and fixation: The more rigid the fixation at the ends of the beam, the more load can be carried.

Relationship 4: Geometry vs span: For constant load and stress the longer the span, the higher the moment of inertia must be.

Relationship 5: Span vs fixation: For constant stress, the more rigid the fixations the longer the span may become.

Relationship 6: Fixation vs geometry: For constant stress conditions, the more rigid the fixation, the lower the required moment of inertia will become.

In another example, a building that houses a large vibrating machine is connected via a short conveyor to an adjacent building that houses sensitive laboratory equipment. A functional analysis can be carried out to determine particular specifications of elements that contribute to the excessive vibrations that are transferred from the vibrating machine to the laboratory building. Two Functional Requirements (FRs) can, for example be identified, i.e., first, the requirement to ensure a sufficient fatigue life of elements of the connecting conveyor, and the second FR is to limit vibration transfer to the sensitive laboratory equipment. There are several contributing elements and these are listed in the FR matrix. These elements can be derived from concept maps and analysis, using pairing of concepts and other problem-solving techniques (not part of this example). The FR matrix is shown in **Figure 5.8**.

Table 5.8 Illustrative example of a Functional Requirement (FR) matrix

Object/Attribute **Functional Requirements (FRs)**	**Functional Requirements (FRs): e.g. limiting vibration in laboratory building with highly sensitive equipment. eg., Laboratory building forms part of adjacent plant building that houses heavy-vibrating plant (ULFR).**	
	Fatigue life (No. of repetitions) ULFR1 (Elements that need specifications or values for their attributes)	**Vibrations on each piece of laboratory equipment to be limited ULFR2 (Elements that need specifications or values for their attributes)**
LLFR1	Span of beams (supporting lattice structure).	
LLFR2		Affects stiffness of structure.
LLFR3	Static loading conditions.	Affects natural frequency of structure.
LLFR4	Dynamic loading conditions.	Dynamic loading conditions.
LLFR5	Direction of loads (static & dynamic).	
LLFR6	Time dependence of loads.	Depends on equipment details.
LLFR7	Amplitude of dynamic load.	Amplitude of dynamic load.
LLFR8	Stress.	Stress.

Object/Attribute **Functional Requirements (FRs)**	**Functional Requirements (FRs): e.g. limiting vibration in laboratory building with highly sensitive equipment. eg., Laboratory building forms part of adjacent plant building that houses heavy-vibrating plant (ULFR).**	
	Fatigue life **(No. of repetitions)** **ULFR1** **(Elements that need specifications or values for their attributes)**	**Vibrations on each piece of laboratory equipment to be limited** **ULFR2** **(Elements that need specifications or values for their attributes)**
LLFR9	Geometry.	Geometry.
LLFR10	Type of steel.	
LLFR11	Bending moments.	
LLFR12	Shear stress.	
LLFR13	Buckling of top flange.	Unlikely, but depends on configuration.
LLFR14	Stiffness.	Stiffness.
LLFR15	Mass inertia.	Mass inertia.
LLFR16	Torsion.	
LLFR17	Dampening.	Dampening.
LLFR18	Shear modulus.	Part of properties of steel.
LLFR19	Density of member.	Part of properties of steel.
LLFR20	Poisson’s ratio.	Part of properties of steel.
LLFR21	Slenderness ratio	
	OTHER CONCEPTS	**OTHER CONCEPTS**
LLFR22	Codes and standards	Codes and standards
LLFR23	Constructability	

In **Table 5.8** the top row represents the Upper-Level Functional Requirements (ULFRs). There could be as many FRs as required. The left-hand column contains all the possible concepts or elements. Each element that requires specification is listed as a LLFR. The descriptions of the attributes are given for each ULFR in the second and third columns. In these columns, the descriptions are given to which attributes and values must be assigned. The relationships between the ULFR and the LLFR, or between the LLFR and the attributes can be discrete mathematical, empirically derived, statistically correlated or logical relationships. These can be hyperlinked to the mathematical expressions, graphs or other technical information that the user would require to determine the details of the relationships and to calculate, in this instance, the fatigue resistance. All the learnings, experience and practical advice can be part of the references. The user can, by using the table, be appropriately prompted to consider the relationships when designing or investigating a particular case (such as an investigation of a structural failure). Case studies often report on the relationships found among various elements. This matrix format would then highlight that, for example, a specific relationship was found or that the formula was found to be different to that normally described in literature. The above matrix therefore ties into the TO as well as to the HLO for detailed design and analysis and can host the various relationships. These attributes can then be conveyed as specifications for design and construction.

5.8 SUMMARY OF COMPONENTS OF THE LOGIC BASE

5.8.1 The suggested operations in the logic base are as follows:

a) Evaluation of concepts (existence, applicability, appropriateness, completeness, proposed changes in concepts)

b) Evaluation of assumptions

c) Evaluation of relationships (types and quality)

d) Problem and/or constraint identification (viz., TRIZ, TOC, etc.)

e) Solutions to problems (TRIZ, TOC, HOT functional analysis techniques can be useful)

f) Lessons learned

g) Output protocols

5.8.2 Output Protocols

One of the suggested outputs of the logic base is Output Protocols. An output protocol is defined as a suggested rule for practitioners to follow. It emanates from the analysis of cases and put forward as general rules to follow, not limited to only the case study under consideration. The protocols should form part of the industry-knowledge base for every practitioner to take careful note of. This is necessary to prevent, in a general sense, re-invention of the wheel and to prevent recurring mistakes or oversights in design and construction of civil engineering projects. Almost all case studies will contribute to the knowledge base of protocols. It must be noted that the output protocols are not necessary unique, but may re-state requirements found in standards, specifications and procedures, etc. Of importance is that these protocols are restated because it reinforces issues commonly encountered in practice.

5.8.3 The architecture and functioning of the logic base

From the foregoing, the architecture and functioning of the logic base is summed up best by the graphical presentation in **Figure 5.6**.

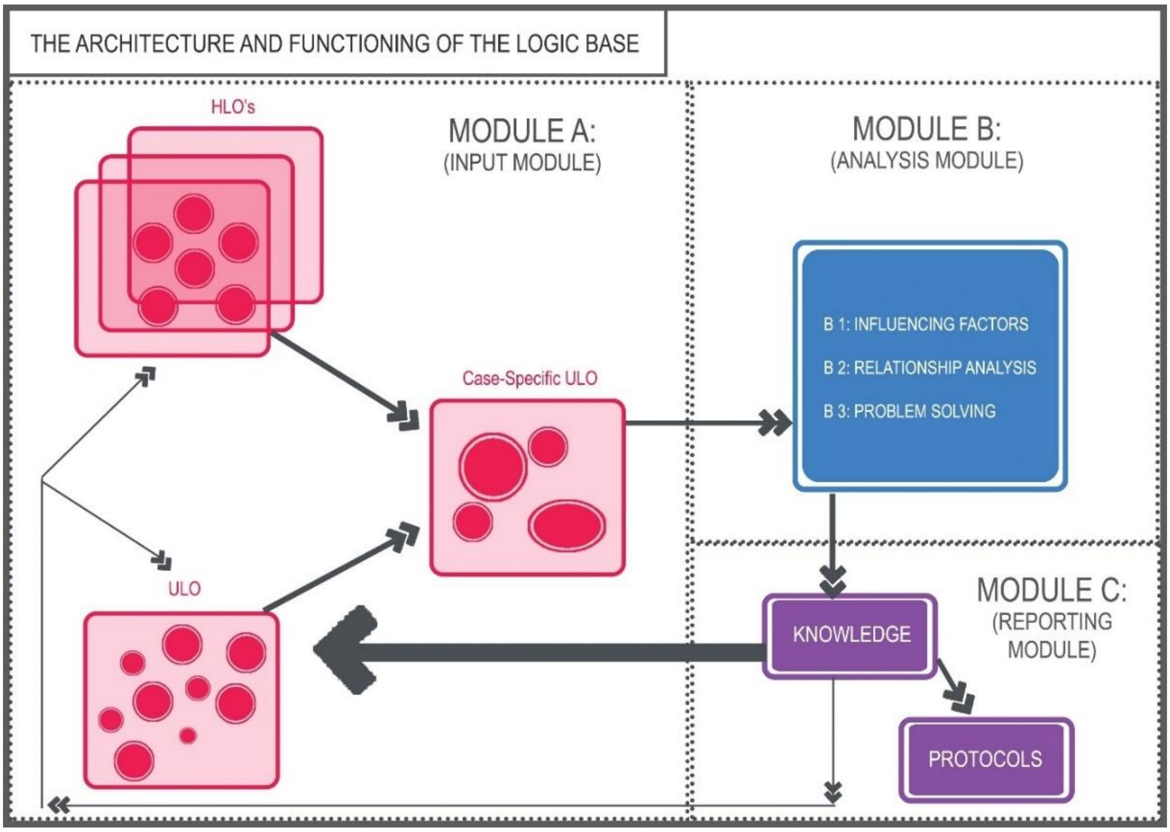

Figure 5.6 The architecture and functioning of the logic base

The first module of the logic base, Module A is where concept maps are produced and related to the ontologies. The TLO, HLOs, ULOs and CSOs are mapped in this module.

The second module, Module B represents the analysis part where relationships are studied and the contradictions and constraints are identified. Concept matrices are drawn up to identify all the possible relationships and the effects of influencing domains are studied. Problem-solving techniques are applied; RCA, FMECA, HOT, TRIZ, TOC and Functional analysis are done to arrive at solutions to problems and to formulate actions for execution or for remedial actions. The third module, Module C is a reporting module where the details of the analysis from Module B as described above, are documented. This knowledge is linked to the HLO for storage and retrieval purposes. Output protocols are formulated from Module B and stated in Module C.

Engineering processes involve mostly very complex processes. Rigid sets of rules to structure the compilation of concept maps might be restrictive and might hamper the identification and presentation of problems and, therefore, also of the associated knowledge. The studies of all the relationships, as discussed above, sufficiently describe the building blocks to uncover knowledge and knowledge for later reuse, and creation of new knowledge. However, it is realised that any additional relationships could be established to portray the thought processes as best as possible. It is considered that concept maps should be kept rather small – no more that 10 to 15 elements per map to render the maps easily readable. It is better to break up maps into smaller ones with appropriate linkages if the need arises.

It is contemplated that the logic base would form or define the working space where existing knowledge is studied, mapped, relationships studied and knowledge enhanced. The end-users of the logic base must also be taken into account. The logic base must be made as simple, yet, as effective as possible.

5.9 THE OPERATION OF A LOGIC BASE

5.9.1 Ontology

Starting from the specific case under consideration, a CSO is compiled. This CSO maps to the ULO or HLO and automatically links to the TLO. Once the CSO has been compiled, the relationship between the concepts are identified and studied. Allowance is also made for a TO to cater for discipline technology.

5.9.2 Interrelationships

The interrelationships among the knowledge domains and their attributes were pointed out as a most important part of problem identification and necessary to find solutions. Systematic pairing between the concepts and attributes of the ontology and identification of the types of relationships (e.g., effective, missing, insufficient, excessive, harmful) would yield where constraints or contradiction occurs. Many types of relationships and reference can be made to **Table 5.4**. In addition to the qualitative relationships, quantitative relationships may exist. The identification of all the parameters participating in the system's operation has to be done.

5.9.3 Problem-solving

From a study of the relationships, areas of constraints and contradictions can be identified that can then lead to the solution of problems. There are many problem-solving techniques as discussed in Chapter 2 of this study. However, the techniques described in Chapter 2 are not exhaustive. From the problem-solving techniques, the following are of particular use in this study:

- TRIZ (Theory of Inventive Problem Solving)
- TOC (Theory of Constraints)
- HOT-technique (and related FAST-technique)
- RCA (Root-Cause Analysis)
- FMECA (Failure-Modes, Effect and Criticality Analysis)
- FA (Functional Analysis).

Each of the above techniques has a particular function and can be applied as required by the type of problem or circumstances.

The process of problem-solving is crucial when it comes to the replication of knowledge. The knowledge gained by solving a particular problem forms the basis for solutions of future problems.

5.9.4 Contents of the logic base

The contents of the logic base is as follows:

- Case facts
- Concept maps
- Relationships and analysis of relationships
- Identification of contradictions and constraints
- Test all the relationships for effects that can be caused by all the elements of the influencing domains, including time, space, resources and interfaces
- Functional analysis
- Identification of problems and solutions
- Lessons learned – knowledge and experience gained from the case/ educational aspects
- Output protocols

- References

5.9.5 Intended use of the logic base

The logic base should be developed as interactive computer software; however, this is not part of this study. The use of the logic base is aimed at the engineering practitioner who is involved in the design, manufacturing/construction or maintenance of civil engineering infrastructure. Interaction with the logic base is designed to assist the user in systematising, and to guide him or her in a process to achieve a holistic view. It is also meant for practitioners who wish to analyse or evaluate the performance of existing engineering infrastructure. The logic base could be centrally hosted, either on a web-based service or as software for use within an organisation.

5.10 SUMMARY

The proposed logic base is seen as the platform where one can post concept maps for case studies. The way concept maps are constructed is evident from the preceding sections (HLO, ULO and CSO). The Technical Ontology (TO) is also provided. The concept maps contain relationships. These relationships can be described or classified according to the given standard list in **Table 5.4**. The quality of the relationships can be described according to the standard list, viz., effective, missing, insufficient, excessive or harmful or grades of each appropriate type. The study employs problem-solving techniques to identify problems and constraints. The concept maps, relationships, outcomes of the concepts and relationships study and outcome from the problem-solving study are then summarised and are linked to the HLO that would form the basis for the storage and retrieval of knowledge. Referring to Chapter 2 of this study (Section 2.8), a summary is given of aspects from various problem-solving techniques. Allowance is also made for technical analysis by way of a TO and for using the functional analysis technique to determine specifications. The study of relationships, relating to cause-and-effects, contradictions, constraints, consequences, analogies, classification of themes and hierarchical divisions are mentioned. These form part of the HLO and the subsequent study of relationships. Other aspects are the prompting to expand discovery and innovation, and anticipative thinking techniques by using concept maps.

5.11 PRACTICAL EXAMPLES OF THE OPERATION OF THE LOGIC BASE

5.11.1 Example 1 – Case study: Ellis Brown Viaduct (Fenton, 2013)

MODULE A:

a) Synopsis/narrative

Four curtain wall beams on the sea-facing side of the *Ellis Brown Viaduct* in Durban-North collapsed. These arched-shaped curtain beams were not part of the main roadway structure, but part of an additional, separate structure. These beams were mechanically connected to the main structure and mainly served an aesthetic purpose, but also provided support for a pedestrian-way across the bridge. The mechanical connections between the two structures were vandalised for scrap steel and caused the collapse of the four curtain wall beams on the sea side. It was argued in the case study that the engineering-ethical considerations of providing a false impression of the type of structure (an arched bridge structure), as against the true nature (simply supported precast beam structure) was not well received by the engineering fraternal. The Case-Specific Ontology (CSO) is presented in **Figure 5.7**.

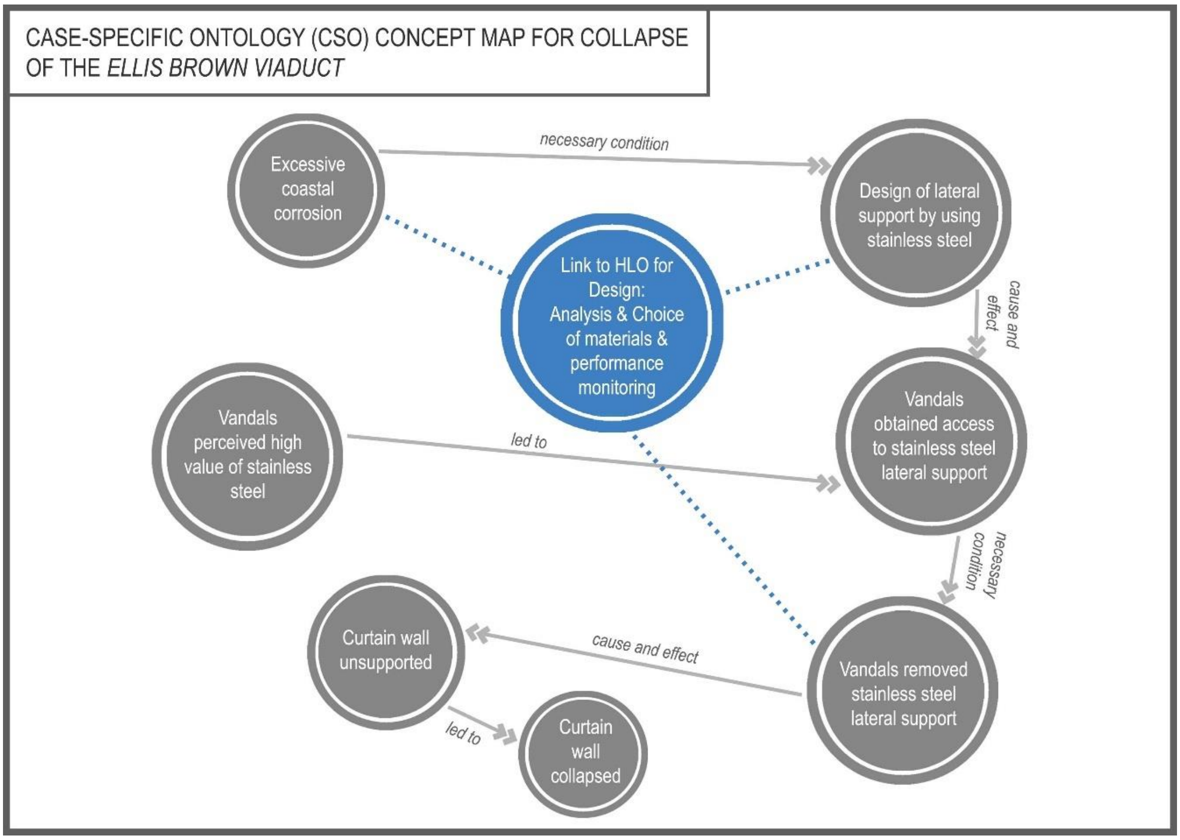

Figure 5.7 Case-Specific Ontology (CSO) The *Ellis Brown Viaduct*

Study of CSO concept and relationships (comments on the tests are put in italics).

b) Challenging of concepts, assumptions and relationships

i) Concepts

- Validity of the concept. (*The actual case states the concepts and are therefore not speculative but valid.*)
- Coexistence. (*No conflicts are identified*.)
- Overlap. *(No overlaps are identified.)*
- Mutual exclusivity. (*Concepts link to one another and the statements are each valid on its own.*)
- More of something? (*Not applicable.*)

- Less of something? (*Not applicable.*)
- Is there sufficient cause? (*Apparently, the need for money overshadows any potential consequences of actions of vandalism. The question is also whether the vandals were aware of the consequences and if they were aware, whether it would have changed the vandals' minds.*)
- Can the effects be predicted? (*From details of the configuration, the removal of the connections will undoubtedly cause a loss of support and collapse.)*

ii) Assumptions

- Assumptions must be uncovered and challenged. (*It is assumed that the designers never suspected any possible problem with vandalism of the connectors and no thought was given to redundancy in the design.*)
- Participation of assumption in conflict relationship. (*The assumption is that, due to the history or corrosion of the connectors, the designers thought of providing easy access to the connectors for inspection or maintenance work to be conducted. This is in conflict with the need to limit access to prevent vandalism*.)
- Validity and applicability of assumptions. (*The case study deals with the vandalism. The assumptions made are deduced from the case.)*

iii) Relationships

- Determine the type of relationship. (*The CSO contains cause-and-effect relationships, but also "follow-on relationships" and "necessary-condition" relationship. The latter refers to the fact that a necessary condition for vandalism is the perception which vandals have of the value of the stainless steel. It also a necessary condition to have gained access to the bridge by way of a sand bank in the river.*)
- Does it have a positive result? *(Not applicable.)*
- Does it have a negative result? (*A negative result from removal of the connectors is the loss of lateral stability.*)

- Determine the validity of the relationship. (*The validity is not an issue as it is deduced from the facts presented in the case study*.)

- Determine the quality of the relationships. (*The relationship between the design of lateral support with stainless steel and vandals obtaining access to the lateral supports is a harmful relationship.*)
  (Effective, missing, insufficient, excessive or harmful.)

From the above, the most important concept (connector point – concept with most arrows to it) is: “vandals obtained access to the stainless-steel supports”. This is seen as the key problem in this case study. It also is a necessary condition for the removal of the lateral supports.

MODULE B:

a) Treatment of case in terms of the generic ULO (Upper-Level Ontology)

It is important now to bring the CSO in context or to map it to the higher-level ontologies. In this case the generic ULO is considered suitable. The concepts appearing in the generic ULO are placed as headings and the details of the case study under consideration are discussed under each heading. This now incorporates the CSO.

i) Purpose

The viaduct's purpose is to cross the Umgeni River. The FR is to span a particular distance with the simplest of form and minimal material. When comparing the actual construction with the purpose, one can see that it was by the construction of a roadway where a series of precast beams were employed to span between piers.

ii) Design and configuration

A series of precast beams were employed to span between piers to provide pedestrian access on the outer sides of the bridge. Curtain wall beams were later added as facades to the bridge. This changed the aesthetics of the bridge completely and left observers with the impression that the entire bridge is an arched bridge, as depicted by the arch-curved curtain walls on either side of the main roadway structure. The curtain walls were laterally connected to the main structure by way of steel connector pieces.

iii) Operational principles

The curtain walls were not regarded as stable enough, hence lateral connectors were installed as part of the construction of the “add-on” walkway structures.

iv) Rules and legal requirements

The rules and legal requirements in this instance would relate to the structural design and detailing codes, as well as the consent and approval by the eThekwini municipality.

v) Initialising (events)

Vandalism for scrap metal removed the horizontal stainless-steel couplers that provided for horizontal stability of the curtain walls. The removal of the lateral supports rendered the structure unstable and caused the collapse.

vi) Operational philosophies and maintenance

The original steel connectors were corroded and replaced as maintenance operations with stainless steel. (Replacement of lateral connectors with stainless steel.)

vii) Influencing domains – environmental matters

The following factors played a role:

- Corrosive atmosphere
- Aesthetics
- Public opinion
- Hydrology

vii) Time, space and resources

The influence of time and space on all the above need to be modelled. For instance, working space may be very limited between the bridge and curtain wall. Time plays a role, because the design life of the connections has to be the same as the bridge – typically more than 50 years.

viii) Knowledge-acquisition techniques

This case study urges a practitioner to take note of the occurrence of vandalism and also at the extent to which it goes. Knowledge spill-over can suggest the designers should design facilities so as to minimize the risks of similar events. Reflective thinking is required to change designers' paradigm in designing for risks. This case study serves a purpose of learning practitioners about designing with greater redundancy in mind, so that if a particular structural element fails for some or other reason, that the structure will not collapse.

b) Problem-solving analysis

i) TRIZ

The first step in the application of TRIZ is to analyse the substance-field (S-Field) relationships. In this case study the following fields are identified:

- ***The main motorway structure and the curtain wall structure***

  The field interaction between the two structures is by way of a structural connection part, capable of transmitting tension and rotational movements. The question is then whether the field is effective, missing, insufficient, excessive or harmful. In this case study, the field was effective. When this field (the tensile forces) were destroyed by acts of vandalism, the structure became unstable.

  The solutions offered by TRIZ regarding the field, are either to complete an incomplete model, to modify one or more of the substances, to add new substances or by transitioning to a higher or lower hierarchical level. In this case study the solution was to modify a substance and design the curtain structure to act independent of the main motorway structure. Elimination of the linking connectors is one possible solution.

- *Curtain-wall structure and pier foundations.*

- The field of interaction is the placement and suspension of the curtain walls from modified pier structures. The interaction was sufficient as the piers offer good support.

- *New concrete bullnose structure and existing reinforced-concrete pier structure.* The field is the positive connection of new concrete work and the existing concrete. This interaction is critical to the stability of new sections added to the sides of the existing structure. The field is sufficient but needs careful design and construction – this will have to be done through rigorous quality assurance.

In the TRIZ-technique one would identify the constraints/contradictions, and then search for solutions to these.

The contradictions identified are as follows:

- Use relatively valuable material (in the minds of scrap vandalists), *but* prevent vandalism. (Stainless steel is sought-after by scrap thieves. This contradiction was never contemplated. The eventual access that thieves obtained to the bridge via a sand bank in the river and the access to the stainless-steel connectors led to their removal and subsequent instability and collapse.)

- Adding on a reinforced curtain wall to the side of a main structure, *but* retain structural stability. (This led to the design and installation of lateral supports.)

- Keep structure stable, *but* do not have lateral connectors. (Through vandalism the connectors were removed.)

- Maintain easy access for maintenance purposes, *but* prevent access to avoid vandalism.

The solutions to the above can be searched for in TRIZ's standard solution matrix.

The following parameters can be considered: the reduction or improvement of harmful effects (no. 31) vs reduction in stability (no. 21). In the matrix, it defines the following solutions (Mann, 2009):

- Inventive principle no. 40 – Composite materials
- Inventive principle no. 4 – Asymmetry (change the shape of an object)

- Inventive principle no. 35 – Parameter changes (step-change new way of solving the problem)
- Inventive principle no. 14 – Curvature (turn flat surfaces into curves)

Among the above, composite materials could offer the best solution for the connecting elements. If the connecting elements are made of composite material, the mechanical properties could be enhanced (composites often exhibit superior strength characteristics as compared to steel) and the attractiveness of the composite material to scrap dealers is effectively eliminated. Parameter changes could also mean that a new structural solution should be sought. (In this case a structure that is redesigned to be stable without connecting parts.)

ii) RCA (Root-Cause Analysis)

In the case of the collapse of the curtain walls, the root cause was the demand for scrap metal, and more specifically, stainless steel. The stainless steel attracted vandals who attached monetary value to the stainless steel and subsequently removed the new stainless-steel connectors. This removal led to lateral instability and caused the curtain walls to collapse. The secondary root cause is that vandals could gain access to the structure by way of the sand island in the Umgeni River.

iii) FMECA analysis

The failure mode was that lateral instability caused collapse. The vibrations, due to traffic on the adjacent motorway, could have caused the lateral movement of the curtain walls, which were in limiting equilibrium and could result in toppling at the slightest lateral forces.

iv) HOT-technique

In this case the objectives would be to enhance the structural stability of an add-on walkway structure to the main motorway bridge.

Tactics:

- To design and construct an independent pedestrian/cycle bridge (functioning completely independent of the motorway bridge).

- To widen existing piers and place new prestressed beams to widen the existing structure.
- By using the existing structure to hang or cantilever lightweight steel structures from for the proposed pedestrian and cycle ways.

Solutions:

- The case solution was to widen the exiting piers and add a new stable structure to the side of the bridge, without reliance on lateral support connectors.

The above analysis should be mentally modeled in terms of time, space and capacity and should also be paired with the various influencing factors.

From the above, a logic is defined, peculiar to the case study, but that is useful for future cases or that can be used in the establishment of new infrastructure.

vi) Functional Requirements (FRs)

The functional analysis contains the desired LLFR that can be specified to meet the objective stated in the ULFR. This is shown in **Table 5.9**:

Table 5.9 Functional Requirement (FR) matrix

LLFR	**Upper-Level Functional Requirement (ULFR):** **Stable and durable curtain wall**
	Elements, attributes & values
LLFR1	Connectors to cater for tensile forces.
LLFR2	Connectors to cater for rotation/moments.
LLFR3	Connectors to be durable in warm marine environment.
LLFR4	Connectors to have no scrap value.

MODULE C:

It is considered that the best way to record the logic is by way of an output file, containing the lessons learned and knowledge gained from the study. Output protocols are also deduced from the analysis and reported in the output file. This is shown in **Table 5.10**.

Table 5.10 Reporting in the logic base: Module C

	ONTOLOGY **(Include concept maps as required).**	**CASE FACTS AND LESSONS LEARNED – KNOWLEDGE GAINED FROM THE CASE**	**OUTPUT PROTOCOLS**
1	User requirements.	A user requirement to add on arched curtain walls created a false impression of the type of structure. This was considered by architects as not acceptable as proper, aesthetic design.	Aesthetics of add-ons to match true nature of main structure.
2	Configuration.	The structure of the curtain wall was separate, but was connected to the main motorway structure to provide lateral support. Integrity of connections was critical to the stability of the curtain structure. Access was possible to the structure and connectors via a sand bank in the Umgeni River at that particular time. It would have been rather unlikely to foresee that a sand bank could have formed to such an extent that access became possible to the bridge elements. (If one had experience of the Umgeni River, where sand banks often form, it would have been more likely that	a) Add-on structures to be independently supported if possible. b) Limit the possibility of human access to critical parts, especially in less visible areas.

	ONTOLOGY **(Include concept maps as required).**	**CASE FACTS AND LESSONS LEARNED – KNOWLEDGE GAINED FROM THE CASE**	**OUTPUT PROTOCOLS**
		the potential for access to the bridge from a sand bank could have been foreseen.)	
3	Rules and legal requirements.	*Best practice* calls for redundancy in critical elements. There was no redundancy due to single connectors between the main motorway structure and the curtain walls.	Design for redundancy.
4	Principles of operation.	Bending and shear forces in beams and lateral support through connectors.	Lateral connectors between structures must be able to accommodate the deflection and direction caused by all forces – check for both rotation and axial forces.
5	Initialising/Events.	Corrosion of connectors and replacement with stainless steel. Vandalism for scrap severed the lateral connections that led to failure of curtain walls.	Choose material that is less prone to vandalism – use for example, composite materials.
6	Operations and maintenance.	Maintenance of the connectors took place by way of replacement of corroded steel connectors with stainless steel connectors.	Conduct bridge inspections, identify critical elements and do regular maintenance.
7	System operations and controls.	Controls were by way of bridge inspections that took place where the corroded connectors were discovered.	Do regular inspections or monitor performance of critical structural elements.

	ONTOLOGY (Include concept maps as required).	CASE FACTS AND LESSONS LEARNED – KNOWLEDGE GAINED FROM THE CASE	OUTPUT PROTOCOLS
8	Influencing domains.	Societal (vandalism), economical (selling of scrap metal), climatic factors – high corrosion rate at the coast.	Vandalism of structural components is a growing problem – take measures to protect critical elements.

The output protocols are derived from the operation of a logic base. When a design engineer goes about a design, he or she would work their way through the ontology of the logic base. This ontology would prompt the person to consider various aspects, but also ensures that cognisance is taken of many factors. Problems can be solved throughout the design process by using the various problem-solving techniques. Prompting to consider the output protocols can enhance the quality of designs.

5.11.2 Example 2 – Mechanically Stabilised Earth (MSE)

This descriptive study informs the readers of the method of functioning of Mechanically Stabilised Earth (MSE) and describes the applications and advantage of this method (Smith, 2013, pp.45-47).

MODULE A:

a) Synopsis/narrative

This method was invented in 1957 by Henri Vidal, a French architect and engineer, whilst playing with pine needles and beach sand. The method involves stabilising of an earth embankment by means of tie-back strips inserted during the construction of an earth fill. Typically, flat metal strips are inserted perpendicular to a vertical face of an earth fill. The metal strips are then tied to a facing material for the retention of earth on the vertical face of an embankment. This method of building stable-fill embankments has became popular and is used throughout the world. These fill embankments can be used successfully for the support of bridge decks.

The sketch in Figure 5.8 illustrates the method.

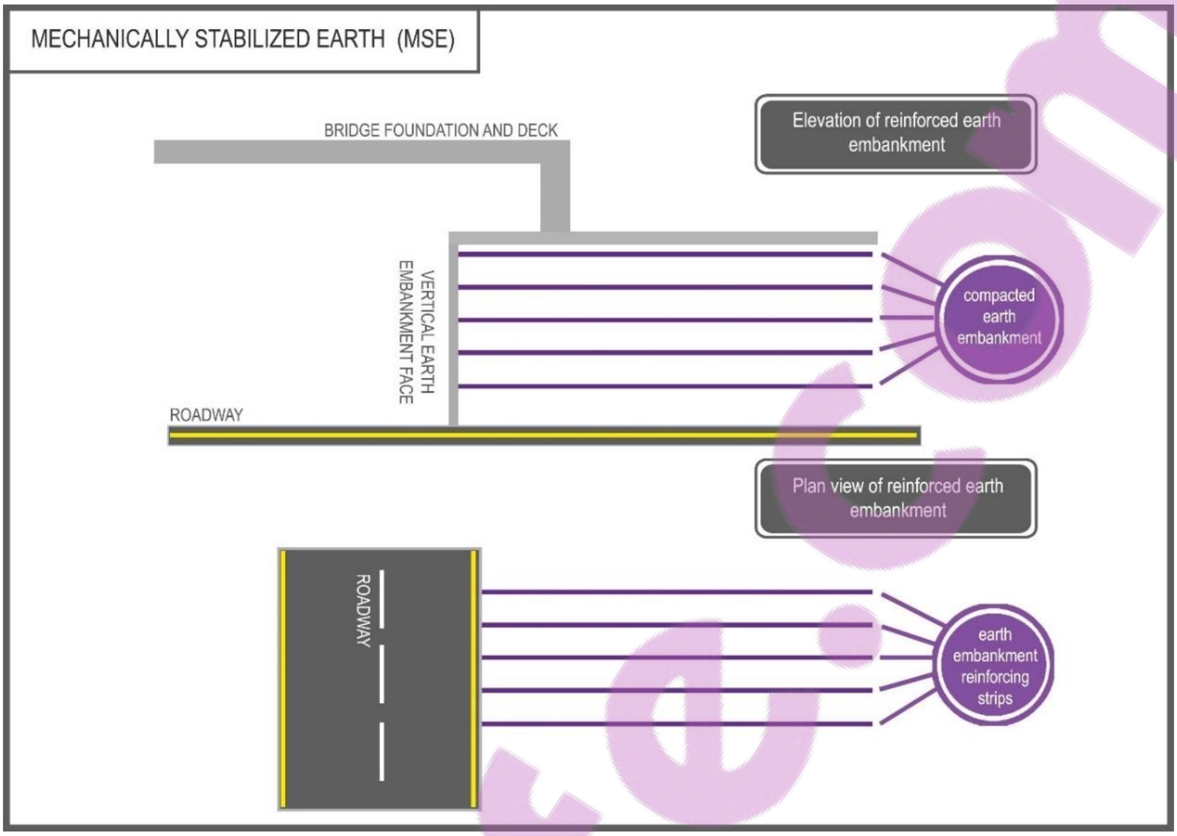

Figure 5.8 Mechanically Stabilised Earth (MSE)

The Case-Specific Ontology (CSO) concept map is shown in **Figure 5.9**.

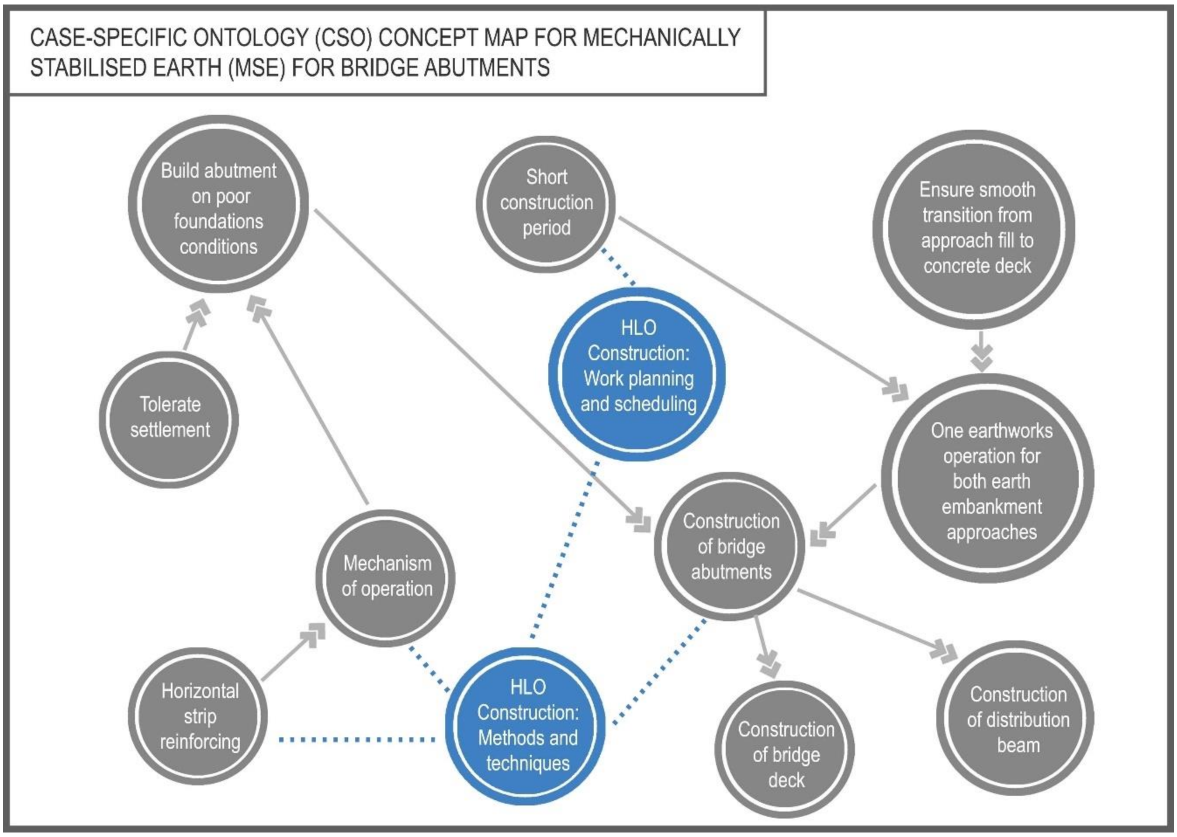

Figure 5.9 Case-Specific Ontology (CSO) for Mechanically Stabilised Earth (MSE)

The CSO concept map in **Figure 5.9** shows the main concepts of construction of an embankment by using Mechanically Stabilized Earth (MSE). The next step is to map the CSO with the generic ULO. This is described in the paragraphs below:

MODULE B:

a) Treatment in terms of ULO

i) Purpose

The purpose of this method is to create a stable embankment, on which infrastructure can be constructed.

- Construction must be possible on poor founding conditions.

- The structure (both the abutment and the bridge) must not be sensitive to settlements.
- It must have a short as possible construction duration.
- There must be a smooth transition between the earth approaches and the concrete deck.

ii) Configuration

In this method, horizontal reinforcement is placed in an embankment fill. The reinforcement is placed in alternating layers of compacted soil, and soil where reinforcement was placed. The face(s) of the embankment are typically vertical and cladding is positively connected to the horizontal reinforcement to provide an aesthetically pleasing facade.

iii) Mechanism of operation

The horizontal reinforcement in the fill restrains lateral strain by friction between the soil and the reinforcing elements in the soil. The effect is the same as if a lateral restraining load is applied to the soil. As the vertical stress is increased, so do the lateral stresses increase in direct proportion. The horizontal strain in the earth is captured by the reinforcing elements.

iv) Operational principles

In soil mechanics, the volumetric-stress strain relationship is of importance (this is part of the TO). If a vertical stress is applied to a soil specimen, horizontal stresses increase in direct proportion (and vice versa). However, due to the behaviour of particulate media, such as compacted soil, a small lateral force or restraint would have a larger proportional effect on the vertical-load bearing capacity. (This is illustrated and can be calculated with reference to the Mohr-Coulomb failure criteria (Das and Sobhan, 2014, pp.429-451).

v) Influencing domains

- Geotechnical considerations
- Geochemical environment
- Construction quality control and assurance
- Seismic events

vi) Relationships and possible failure mechanisms (combining it with problem-solving techniques)

Relationships are stated and evaluated according to the TRIZ method (substance-field relationships). Comments on the relationships are shown in *italics*.

- Embankment and subsoil. *(Potential failure of foundation soil and potential settlement – both conditions can adversely affect the mechanically stabilised earth embankment.)*

- Soil and compaction equipment. *(It might not be possible to properly compact poor soil to the required specification.)*

- Metal or polymer strips and soil. *(Strips my slip due to insufficient friction between strips and poorly compacted soil.)*

- Metal or polymer strips and moisture in soil. *(The frictional resistance between the metal or polymer strips and the soil can reduce due to a reduction of effective stress as a result of excess pore pressure. Moisture could also be corrosive and could destroy the strips.)*

- The extensivity of the metal or polymer strips and the lateral strain in abutment fill. *(Extension of strips such that lateral forces cannot be mobilised.)*

- Metal or polymer strips and facing material and connections. *(Possible failure of metal connections due to poor design/manufacturing or due to corrosion.)*

- Bridge foundation and soil embankment. *(Soil in MSE may settle and cause excessive settlement of bridge.)*

- Rainfall and embankment. *(Rain can dam up on embankment and saturate the soil, weakening the soil structure as a result of excessive pore pressure. Insufficient drainage of fill, as well as surroundings can result in failure of the embankment.)*

The above set of relationships are deduced from the case study and not necessarily directly reported in the script of the study.

v) Technical Ontology (TO)

The functioning of the metal strips relative to the soil can be expanded in a Technical Ontology (TO). For example, the shear resistance of the strips can be considered. There is a functional relationship between the soil properties and the vertical-effective stress and the shear that can develop between the soil at particular points along the strips. The relationships can be determined by laboratory testing to obtain the relationship between the shear stress that develops between the strips and the soil. There are other relationships as well and these are conceptually shown in **Table 5.11**. Each FR represents a concept statement that can be further expanded in a TO.

The FR matrix can also be compiled to extend the analysis as shown in **Table 5.11** (in slightly different format than previous):

(The relationships are sequentially numbered.)

Table 5.11 Functional Requirement (FR) matrix

Attributes	**Functional Requirements (FRs)**		
	Tolerance to settlement	**Limiting lateral restraint**	**Stable facing of retaining wall**
Soil type.	**1**	**2**	3
Strips type.	4	**5**	6
Friction between strips and soil.	7	**8**	9
Extensiveness of strips.	10	**11**	12
Foundation strength.	**13**	14	15
Foundation settlement.	**16**	17	18
Horizontal strain of embankment.	**19**	20	**21**
Connections between strips and front facing.	23	23	**24**

	ONTOLOGY	CASE FACTS AND LESSONS LEARNED – KNOWLEDGE GAINED FROM THE CASE	OUTPUT PROTOCOLS
1	User requirements.	Rapid embankment construction Construction on relatively weak foundation. (Foundation strength to be assessed vs loading and rate of loading.) Structure not very sensitive to settlements. Smooth transition between approaches and concrete bridge.	
2	Configuration.	Friction strips built into fill to retain vertical face. Strips made of steel or polymers.	Complement natural material with steel or polymers for construction.
3	Governing laws.	Friction, consolidation settlement and collapse of soil, compactability of soil, chemical resistance.	
4	Principles of operation.	Friction between strips and soil develop horizontal forces, resisting lateral movement. Friction between steel/polymer strips to be assessed, and spacing between strips determined.	
5	Events.	Possible failure mechanisms: Weak compaction – low density. Slip between strips and soil. Loss of effective stress due to water ingress and establishment of phreatic surface. Strips extensiveness too large to mobilise lateral forces.	

		Failure of connections of facing to strips.	
6	Operations and maintenance.	Very little, if any, maintenance is required.	
7	System operations and controls.	Only drainage and settlement need to be monitored.	
8	Influencing domains.	Corrosion.	
9	Element/parameter analysis.	**Refer to Table 5.11**.	

The individual cells that have important relationships are marked with bold numbers. These may need special attention by way of laboratory analysis of soil properties. One particular example would be the friction between a kind of strip and the compacted soil. Shear-box tests would probably be the best type of test to perform. A database with typical friction values may be of great assistance in this regard.

This case study is in fact a descriptive study and does not present specific experience or convey knowledge other than introducing the technicalities of employing mechanically reinforced earth for use in bridge abutments. The above concept maps and relationship study provides a useful framework for future use, as an ontology for mechanically reinforced earth structures.

vi) Knowledge-acquisition techniques

The use of mechanically stabilized techniques introduced a new era in soil mechanics. The use of mechanical elements to reinforce earth embankments, and even layers in pavement structures, is becoming more popular. This is an example of knowledge spill-over. When analysing this case study, reflective thinking occurs, whereby content reflection, process reflection and premise reflection can take place. Regarding premise reflection, the transformation of the meaning framework takes place, converting explicit knowledge to tacit knowledge.

MODULE C:

Reporting in the logic base is done in **Table 5.12**:

Table 5.12 Module C: Output from logic base

	ONTOLOGY	**CASE FACTS AND LESSONS LEARNED – KNOWLEDGE GAINED FROM THE CASE**	**OUTPUT PROTOCOLS**
1	User requirements.	• Rapid embankment construction. • Construction on relatively weak foundation. (Foundation strength to be assessed vs loading and rate of loading.) • Structure not very sensitive to settlements. • Smooth transition between approaches and concrete bridge.	
2	Configuration.	• Friction strips built into fill to retain vertical face. • Strips made of steel or polymers.	Complement natural material with steel or polymers for construction.
3	Governing laws.	Friction, consolidation settlement and collapse of soil, compactability of soil, chemical resistance.	
4	Principles of operation.	• Friction between strips and soil develop horizontal forces, resisting lateral movement.	

	ONTOLOGY	**CASE FACTS AND LESSONS LEARNED – KNOWLEDGE GAINED FROM THE CASE**	**OUTPUT PROTOCOLS**
		• Friction between steel/polymer strips to be assessed, and spacing between strips determined.	
5	Events.	• Possible failure mechanisms: • Weak compaction – low density. • Slip between strips and soil. • Loss of effective stress due to water ingress and establishment of phreatic surface. • Strips extensiveness too large to mobilise lateral forces. • Failure of connections of facing to strips.	
6	Operations and maintenance.	Very little, if any, maintenance is required.	
7	System operations and controls.	Only drainage and settlement need to be monitored.	
8	Influencing domains.	Corrosion.	
9	Element/parameter analysis.	**Refer to Table 5.11.**	

Since the above example is merely a descriptive study, little potential for output protocols are available.

5.11.3 Example 3: The identification and treatment of poor durability Karoo dolerite base course aggregate – evidence from case studies (Leyland *et al.*, 2016).

MODULE A:

a) Synopsis/narrative

In this case study, research is reported on the performance of Karoo dolerite used for base course in surfaced roads. It was recorded that dolerite base course performed satisfactory, but in some instances premature failure of the road pavement structure took place. Road authorities specify that certain tests are to be conducted and limiting values of the attributes are given for material that is to be used as base course. It was found that these specified tests do not adequately predict the durability of the dolerite aggregate in base-course layers and that additional testing would be advantageous. Treatment of potentially poor aggregate with a small quantity of lime, below the percentage of lime required to satisfy the initial lime demand of the material, potentially reduces the risk of degradation after construction.

b) Case-Specific Ontology (CSO)

The CSO for this case study is shown in **Figure 5.10**.

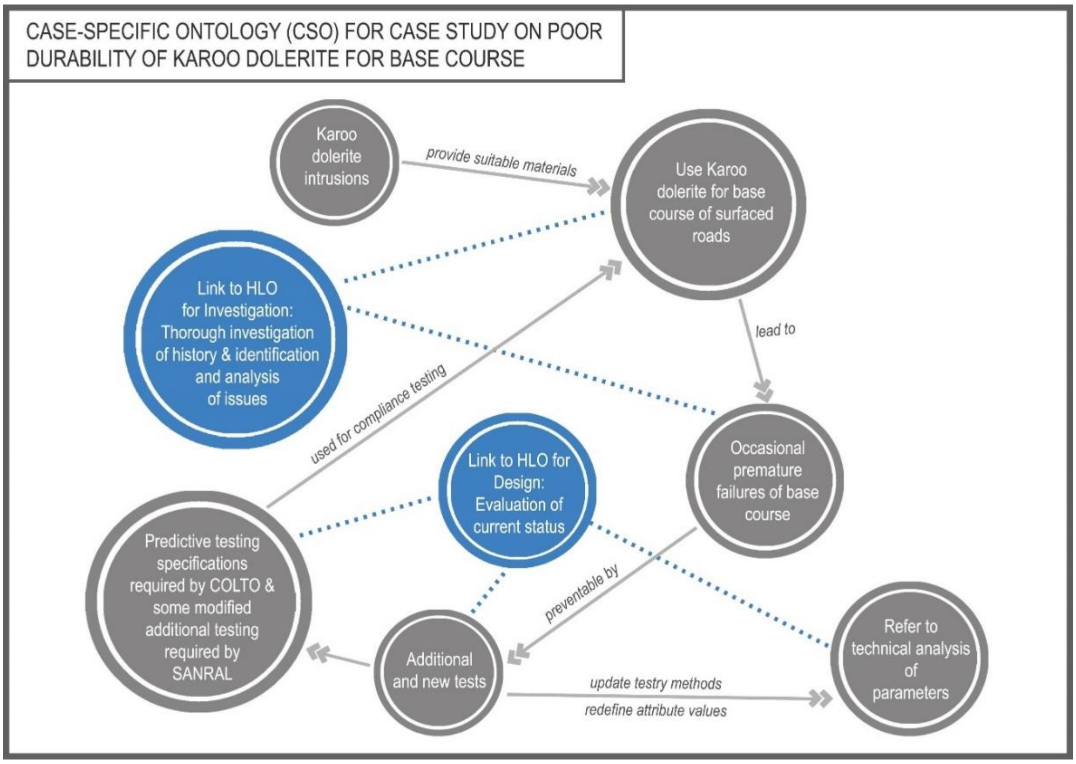

Figure 5.10 Case-Specific Ontology (CSO) Karoo dolerite for base course

In **Figure 5.10** it is shown that premature failure should cause additional tests and that COLTO (Committee for Land Transport Officials) and SANRAL (South African National Road Agency Limited) required specification needs to be updated to improve the use of dolerite as base course for surfaced roads. It can be seen that reference is made to the analysis of technical elements. As this case study provides knowledge regarding additional tests, this should be added to the concept map. This is shown **Table 5.13**.

c) Mapping of the CSO and the HLO for "investigation"

Mapping is done to the High-Level Ontology (HLO) to map for "investigation" as shown in Chapter 4 of this study. This is briefly done in the sections below.

MODULE B:

A Technical Ontology (TO) is deemed be best suited for the analysis of this case study. This example starts with a comparative functional study of the FRs stated in the case study. (This indicates the flexibility in the procedures of the logic base.)

Table 5.13 Functional Requirement (FR) matrix

Element	**Upper-Level Functional Requirements (ULFRs): Satisfactory trafficability of road (rutting bleeding, stone loss, raveling, crocodile cracking)**	
	Durability of base course layer (LLFRs) – COLTO Specifications	**Durability of base-course layer findings from case study LLFRs**
LLFR1	10% FACT: Specification 110 kN.	
LLFR2	Wet/Dry 10% FACT ratio >=75%.	
LLFR3	ACV (Aggregate crushing value)<29%.	
LLFR4	LS (Linear Shrinkage)<=2.0.	
LLFR5	PI (Plasticity Index)<=4.	
LLFR6	DMI (Durability Mill Index)<=125.	
LLFR7	Aggregate Impact Value (AIV).	
LLFR8	Compressive and shear wave velocity.	Potential wave test in borrow pit.
LLFR9	PLI (Point Load Index).	

Element	Upper-Level Functional Requirements (ULFRs): Satisfactory trafficability of road (rutting bleeding, stone loss, raveling, crocodile cracking)	
	Durability of base course layer (LLFRs) – COLTO Specifications	**Durability of base-course layer findings from case study LLFRs**
LLFR10	MEGDI (Modified Ethylene Glycol Durability Index).	Ref 1.
LLFR11	Water absorption.	Degradable material has potentially higher water absorption.
LLFR12	Stabilising with lime.	Ref 2.
LLFR13	Petrographic examinations no. deleterious matter such as weathered rock.	Ref 3.
References:		
1. Leyland, Momayez & Paige-Green, 2016, pp.26-33		
2. Kleyn & Bergh, 2008.		

(i) Thorough investigation of history

Failures were observed and it was found that certain road pavements built to the COLTO specifications failed prematurely. No detailed observations of the actual performance and traffic counts and loads (E80s) were reported in the case study. The assumption seems to have been made that the traffic on the various roads that formed part of the case study were comparable. However, it appeared that the failures took place shortly after construction.

(ii) Identification of issues and analysis thereof (typical identifiers of issues)

The observed three road-pavement failures exhibited localised bleeding, stone loss and rutting. One road exhibited crocodile cracking of slurry seal and the other bleeding and rutting. These were regarded by the authors of the case study to be attributable to base-course failure.

(iii) Risk analysis

The observations by the authors are that premature failure occurred when Karoo dolerite is used. This occurred despite the fact that COLTO specifications were used. This brings about the risk of substantial economic risks and rigorous testing to reduce the risk of premature degradation of the dolerite is essential.

(iv) System responses

The road considered part of a transportation system, is considered in a state of failure when rapid deterioration is observed to take place. The deterioration will, most likely, lead to potholes and may cause damage to vehicles.

(v) Unwanted events

This relate to the consequences of road pavement failure that may include potholes and motor accidents as a result.

(vi) Root causes

The root cause was identified as being the rapid deterioration of Karoo dolerite. The dolerite used in the road pavement structure as a base course exhibited weathered products and degraded rapidly, thereby losing its strength as a base course layer, and subsequently failed. This was evidenced by the results of the Durability Mill Index (DMI) which showed that the dolerite deteriorated during milling, as against the non-weathered dolerite which deteriorated less during milling.

(vii) Evidence

The case study is based on the evidence that some roads that utilized Karoo dolerite deteriorated, whilst others did not.

(viii) Problems, constraints and issues

The issue is mainly that of identifying dolerite that would have the propensity to degrade and lose its strength.

a) Relationships

The S-Field approach would best describe relationships.

The relationships between the stated parameters are as follows:

- Aggregate in the quarry AND selected aggregate to be used for road building. (*Field: Mechanical energy – excavate/blast-apply breaking energy.*)
- Selected aggregate AND excavation technique. *(Field: Mechanical energy – apply loading energy, abrasion between particles.)*
- Length of time it is stockpiled/stored in the borrow pit AND rate of deterioration. *(Field: Chemical reaction with water and oxygen.)*
- Conditions of stockpile AND rate of deterioration. *(Field: Chemical reaction – water and oxygen; e.g., not well-drained pit and stockpile can be inundated.)*
- Breaking down of material AND The method of handling. *(Field: Mechanical energy – loading and hauling.)*
- Breaking down of material AND methods of placement and compaction effort. *(Field: Mechanical energy resulting in compressive forces between particles.*)
- Exposure of completed layer AND process of base course on top of the dolerite. *(Field: Mechanical and chemical weathering.)*
- Potential ingress of water AND pavement-surfacing type and quality. *(Field: Mechanical strength properties – loss of effective stress.)*
- Drainage conditions on the road AND potential water ingress into base-course layer. *(Field: Mechanical strength – loss of effective stress and chemical reaction – degradation of aggregate.)*
- Traffic conditions on the road AND rate of mechanical degradation of sub-base course. *(Field: Mechanical forces due to traffic.*)

The above interactions between concepts were not specifically addressed in the case study. The authors suggested the use of wave propagation techniques between boreholes to assess the quality of the material. The above S-field relationships (in italics) indicate potential areas of concern and need to be considered when dealing with potential degradable aggregates.

b) Knowledge-acquisition techniques

The instance of the Karoo dolerite triggers thoughts about the performance of many other road-building materials and raises questions regarding the accuracies in the prediction of durability, and if current methods are satisfactory. One can probably come to the conclusion that rigorous monitoring needs to be done to correlate the performance of particular roads with the materials and construction methods employed. Experience gained by analysing this case study may alert practitioners doing designs and drafting specifications of Karoo dolerite in other projects, perhaps even in the use of dolerite elsewhere, or weathered igneous rock in general. This represents examples of critical thinking and knowledge spill-over, as well as case-based reasoning.

MODULE C:

The reporting is done in **Table 5.14**

Table 5.14 Outputs of logic base – Module C

	ONTOLOGY	**CASE FACTS AND LESSONS LEARNED – KNOWLEDGE GAINED FROM THE CASE**	**OUTPUT PROTOCOLS**
1.	Thorough investigation of history.	Important observations were made of premature road failure. Good records were kept of borrowpits used to source the dolerite. Records were kept of materials used during construction.	
2.	Identification of issues and analysis thereof (typical identifiers of issues).	Premature road failure, mainly rutting, bleeding and crocodile cracking.	
3.	Risk analysis.	Early identification of the problem of dolerite degradation is important to prevent recurrence.	
4.	System responses.	COLTO specifications for durability of base course aggregates need updating.	Ensure specifications adequately address the correct/applicable attributes of material in the

			required application.
5.	Unwanted events.	This is the degradation of the aggregate.	
6.	Root causes.	Root causes: the lack of ability to identify potentially degradable aggregate.	
7.	Evidence.	Evidence comes down to the keeping of good records of material properties.	Records of material properties and construction techniques must be kept.
8.	Problems, constraints and issues.	Ability to identify and select durable dolerite from the borrow pit.	Selection of material at source and all subsequent activities should support material characteristics.
9.	Functional analysis.	**Table 5.13**	

5.7.4 Remarks on the examples

The above three examples show that logic base contains three modules that can be used to map and analyse case studies. The three case studies differ widely in their nature: the first is of a structural nature, the second of an information nature and the last of an investigation nature. The examples indicated that, despite the variety in nature, the logic base demonstrated its capability to cater satisfactory for each case.

When designing or drafting concept maps, tacit knowledge can be revealed. It also gives the opportunity to give consideration to knowledge theories, which were discussed in Chapter 2, such as critical thinking, knowledge spill-over and the handling of complexities.

5.12 CHAPTER 5 SUMMARY

In this chapter the final design of the logic base was done. The preceding chapter (Chapter 4) introduced the subject of concept maps and showed how these could be construed as ontologies. In this chapter, the focus is concepts and on how relationships are treated. The treatment of technical parameters is introduced. A method is developed whereby an ontology could be formed through consideration of objects and attributes and pairing these with FRs. A conceptual model is developed to show how technical parameters could be treated. Finally, three examples of how case studies could be analysed, are presented.

The case studies demonstrate how case studies could be used to generate simple CSOs. The CSOs must be incorporated or mapped to an ULO, which then provides the necessary guidance to abstract the knowledge underlying the case. The analysis is done by way of classifying knowledge into the ontology provided by the ULO, which is sub-ordinate to the HLOs and the TLO. Knowledge can then be linked to the TLO for storage and retrieval purposes. Knowledge creation is advocated and alternative solutions can be generated. In addition, some possible areas of risk are highlighted. Output protocols are derived from lessons learned and are formulated to serve practitioners. These protocols are of general interest to industry although they were derived from specific case studies.

In the process of drawing concept maps and conducting analyses, various knowledge theories, in particular knowledge-acquisition methods may play a role and can be used to assist users. These can be case-based reasoning, evidence-based management, experiential learning, reflective learning, critical thinking and knowledge spill-over.

New knowledge can be created from the analysis of a case study and can be reflected in the concept map. A concept map can be updated to reflect such new knowledge. The outcome of analysis of a case study can produce some unexpected new concepts and some additional relationships can evolve. With an updated concept map, the outcome of an analysis can be viewed.

It is envisaged that a logic base will come into being, containing a library of CSOs and ULOs, together with associated relationship matrices. The logic base could reside in the cloud for any engineer to access and use in everyday work.

In the following chapter, Chapter 6 of this study, a summary is given of the interaction between the theories of knowledge and ontologies. Consideration is given at the same time to the research questions in Chapter 1 and it is indicated how this research addresses these questions. Suggestions are made for the practical implementation of the logic base.

CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1 INTRODUCTION

This chapter summarises the research, findings and conclusions of the research conducted in this study. At the end of this chapter remarks are made about the contributions of this research to knowledge management, and suggestions are made for future research.

In the first chapter of this study, the need for this research study was described. This need emanated from the requirement for learning and adaptation in the fast-changing world we live in today. Turton (2007) remarked that what we have learned in the past, is not necessarily relevant to the future due to the propensity for greater complexity over time and that we cannot base tomorrow's solutions on yesterday's experiences and today's science. New thought processes are therefore needed to meet today's challenges.

South Africa experienced a decline in the number of civil engineering professionals, who are considered as a critical and strategic resource in economic development. Lawless (2005, p.3) reported that South Africa graduated 45 engineers for every one million people in the country, lagging far behind China and the USA, graduating between 225 and 290 civil engineers per one million of each respective country's populations. This has a direct effect on economic growth and sustainability of the economic infrastructure. A large gap exists in the demand for experienced engineers and their availability. (Refer to discussions in Chapter 1.)

The objective of this research was to develop a model (termed a logic base in this study) for the acquisition, reuse and creation of engineering knowledge to address the aforesaid knowledge gap.

In this concluding chapter of this research study, the various research questions in Chapter 1 of this study are answered. Several sub-research and sub-sub research questions and their answers contribute to answer the key research question. A summary of all the research questions in this study is given in **Appendix I**.

In the following section, Section 6.2, a summary is given of the research work in this study, indicating how the research unfolded and how the logic base was designed to act as the required model.

6.2 RESEARCH QUESTIONS

6.2.1 The main research question is as follows:

***What are the key characteristics of a model (termed a "logic base" in this study) for* the acquisition, reuse and for the creation of knowledge in a civil engineering environment?**

The main research question can be answered best by considering a series of sub-research questions, numbers (a) to (h), where the answers of each sub-research question build up to the answer to the main research question. Most of the sub-research questions have several sub-research questions (these are sub-sub-research questions in terms of the main research question).

a) What are the most appropriate knowledge elements to be considered for inclusion in the proposed logic base?

The following sub-sub-research questions need to be answered to enable answering sub-research question (a) above: (Note that the numbering follows the original numbering of the research questions as described in Chapter 1. The research questions are given in italics.)

i) What are the most applicable definitions of knowledge in this model?

There are numerous definitions of knowledge. In Chapter 2, (refer to section 2.3.1) an overview was given of the definitions of knowledge. From the various definitions, a definition of knowledge was formulated that would best apply to this study.

The definition of knowledge, for the purpose of this study, was formulated as, "Knowledge is an awareness, consciousness, familiarity, perception or understanding that causes the possessor to have a practical command of, or competence, skill or expertise in, or the capacity to act on a particular subject. It is acquired through learning, erudition, instruction, study or practice (actions)."

Furthermore, an exposition was given of the various aspects comprising the definitions and it was shown that the definition describes what knowledge is, how it is acquired, processed and applied. It was also explained how the definition could be seen to describe a system.

Since a logic base follows a systems approach, this definition of knowledge is highly applicable to this study.

From the definition one can see that knowledge is very personal (seen as a human asset) and the question arose how knowledge is represented in the human mind. This led to the second sub-research question.

ii) In what way is knowledge represented in the human mind and how does this relate to the logic base?

In Chapter 2, an exposition is given of aspects of cognitive psychology and how knowledge is represented in the human mind. Mental representation deals with objects, events and ideas (Sternberg, 1999, p.115). The view of researchers is that thinking involves the processing of mental presentations in one's mind. These mental representations can be interpreted as mental models (or images) and are powerful ways of representing certain kinds of knowledge (Smith, 1998, p.18). From the discussions on mental representation it was deduced that symbolic models and associations are strongly related to visual images. The conclusion was made that cognitive psychology supports the idea of producing sketches, diagrams or maps to emulate the representation of knowledge in the human mind. This led to the use of concept maps as part of the ontology of the logic base.

Knowledge comprises different types and are addressed in the third sub-research question.

iii) What types of knowledge can be identified in the civil engineering environment?

This topic was covered in several sections in Chapter 2. The knowledge hierarchy and different types of knowledge were discussed. Distinctions were made between data, information, knowledge and wisdom. It was pointed out that "knowledge is information incorporated in an agent's reasoning and made ready either for active use within a decision process or for action" (Pomerol and Brezillon, 2001, p.2). It was also pointed out that one has to have prior knowledge to be able to transform data into information and information into knowledge.

Different types of knowledge can be identified. Firstly, work by Polanyi (1958) was noted who drew a distinction between tacit (unconscious) and explicit (conscious) knowledge. Referring to Sveiby (1998) and Zack (1999), tacit knowledge develops as a by-product of action and functions in the background to assist in accomplishing a task in focus.

The above perspectives on what knowledge is and the two very basic types of knowledge, namely tacit and explicit knowledge, are aspects of knowledge that function in the background, in the logic base, and are used to formulate concepts about the work in focus.

Zack (1999) distinguished between different kinds of explicit knowledge. These are declarative, procedural, causal knowledge and context-specific knowledge (refer to **Table 2.1**).

In Section 2.11 the work of Zack,1999; Tobin 2006; and Gašević, Djuric and Devedžić 2009, were combined in **Table 2.7**, where different knowledge types were summarised, as well as the knowledge sources from corporate-management practices. **Tables 2.2** and **Table 2.7** refer to the different types of knowledge and also to the sources. Although this has a generic character, this equally holds true for civil engineering. This was illustrated in **Appendix C**, showing abstracts from published literature in civil engineering.

Summarising the foregoing, in answer to the first sub-research question a), the most appropriate knowledge elements that were to be considered for inclusion in the knowledge base were found to be the representation of knowledge by way of concept diagrams and to take cognisance of the different types of knowledge. This included both tacit and explicit knowledge that form important knowledge elements.

Once one became aware of the different types of knowledge, one then has to consider the sources of such knowledge. This is covered in the next sub-research question.

b) What sources of existing knowledge are available and how does this knowledge relate to the proposed logic base?

In order to answer this research question, it is most useful to consider two sub-sub-research questions.

i) In what form or structure is existing knowledge available?

It was found that there is a plethora of sources of engineering knowledge and, more specifically, in the field of civil engineering. Apart from numerous subject-specific publications, knowledge in electronic media abounds. An example was given in **Appendix C** of Chapter 2, of the types of knowledge found in publications and journals of the South African Institution of Civil Engineering (SAICE). A further development in knowledge management was referred to in Chapter 2), dealing with knowledge representation techniques in the software environment. Specific mention was made to software named “E-COGNOS” which was designed using a construction-specific ontology. It was designed to function as a single point of entry to enable the search of knowledge bases (E-COGNOS Project, 2003).

In Chapter 2, dealing with ontologies, the approach to knowledge management in the E-COGNOS project was discussed. For example, to identify the taxonomy for the domain knowledge of construction contracts, the publication “General Conditions of Contract for Construction” of the American Institute of Architects, was selected as the knowledge source. Several papers were published over the years on the representation of knowledge in the architectural, engineering and construction domains (AEC). The focus was mainly on the development of hierarchical systems and ontologies supporting the knowledge domains. Work breakdowns, process flows or indexing approaches were mostly followed and interrelationships between entities were studied. Once an ontology was developed for a specific domain, knowledge about entities and the attributes could be linked to the ontologies.

In answer to sub-question i) above, the structure of existing knowledge comes in both structured and unstructured forms. The unstructured knowledge can be, for example, the knowledge contained in magazine articles containing several types of knowledge in a single article and the knowledge can therefore be seen as unstructured. In subject-specific journals for instance, specific knowledge is addressed and is therefore more structured. As described above, the recent developments in ontologies provide a platform for organising and staging of knowledge. The necessary structure was designed and taxonomies created to arrange knowledge in a systematic way.

Once the knowledge became available, how usable is it? This aspect is discussed in the following sub-research question.

ii) How usable is existing knowledge to the practicing engineer?

In answer to this second sub-sub-research question, the usability of the knowledge is determined by the needs of the person accessing the knowledge. The knowledge is taken from various sources and linked into a knowledge base to the various taxonomies. It is difficult to use such knowledge as complete entries. The knowledge can be fragmented and one has to follow links to other parts of the taxonomies to enable harvesting of a complete knowledge entity. The existing ontologies make use of tree-like structures or work-breakdown structures, process flow and/or indexing. Furthermore, information is typically provided and referenced, but much knowledge is not necessarily provided. This approach was not considered particularly suitable for knowledge recording and reuse in civil engineering. The approach used in this study was to rather use concepts in a systems context to build ontologies representing knowledge and, for example, contain logic for recording learnings and analysing problems. The emphasis in this study was on the formulation of concepts, their classification and for studying interrelationships between concepts. This approach enhances knowledge because a systematic way, through the use of suitable ontologies is used to analyse existing knowledge and search for more knowledge within existing sources.

In Chapter 4 of this study, the ontology of the logic base was designed with the end-goal in mind. This was to enhance knowledge through acquisition, reuse and knowledge creation. This approach would, greatly enhance reusability.

Once knowledge is harvested, the next sub-research question follows of how to reuse knowledge.

c) How can existing engineering knowledge be reused?

In answer to this sub-research question, two sub-sub-research questions need to be answered.

i) ***What methods and processes are there for transferring knowledge to individuals for reuse?***

Knowledge transfer has to be seen against the background of knowledge conversion. The Nonaka and Takeuchi model of knowledge conversion was discussed in Chapter 2, under the role of organisations. Reference is made to Figure 2.10 in Chapter 2, duplicated as **Figure 6.1** in this chapter.

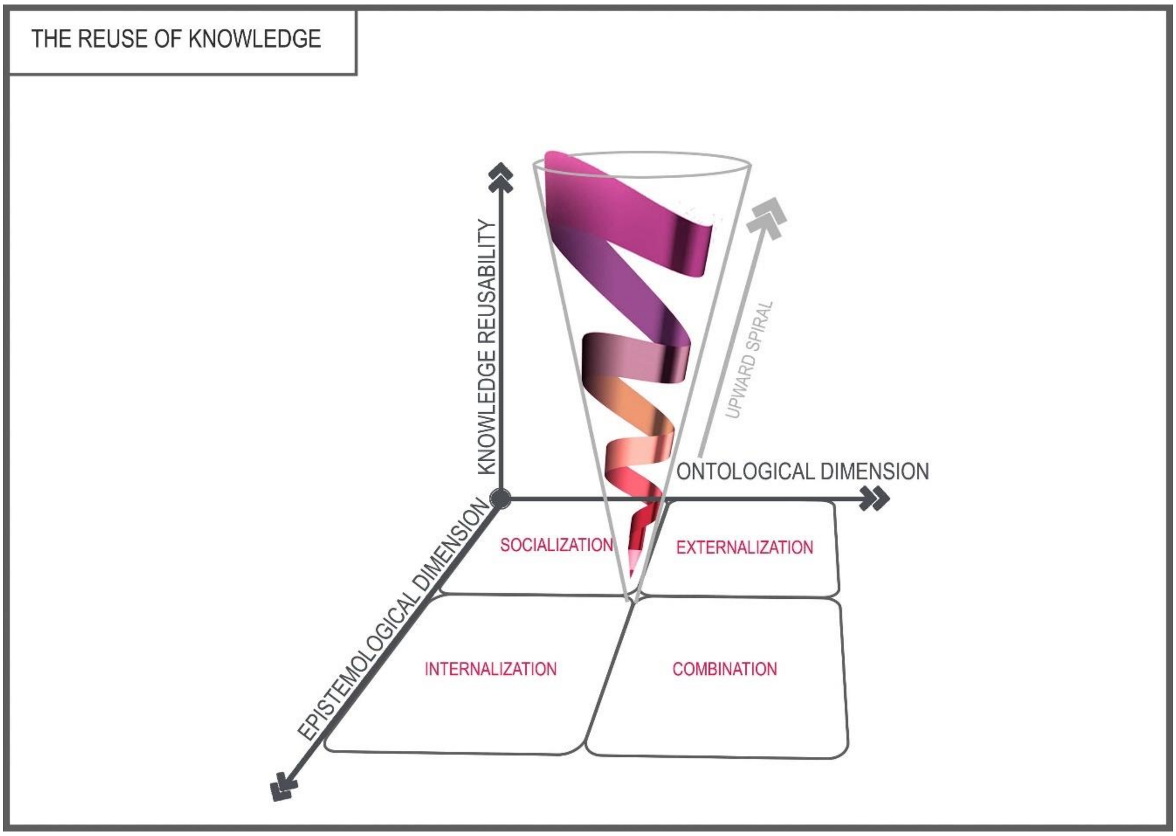

Figure 6.1 The reuse of knowledge (Harsh, 2009)

In Chapter 2, the processes of knowledge were explained and summarised as follows:

By studying the four quadrants of the two-dimensional block at the base of the diagram in **Figure 6.1**, it shows that when Individuals participate in socialisation and in other interactions with people, knowledge conversion takes place from the tacit to explicit domains and from the explicit to tacit domains through internalisation. Tacit knowledge is converted to explicit knowledge when reports are written or narratives are shared. Explicit knowledge can be seen as independent of the individual and can be shared with others, i.e., this knowledge can be retrieved to make it available as usable knowledge. When experience is recorded, actions of other people are revealed and assimilated. Through internalisation, this adds to the tacit knowledge of individuals.

Based upon the Nonaka and Tacheuchi model of knowledge creation, Harsh (2009) added a third dimension, shown as a cone above the two-dimensional model, representing knowledge increase through reuse. Harsh's argument is that as knowledge reusability increases, knowledge increases. It also implies that as knowledge is converted, knowledge as well as knowledge reuse increase.

Markus (2001) mentioned four types of knowledge reuse situations, namely:

- shared-work producers that produce knowledge that they can reuse later;
- shared-work practitioners who reuse each other's knowledge contributions;
- expertise-seeking novices; and
- secondary-knowledge miners.

In civil engineering the above situations and processes also take place. For example, investigations are carried out, feasibility reports are written and drawings are prepared as part of design and development processes, thereby communicating knowledge to others. Meetings are held on projects, whereby knowledge transfer takes place by way of socialisation processes.

Gaining knowledge always implies that one has to understand the context to enable reuse. This led to the next sub-sub-research question.

ii) How would one understand or assimilate the context of existing knowledge?

This question can be answered by considering the various knowledge management practices as described in Chapter 2, Table 2.2, depicting a consolidated list of knowledge management practices. Each so-called practice puts knowledge in a different context. The context is represented by the milieu and the purpose for reuse. For instance, the purpose of an incident report on a failure is mainly to educate people from the lessons learned about potential problems or hazards that one may encounter in future, in similar situations. The same knowledge contained in lessons learned could find its way into standards and specifications which differ in context and content from the sharing of lessons learned. Taxonomies and ontologies should cater for context-specific applications.

The design of a logic base was aimed at addressing context and knowledge reuse. As was discussed in subsequent sections in Chapters 2 and 4, ontologies were developed by using concept diagrams to capture context-specific applications. Contents and context are embedded in the drafting of case-specific ontologies. For example, one of the Top-Level concept groups is "Setting and context" (refer to **Figure 4.7** in Chapter 4). In Section 4, a more detailed exposition was given on this concept. This concept contains 11 sub-domains covering aspect such as the location of the case, people-related issues, organisation and management thereby discloses contextual information.

The question regarding reuse and context therefore answers the research question about knowledge reuse. The knowledge being entertained in this case related primarily to engineering knowledge, but not necessarily limited to engineering.

Apart from reuse of knowledge, development was needed. The dynamics of civil engineering demand ongoing problem-solving, leading to knowledge creation. This is covered by the following sub-research question.

d) How can knowledge be created?

This question raises two sub-sub-research questions.

i) What stimulates thought processes to create engineering knowledge?

In answer to this first sub-sub-research question, Sections 2.4 and 2.7 of Chapter 2 of this study, it was pointed out that the creation of engineering knowledge was mainly driven by the need for problem-solving. Problems encountered by engineers, stimulate devising new ideas to overcome these problems. Problem-solving in itself involves a process of knowledge creation and updating of existing knowledge. There is a vast number of problem-solving techniques available. In Section 2.7 of Chapter 2 of this study, various problem-solving techniques were chosen and discussed in support of the logic base.

The chosen techniques were as follows:

a) The Cynefin framework. (Considered as part of problem-solving and decision making. (Refer to Section 2 in Chapter 2 of this study.)

b) Engineering design (including axiomatic design), can also be seen as special kind of knowledge creation and problem-solving technique. (Refer to Section 2.8 of Chapter 2.)

- Trigger-word technique.
- Checklist technique.
- Morphological analysis.
- Attribute-seeking technique.
- Brainstorming technique.

- Synectics.
- Analysis and synthesis.
- Root-Cause Analysis (RCA).
- Failure-Modes, Effects and Criticality Analysis (FMECA).
- FAST (Functional Analysis Systems Technique).
- HOT (Hierarchy of Objectives Technique).
- TRIZ (Theory of Inventive Problem Solving).
- TOC (Theory of Constraints).

In summary, the following common aspects to almost all these problem-solving techniques were found:

- Identification and definition of elements and context are done.
- Causes and effects are uncovered.
- Relationships are investigated (common to Morphological analysis, attribute-seeking, RCA, FMECA,TRIZ and TOC).
- Prompting takes place to expand discovery.
- Classification of themes is done.
- Anticipative thinking techniques are involved.
- Analogies are used.
- Analysis and resolving of contradictions are carried out.
- Hierarchical divisions are made.
- Constraints are uncovered.

The above summary of common aspects strongly suggested their incorporation in the functionality of the logic base. The study of relationships was found to dominate the problem-solving techniques. It can be seen in subsequent sections of this study, that the logic base incorporates problem-solving and the study of relationships.

In Chapter 5, section 5 of this study, it was shown how relationships among technical parameters could be catered for. A multi-dimensional concept map is shown in **Figure 5.5**, where concepts are listed, and the interaction among the concepts is illustrated. This could also involve mathematical relationships or correlations. This was included because in the complex real-world cases, the knowledge of relationships among variables can add to experience and learnings.

The application of problem-solving techniques and the study of relationship are stimuli for knowledge creation.

Knowledge creation and knowledge acquisition go hand-in-hand. When any knowledge is acquired, from whatever source, it is weighed up against the background and context and tested by application of problem-solving techniques. This is discussed in the next sub-sub-research question.

ii) What processes would enhance knowledge acquisition and knowledge creation?

Knowledge acquisition techniques were discussed in Chapter 2, Section 2.6. In this study, knowledge acquisition was understood to relate to the acquiring of existing knowledge, whilst knowledge creation goes the step further, by adding to existing knowledge.

Knowledge acquisition techniques seed the process of knowledge creation. Knowledge acquisition and problem-solving are very closely related. This is supported by several authors, (Itabashi-Campbell, Perelli and Wayne, 2011; Nonaka, 1994; Leonard and Sensiper, 1998; Snowden, 2004) indicating that knowledge creation and problem-solving are closely related. “One of the ways that learning and knowledge creation may be prompted is by problem-solving” (Itabashi-Campbell, Perelli and Wayne, 2011, p.1). The goal of their study was to “generate a grounded theory about the way engineering problem-solving results in organisational learning and knowledge creation.”

Pre-existing knowledge is required to solve problems, and for creating knowledge.

As pre-existing knowledge is used to solve a particular problem, existing knowledge is updated with new knowledge which enables the solving of new problems. This process forms a spiral of knowledge increase. This process is illustrated in **Figure 6.1** (where the upward spiral of knowledge reuse is depicted), which indicates an ongoing cycle of knowledge increase resulting in the solutions to problems, and the solutions updating existing knowledge, that in turn increases one’s ability to solve further problems.

As a basis for knowledge creation, it is important for engineers to acquire knowledge. Knowledge acquisition constitutes one or more processes. Useful knowledge-acquisition techniques were selected and were discussed in Section 2.6 of Chapter 2 of this study.

The following knowledge-acquisition techniques were discussed:

- Case-based reasoning.

- Evidence-based management.
- Experiential learning.
- Reflective learning.
- Critical thinking.
- Knowledge spill-over.

The methods of knowledge creation, knowledge reuse and knowledge acquisition were found to exhibit the following common elements (refer to section 2.6.7 of Chapter 2):

- Tacit knowledge plays an important role.
- Awareness is enhanced.
- Complexity is handled (refer to sense-making through the Cynefin framework and also morphological analysis).
- Reflective actions are evaluated.
- Content-process premise is considered.
- Critical thinking takes place.
- Cause-effect relationships are identified and analysed.
- Experiments take place (even in a very controlled manner).
- Exaptation (knowledge spill-over) takes place.

The aspects of knowledge creation, reuse and knowledge acquisition were taken into account in the operation of the logic base. This is in essence done when one constructs concept diagrams for particular cases. The construction of the concept diagrams causes knowledge to be converted from tacit knowledge to explicit knowledge. This was described in Chapters 2, 4 and 5 of this study.

In order to conduct further research, it was necessary to consider various research methodologies to establish a basis for the development of ontologies. The research method are discussed in answer to the following sub-research question:

e) What research methodologies are most applicable for the discovery and application of engineering knowledge?

6.2.2 General remarks on research methods

Research design and methodologies were discussed in Chapter 3 of this study. The findings of the research conducted in Chapter 3, formed important inputs to the design of ontologies for incorporation in the logic base as described in Chapters 4 and 5.

a) Applicable research methods

A study of research methods was conducted in chapter 3 whereby a ranking system was used to identify the research methods that were considered most applicable to this research. The following research methods were considered in the evaluation and ranking:

- Qualitative research
- Case-study research
- Action research
- Evaluative research
- Descriptive research
- Exploratory research

All the above methods are aligned to qualitative research. Case-study research was found to align well with descriptive, evaluative and exploratory research. Only case-study research and action research were considered for further discussions since these incorporate the other research methods.

6.2.3 Action research

Action research was reported to be unlike traditional research, essentially work-place based. It could be seen as a form of professional learning. The main reason for professionals doing action research is firstly to improve learning in order to improve workplace practices. Secondly, one can advance knowledge and theory about how things can be done and why. The process of action research involves observation and reflection on the observations. Actions are then devised in response to the observations and reflections. The actions are evaluated and modified as required to produce the desired outcome or results from the actions.

These are similar to experiential learning and reflective learning, previously described in knowledge acquisition methods in Chapter 2, Section 2.6. Also applicable is the Cynefin framework, where use is made of the same processes, especially in the chaotic and complex domains. (Refer to Chapter 2, Section 2.4.8.)

Action research plays an important role in engineering practice and constitutes a dynamic environment with both practical and theoretical components. Practical experience and theories are seldom recorded as such and remain in the memories of practitioners as tacit knowledge. Action research endeavours to formalise learning and experience and to create new theory. McNiff and Whitehead (2011, p.2) put it that, “Your practice is the grounds for your own theory”. Published case studies are often the result of action research. The logic base sought to provide a basis for the extracting and recording of such knowledge generated by action research and to enable replication thereof.

This study can also be construed as an action research study.

6.2.4 Case-study research

Case studies form important sources of knowledge in the civil engineering industry. **Table 3.3** in Chapter 3 of this study mentioned some examples of sources of case studies in engineering. The major objective of a case study is to provide a way through which learning (e.g. analysing, applying, reasoning, drawing conclusions) could take place.

Case studies are very specific in the knowledge they convey since case studies typically focus on a single bounded system and involve a limited number of units of analysis (Welman, Kruger and Mitchell, 2005, p.25). Case study research is a common form of descriptive research in management It is an in-depth description of an individual, group or organisation, either for the purpose of testing whether one or more cases fit a particular theory better than another or to determine what makes a case superior, inferior or different to another (Page and Meyer, 2000, p.22). “The term *case study* does not refer to a specific technique that is applied” (Welman, Kruger and Mitchell, 2005, p.25 and p.193). Hofstee (2006, p.123) remarked that “a case study examines a single case in a tightly structured way.” The former two aspects made case studies ideal for this study in the development of ontologies. This structured form of case studies was one of the important characteristics that led to consider the suitability thereof for defining the ontology of the logic base.

6.2.5 Case studies and types of knowledge

Following the research conducted on the applicability of case studies to the development the logic base, a further assessment was described in Chapter 4. In this assessment, summarised in **Table 4.1**, the various types of knowledge were mapped against the specific knowledge as detailed in **Table 2.7** of Chapter 2. The various knowledge types were:

- Procedural knowledge
- Declarative knowledge
- Meta knowledge
- Heuristic knowledge
- Structural knowledge
- Inexact and uncertain knowledge
- Common-sense knowledge
- Ontological knowledge
- Specific knowledge

The mapping showed that all the above types of knowledge could conveniently be addressed by case studies. From this mapping, it was concluded that case studies, albeit in many forms, fulfil the needs required for the development of a logic base. Case-study research was therefore chosen, as the most suitable research method. Case studies are considered important as source of knowledge that should be recorded in the logic base.

6.2.6 Topics of case studies

The chosen topics of case studies were considered to be typical, generic, descriptive and sufficiently representative of the characteristics of case studies in general. The topics of case studies were found to meet the requirements for structuring a suitable ontology for the logic base. A mapping was shown in **Table 4.1** in Chapter 4 to show that case studies are capable of reporting on all types of knowledge. (Types of knowledge refer to procedural, declarative, meta, heuristic, structural, inexact and uncertain, common-sense, ontological and specific knowledge.) Another mapping was carried out and shown in **Table 4.2**, indicating that the characteristic topics of case studies, also matched the desired attributes of the proposed logic base. (Refer to the list of desired attributes of the logic base in **Table 2.4** in Chapter 2; and in section 4 of Chapter 4.) The mapping of knowledge types, the exercise on practical case studies and the mapping of desired attributes, (refer to **Appendix F**) demonstrated that all the required attributes of the logic base can be accommodated under the various topics of case studies. This led to the choice of developing the ontologies from the topics of case studies.

The chosen topics of case studies were synthesised from work by Hofstee, 2006; Page and Meyer 2000; Welman, Kruger and Mitchell, 2005; Yin 2003. When considering a complete system, the topic, "Operations and Maintenance" is added. Finally, the topics chosen were as follows:

- Introduction and scope.
- Design.
- Construction/manufacturing.
- Operations and maintenance.
- Setting context/narrative/role players/relationships.
- Sequence of events and causal path.
- Investigation and analysis.
- Interpret outcomes, solutions and actions taken.
- Lessons learned/education.
- References.
- Influences.

These topics were then re-defined in this study as the highest hierarchical level of an ontology (Top-Level Ontology [TLO]) for the knowledge in the logic base, as described in Chapter 4. (This ontology can also be referred to as the foundational ontology or core reference ontology.) (Reference is made to Roussey *et al.*, 2011.) This Top-Level Ontology (TLO) is shown in **Figure 4.7** in Chapter 4, and for convenience repeated in **Figure 6.2**.

The study on research methods provided the input for the definition of the top-level ontology. The next sub-sub-research question is what the components of the logic base should be. This is discussed in the next sub-sub-research question.

f) What components are required for the logic base?

The following sub-sub-research questions pertain:

i) How can knowledge acquisition, reuse and knowledge creation be translated into components of a logic base?

The answer to this question can be found in Chapters 4 and 5 in the development of the logic base. Knowledge in the case of the logic base, consists of several components or modules. The modules consist of three modules, namely, the concept diagrams (input module), analysis and reporting modules.

The ontologies developed for the logic base could provide the facility to act as repositories for engineering knowledge. When recording specific knowledge, appropriate indexing can be done for linkage to a civil engineering ontology. (It was not part of this study to develop a suitable ontology for civil engineering.) Such links could guide an engineer to other areas of interest, as normally done when searches for information are conducted. The TLO and HLO's contain a large number of concepts that can act as prompters for knowledge. When drafting concept maps the user/engineer is reminded or prompted for relevant knowledge. This reference to the TLO and HLOs assists with knowledge conversion from tacit to explicit knowledge. This process can be enhanced when more than one engineer or a group of engineers deliberate cases whereby the socialisation assists with knowledge conversion. Once knowledge is in the tacit knowledge domain, reuse becomes possible. In addition, it was noted in Chapter 2, sections 2.5.3 and 2.7, that problem-solving added to knowledge acquisition. Knowledge acquisition was covered by this component and also by the component for problem-solving (in the analysis module). Problem-solving was found to be strongly related to knowledge creation for which the analysis component made provision.

In Chapter 2, a prerequisite for knowledge reuse was found to be the context of existing knowledge. The Top-Level concept diagrams provided for a specific Top-Level Ontology (TLO) grouping, named “setting and context”, so that knowledge reuse could be affected.

The components of the logic base therefore provide for knowledge acquisition, knowledge reuse and knowledge creation.

The components are all connected to model a system. The next important aspect of the logic base is the relationships between the components and sub-components are described in the next sub-sub-research question.

ii) What are the relationships among the various components and how would the components contribute to the functioning of the logic base?

This sub-sub-research question is answered by considering the design of the logic base as given in Chapter 4 of this study. Concept diagrams were chosen and used to design the basic ontology component of the logic base. Each component and sub-component represents a concept or a group of related concepts and sub-concepts (also referred to as schemata). The topics of case studies were redefined to form a Top-Level Ontology (TLO) for knowledge management. The relationships between the concepts and even their attributes formed part of the analysis of cases. The relationships among concepts were found to be the most important identifiers of problems and constraints that are necessary to solve problems. The grouping of concepts models a system. The solutions to problems can be stored by making use of the Top-Level Ontology (TLO) or the next hierarchical level, called the High-Level Ontology (HLO). In addition, relationships between concepts could be analysed to identify causes and effects, constraints or contradictions which can be transferred to the output module of the logic base and stored as such.

In summary, each component of the logic base interacts with the others. This was illustrated in **Figure 5.6** where Module A (input module) is followed by Module B (analysis module) and Module C (reporting module). The reporting module contains all the outputs of the logic base and constitutes a source of knowledge.

iii) What criteria are required to provide the functionality of knowledge acquisition, reuse and knowledge creation and how can the criteria be satisfied?

The criteria for functionality relates to the attributes of the logic base and the way the functions of knowledge acquisition, reuse and knowledge creation could be accommodated in the logic base. The logic base utilises concepts and the relationships among the concepts. A specific over-arching criterion is to define concepts correctly as well as the relationships among them. (When concepts are analysed it can be found that some re-definition of concepts is required to better display problematic relationships.)

The criteria for the above functions can be expanded as follows:

- For knowledge acquisition: A repository is required from which to source knowledge. With the term *knowledge,* a criterion is to clearly and appropriately define all the key concepts with their associated attributes, the key relationships among the concepts and the identification and resolution of problems that are described in a case.

- For knowledge reuse: A criterion is to correctly *understand* the context of existing knowledge. When solutions are sourced from exiting knowledge bases, one has to understand the full context to enable reuse.
- For knowledge creation: A criterion is to correctly identify and describe the problems and the *resolution* of the problems in the case under consideration.

g) What is an appropriate architecture of a logic base to fulfil the Functional Requirements (FRs) for the acquisition, reuse and for the creation of knowledge?

The following sub-sub-research questions pertain:

i) What ontology and/or taxonomy can form the basis of the design of a logic base?

ii) How sensitive are the ontologies for different applications?

The answers to these sub-sub-research questions i) and ii) are given together.

A description on the design of the ontology for the logic base was given in Chapter 4. This design was carried out against the background of the discussions on the structure and architecture of knowledge in Chapter 2, section 2.9 and more specifically, ontologies in section 2.9.2. It was shown from the literature that ontologies modelled information and knowledge in the form of concept hierarchies (taxonomies), interrelationships between concepts, and axioms (Noy and Hafner,1997; Noy and McGuinness, 2001). The interpretation and development of the ontology for the logic base is made in Chapter 2 by first considering the typical topics found in case studies. These topics were re-defined into an ontology that provided a generic, logical grouping and sequence of concepts that interacted to form a system. This defined the basic architecture of the logic base. (Also, referred to as the foundational ontology or core reference ontology and in this study the Top-Level Ontology.) The levels of participation of the various concepts in the functioning of a system vary from one case to another, or vary according to time and other influences.

The generic, Top-Level Ontology (TLO). (Refer to **Figure 6.2,** duplicated from Figure 4.7 here for ease of reference.) was considered to be rather fixed, as it represents the most generic grouping of concepts in civil engineering. (Not necessarily limited to civil engineering.)

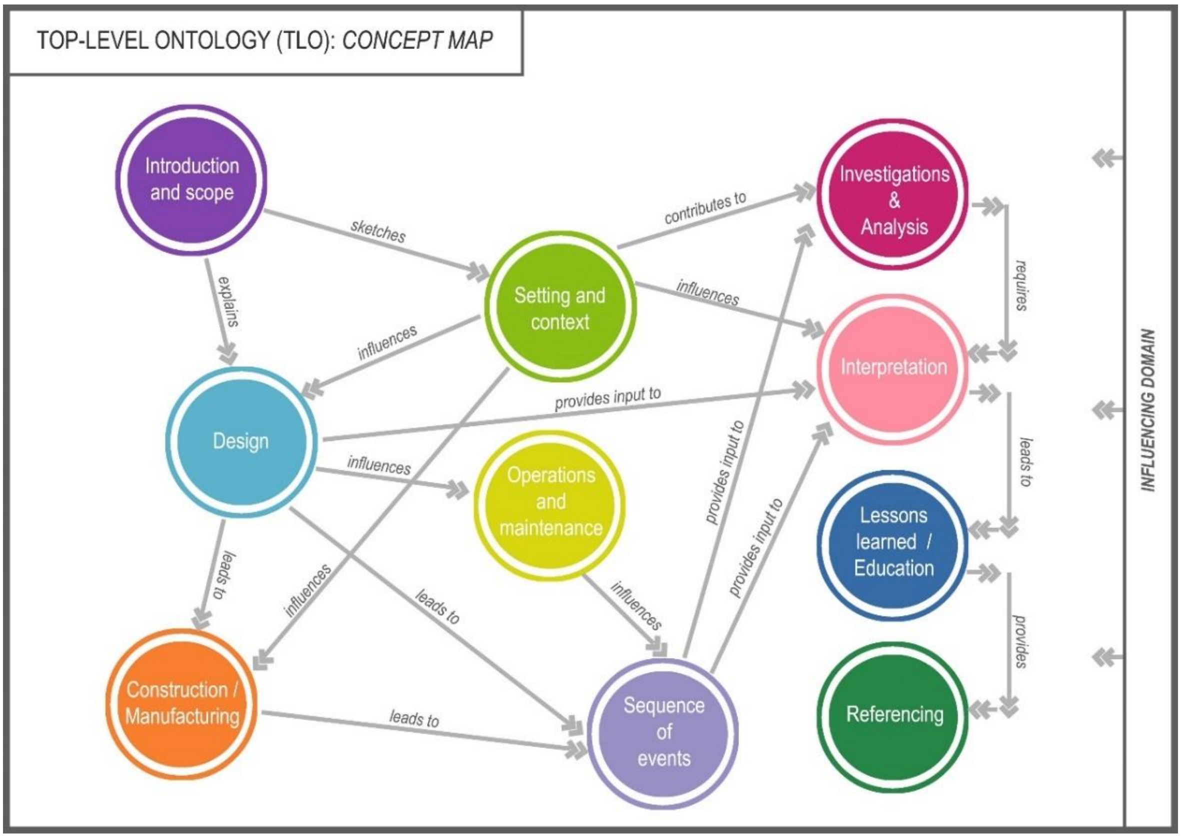

Figure 6.2 Top-Level Ontology (TLO): ***Concept map***

In Chapter 4, detailed descriptions were given of all the concepts in the first sub-ontology called the High-Level Ontology (HLO). These are essentially a break-down of each of the concepts in the TLO into sub-domains. Because of the increasing complexity, the logic base in this study only considered Top-Level, High-Level and Case-Specific Ontologies. The lower hierarchical ontologies become progressively more granular and also more sensitive to different applications. In the case of a Case-Specific Ontology (CSO), the ontology is very specific to the particular case under investigation and bears significant content. It is necessary to link the CSO to the higher-level ontologies to ensure continuity in the overall ontology structure. It also ensures system-performance and retrievability. (This can be described as a bottom-up approach.) The sensitivity to different applications is addressed by the introduction of the CSO. The CSO is case-specific and provides flexibility to enable the analysis of a large variety of cases and tying the cases to the HLOs. The architecture is therefore not considered to be sensitive to different applications. (Applications, meaning different types of cases.)

To simplify ontologies, an Upper-Level Ontology (ULO) was introduced. This comprises a selection of High-Level Ontology (HLO) concept groupings of only those that would be required under the circumstances. The choice of concepts for use in the ULO can be done on a case-specific basis. Linking of CSO to ULO is thereby made easier. The linking to the higher-level ontologies would enhance the systems approach, since many more general concepts could be found and interpreted to expand the analysis, incorporating concepts and factors not necessarily thought of when the initial CSO was drafted.

The structure of the ontologies is shown in **Figure 6.3** (reproduced from **Figure 4.17** in Chapter 4).

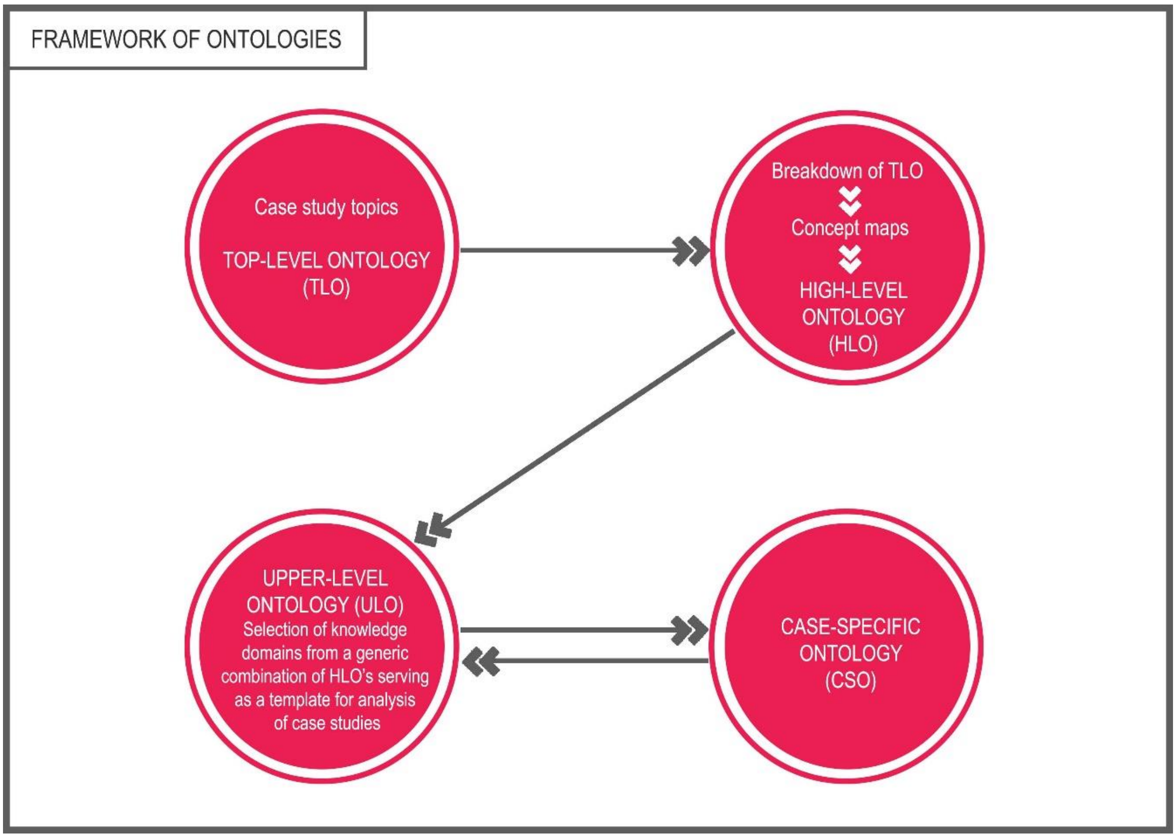

Figure 6.3 Framework of Ontologies

Summarising the answer to the sub-research question g), the architecture of the logic base consists, first of all, of the ontologies composed of concepts and groups of concepts in specific knowledge domains (Module A) and the second module consists of the analysis part (Module B). The overall performance of the system needs to be tested by giving consideration to the various factors, referred to as influencing domains, in the operations of the system (Module B1). In this module, the key applicable elements in each of the influencing domains, can be tested by way of an analysis matrix, containing a list of all the possible elements in each of the domains and all the concepts and sub-concepts. Key influences can be identified, recorded and listed in the output document of the logic base (referred to as the reporting module, Module C).

The next part, Module B2, involves the study of all the relationships between concepts. The relationships between concepts could also depend on the influencing domains. The next module of the analysis part involves problem-solving (Module B3). Problem-solving forms a key element for knowledge creation. The final part of the logic base is Module C, the part where the output documentation (called the reporting module) resides. This is where all the outcomes of the analysis are recorded. The elements in the reporting module need to be structured and aligned to the higher-level ontologies.

The FRs for knowledge acquisition, reuse and knowledge creation were facilitated in the architecture of the logic base. The logic base, and more specifically the ontology, facilitates the input of knowledge (being available for knowledge acquisition by others), whilst the reuse and knowledge creation comes into effect in Modules B (analysis and problem-solving) and C (output documentation).

Refer to **Figure 5.6** in Chapter 5 for a representation of the architecture and functioning of the logic base. The figure is repeated for convenience as **Figure 6.4**.

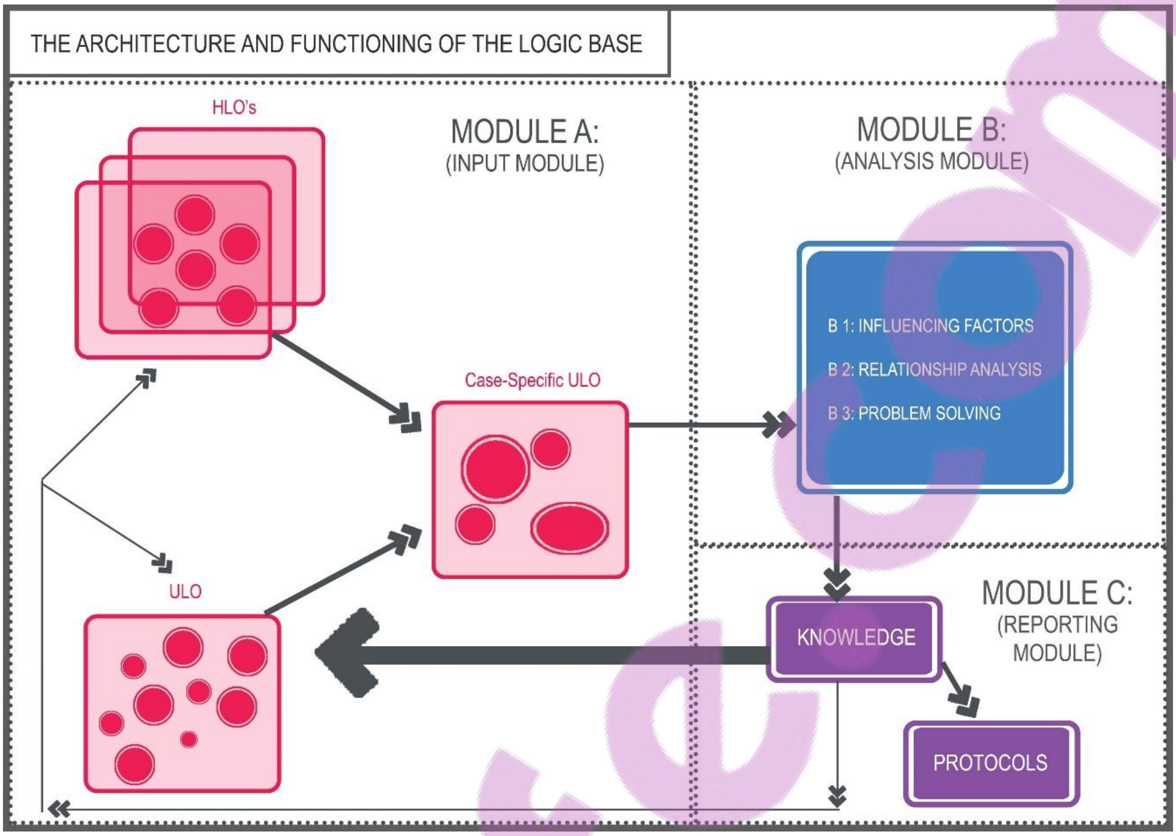

Figure 6.4 The architecture and functioning of the logic base

The architecture of the logic base was defined and the operation of the logic base need to be described. This is discussed in the following sub-research question.

h) How can one formulate an integrated model, i.e., the logic base, to function as a suitable tool for practical application, incorporating elements of knowledge acquisition, reuse and the creation of knowledge?

The following sub-research questions pertain:

i) How would all the components comprising the logic base interact to provide the required functionality regarding knowledge acquisition, reuse and creation of knowledge?

The interaction takes place by way of the integrated model for the operation of the logic base can best be summarised in **Figure 6.4.** (Also refer to **Appendices H and I.**)

The architecture was described in sub-research question g) above. The architecture describes the various components that facilitate the operations of the logic base which functions as an integrated model for practical application. The integrated model comprises three parts, referred to as modules. Firstly, Module A is where the concepts are formulated. The formulation is done by a practitioner (user). The formulation is treated as the representation of a case study or any other knowledge source. The formulation commences by compiling a Case-Specific Ontology (CSO) (bottom-up approach). This ontology has to be drawn up with the end in mind, i.e., incorporating the key knowledge aspects of the case under consideration. The drafting of the CSO requires a practitioner or group to apply their minds to the case under consideration and by so doing, ask questions and thereby reveal tacit knowledge and make it explicit. Analogies and reference to similar cases can be made lead to knowledge acquisition and knowledge creation. Knowledge reuse is thereby enhanced. (Refer to knowledge acquisition techniques in Chapter 2, section 2.6.) This CSO should then link back and tie into a suitable higher-level ontology. This process would, most likely, highlight certain essential aspects of a case that might be missing from the CSO and needs to be added to ensure a complete systems performance. Once Module A has been completed, the actions in the second part, Module B, where analysis is done, can be carried out.

Module B comprises the analysis model. There are three modules, namely,

- Module B1: Influencing domains.
- Module B2: Relationship analysis.
- Module B3: Problem-solving.

Module B1 consists of the Analysis of Influencing Domains (IFD) and the Time-Space-Capacity (TSC) interface. The entire system should be tested against the TSC relationships which could be seen as always present and interfaces with all systems and influencing domains. The list of influencing domains is given in Chapter 4, Section 4.7.13 and 4.7.14. The list of domains was stated as follows (each domain consists of a number of sub-domains and elements):

- System responses and controls
- Environmental aspects
- Influencing factors (comprising a broad list)
- Logistics
- Ownership of asset, entity or thing
- Governance

- Information and communication
- Stakeholder management and affairs
- Processes and methods
- Innovation
- Relevance (obsoleteness)
- Risks
- Safety
- Health
- Reputational impacts
- Goals

In Module B2, relationships among concepts are investigated. This analysis module consists of a matrix with all the concepts on the two axes of the two-dimensional matrix. By pairing the concepts from each axis, the relationships between the concepts, the types and natures of all possible relationships between concepts can be uncovered. The user is then required to identify all the key relationships. A comprehensive, but not exhaustive, list of possible relationships was given in **Table 5.4**. The types of relationships are then evaluated for their effects on the system. These effects are used to identify contradictions and constraints that need to be resolved. (An example of a relationship matrix is shown in **Appendix G**.) This information or knowledge leads to the third part, Module B3.

Module B3 of the analysis module involves problem-solving. The problem-solving techniques are based upon the following:

- Relationships (whether effective, missing, insufficient, excessive, harmful, etc., as listed in Chapter 5, refer to **Table 5.4)**.
- Searching for systems constraints by using techniques offered by the Theory of Constraints (TOC). (This can be made easier by using flow diagrams to represent activities and decisions.)
- Considering root causes of certain events, if applicable.
- Applying FMECA-analysis to the system to search for critical causes and effects. (This analysis also pertains to the second part of the analysis module where the roles of the various influencing factors play a role.)
- Applying TRIZ-techniques for inventive problem-solving.
- Applying FAST- or HOT-techniques.

- Apply other problem-solving techniques as listed in Chapter 2, Section 2.7. A summary of problem-solving techniques is shown in **Appendix B.**

The above would lead to solutions within the context of the case study. By way of the solutions found, existing knowledge could be updated. These should be documented for reuse and is done in Module C (output or reporting module) of the logic base. This is discussed further in the next research question.

The above would lead to solutions within the context of the case study. By way of the solutions found, existing knowledge could be updated. New knowledge is also thereby created. The knowledge pertaining to both existing knowledge and new knowledge must be documented for reuse and is done in Module C (output or reporting module) of the logic base. This is discussed further in the next research question. It is important to note that the outputs of the logic base are linked to the supporting HLOs and by definition also to the TLO. This provides the link to external knowledge bases.

The above discussions showed how the components comprising the logic base interact to provide the functionality for the acquisition, reuse and creation of knowledge

ii) What would be the inputs and outputs of the logic base?

The inputs to the logic base are knowledge derived from any suitable knowledge source where concepts could be identified, classified and put into concept diagrams. For example, a case study could provide the necessary input for concept maps, in full or in part, to link the concepts to the top-level ontology. Other sources of knowledge could also be used, such as knowledge derived from existing knowledge bases, learnings from research, lessons learned, stories told, etc. In many cases pertaining to knowledge sources, complete mapping of knowledge entities to the top-level or lower-level ontologies may not be possible due to the nature of the case. This, however, should not detract from the use of a particular source as input to the logic base. Even if a case is very simple and contains little knowledge, the possibilities of analysing and reporting new knowledge still exists. (One can, for instance find a record of a simple and single piece of knowledge.) Module C (reporting part) of the logic base comprises documentation where the output of the logic base can be put together. The output of logic base can contain lessons learned, specific solutions to problems or constraints, action steps taken, such as remedial actions where applicable, as in the case of a structural failure. Output protocols could also be formulated. Output protocols were defined as statements of industry concern and that should be noted by every practitioner in the field of civil engineering. These can emanate from failures and mistakes made in industry that must never be repeated. These protocols should be related to failures and mistakes, but successes and innovative solutions should also be documented. Examples of what should be contained in the reporting module are:

- Case facts (can be presented as concept maps).
- Comments on the concepts.
- Comments on relationships.
- Problems and solutions.
- Lessons learned – knowledge and experience gained from the case.
- Output protocols.

iii) What knowledge is required to interact with the logic base?

The compilation of concept diagrams does not necessarily require specialised knowledge. It is merely necessary to understand how to identify the key concepts of a case study or of any specific situation that needs analyses and for the identification of problems and their solutions. Any practicing civil engineer would almost intuitively be able to compile such diagrams. The analysis part is somewhat different from everyday engineering, but again an almost intuitive process. The identification of relationships and problem-solving is done by every practicing civil engineer. However, most practicing civil engineers are not very familiar with some of the problem-solving techniques such as attribute-seeking techniques, morphological analysis, word-trigger techniques, synetics, TRIZ, FAST and HOT. To a lesser extent, civil engineers are familiar with FMECA, RCA and TOC (however, mostly applied by industrial engineers, mechanical, electrical, electronic, computer and aeronautical engineers). Most civil engineers are familiar with brainstorming techniques, checklists and with analysis and synthesis. The additional requirement for civil engineers to apply some unfamiliar techniques would be enriching, but would require additional work. If these techniques are applied, it should pave the way for better and more comprehensive analyses of situations that need resolution by a civil engineer. The recording of lessons learned and solutions to problems adds to the knowledge and reuse of engineering knowledge. This could save many practitioners substantial time, and could help with the generation of innovative solutions and the avoidance of very costly mistakes. The logic base could also form a tool for quality control. Young engineers could work through the logic base to arrive at engineering solutions and present their results to their mentors for critique or signing off. Suitable training in this regard may be required.

iv) Who would be the target users of the logic base?

The target users for the logic base would be all the practicing civil engineers but could be more focused on the younger and less experienced engineers. The reason being that the logic base has the capacity to enhance the problem identification and problem-solving abilities of such engineers. Training and familiarisation in the various problem-solving techniques and in the operation of the logic base would have to be done to introduce it into the civil engineering industry.

6.3 CONCLUSIONS OF THIS RESEARCH

The basic problem in industry is the existence of an enormous volume of information, available from an equally enormous variety of sources. The need is to turn vast amounts of information into usable knowledge for use by an engineer in practice. Restructuring of knowledge is one way of approaching this need and is addressed in this study. This shortcoming forms the reason for this research and for the design of a model for the acquisition, reuse and creation of knowledge in a civil engineering environment. This led to the main research question stated below.

6.3.1 The main research question

What are the key characteristics of a model (termed a "logic base" in this study) for the acquisition, reuse and for the creation of knowledge in a civil engineering environment?

This main research question led to various sub-research questions and sub-sub research questions and were dealt with in the foregoing research.

In summary, the answers found to this main research question are summarised below.

It was found that knowledge acquisition and knowledge creation are primarily based on knowledge conversion processes as well as on the study of existing sources of knowledge. The foregoing are supported by techniques, such as the Cynefin framework, case-based reasoning, critical thinking, experiential learning, etc. Knowledge reuse stems from all these, since once knowledge becomes or can be made explicit, it can be reused. Knowledge creation also derives from problem-solving. Numerous problem-solving techniques were presented in this study, of which TRIZ, TOC, FMECA, RCA and HOT- techniques, were of particular importance. Ontologies were designed to provide the logic structure to accommodate the abovementioned knowledge components. The ontologies were configured in such a way that it would represent a logic configuration to fulfil two purposes. The first being to design ontologies capable of structuring knowledge for facilitating the acquisition and retrieval of knowledge. The second being the design of a logic base that would provide all the elements necessary to integrate knowledge components and problem-solving and to structure solutions found to engineering problems This process leads to knowledge creation.

A logic base, founded on suitable ontologies and represented by concept maps was defined to act as a vehicle or model to integrate the ontologies and the various knowledge components. A model, called the logic base, comprising three modules was designed, namely, an input module, an analysis module and a reporting module. Because of the integration of the knowledge components and the ontologies, the knowledge emanating from the logic base resides within an ontology and can be made fully compatible with world-wide knowledge bases in the civil engineering industry, thus being fully discoverable for use by civil engineers.

The above summarises the answer to the main research question.

(A complete summary is given in **Appendix I** of all the research questions.)

6.4 CONTRIBUTION OF THIS RESEARCH TO KNOWLEDGE MANAGEMENT

Koenig (2002, p.3) referred to three stages in knowledge management (refer to Chapter 2, section 2.5.2), the hallmark phrase for the first stage was “best practices”. The second stage had a hallmark phrase of “communities of practice”. The third stage was “content management” (or enterprise content management) and “taxonomies”. The research conducted and the design of a logic base represent an example of content management without leaving out the first and second stages. This research also showed how existing content could be better understood and enhanced by restructuring.

In the past, ontologies were developed after much liaison with industry leaders and expert groups to arrive at an agreed ontology for a particular discipline. This might limit the future expansion when redefinition and changes are required. In the dynamic, changing world of engineering and technology, the management of content without much restriction is of pivotal importance for knowledge management. Individuals or groups may design their own ontologies to suit specific situations. It is, however, in the interest of knowledge reuse, to link the specific situations to a simple and generic ontology to improve retrievability. The contribution to knowledge management is therefore seen to be the design of an application in knowledge management through the introduction of the logic base that restructures knowledge and integrates ontologies, knowledge theories, knowledge acquisition, knowledge reuse and knowledge creation in a civil engineering environment. The logic base therefore fulfils a specific purpose in knowledge management by greatly enriching the knowledge component that lacks in existing ontologies. Current ontologies are mainly focused on organising and classification for retrieval purposes of specific knowledge elements. The logic base takes this further by providing, what one might call a knowledge-development model, that can be linked to the broader engineering ontologies represented in knowledge bases in the world.

6.5 SUGGESTED FUTURE RESEARCH

6.5.1 Further research is required on the development of an ontology for civil engineering in general, covering as many disciplines as possible. At this stage, much work was done in the building and construction domains, but other domains in civil engineering such as water, geotechnical engineering, roads, structural engineering, etc. can form the basis for further research. Such ontologies must integrate the existing work on ontologies in mainly the building and construction domains. The logic base should tie into the civil engineering ontology as a special sub-ontology, where the actual knowledge can be generated and housed.

6.5.2 Further research and development of the ontologies within the context of the logic base are necessary. Expansion of the High-Level Ontologies (HLO) to incorporate more aspects, could add value.

6.5.3 The population of the logic base with suitable case studies will be of much assistance to industry. Further research should be conducted into ways and means to cost-effectively capture and translate the information and knowledge in case studies into a logic base. Further research is required to identify and analyse suitable case studies and other sources of engineering knowledge.

6.5.4. The field testing of the logic base represents an opportunity for research. The introduction and use of concept maps in the daily practise of civil engineers should be researched to get an understanding of how well civil engineers accept the principles and apply it to their daily work. This research could provide knowledge of the training needs which could inform research on training methods.

6.5.5 The introduction of the logic base into industry should be done, as soon as possible. Research should be done on the approach and methods of training, for example, by electronic, self-learning means or by way of contact sessions. The goal of the training should be to assist students and young, inexperienced engineers to develop their own capabilities by using concept diagrams and learning to consider relationships and apply a systems approach to their work.

6.5.6 Top-Level Ontologies (TLOs), High-Level Ontologies (HLOs), the applications of Case-specific ontologies (CSOs) and Technical Ontologies (TOs) were developed. These developments are largely influenced by the experience of this researcher and his exposure to the civil engineering industry. The topics of case studies were selected to build an ontology with. It is necessary to research and re-visit this approach and establish a dynamic ontology that does not necessarily have to conform to a specific structure. Adaptive processes should be researched to develop and extend ontology structures.

6.5.7 The structure of knowledge in organisations could be researched so that knowledge could be captured directly, instead of being an indirect and secondary exercise. For instance; minutes of meetings, recorded under a set of headings and discussions, are recorded verbatim or near verbatim. Knowledge units are contained in some discussions and can be of significant importance to share with others. The purpose of the research should be to reconstruct the format of reports, minutes of meetings, etc. to turn it into knowledge units and into concept maps as close as possible to the sourcing. This means that concept maps could be drawn as a method of communication in the source documents. It may also be expedient to require the drafting of concept maps and population of the logic base by authors of technical publications, especially for case studies. The population of logic bases can be an onerous task. When new publications already provide the contents for a logic base, at least the future work may be captured in an industry-based logic base.

6.5.8 Some refinements may be necessary in the evaluation of relationships. This research mainly focused on evaluation as suggested by TRIZ and TOC. Further research should be conducted to enhance evaluation techniques.

6.5.9 The design and implementation of suitable software is important. This will have to incorporate all the existing available software. In this regard E-COGNOS or similar software should be researched. Research is required to assess various available platforms to enable access to as many available knowledge bases as possible. This will require a large range of language protocols to be handled on the platform. New software to handle the logic base is required that incorporates concept mapping, relationship matrices, the TRIZ system and the TOC. This will provide a powerful user-interface for use by engineering practitioners.

6.5.10 The hosting of the logic base needs further research and development. The question is, if a single host is required, should a single logic base be established for use by all engineers? Or should each organisation host the logic base as they wish? Nothing would prevent an organisation or individual to host its own; however, this approach would deprive the rest of the engineering community of valuable knowledge. This aspect needs further research.

6.5.11 Although a logic base was developed for civil engineering, it is expected that a similar approach could be followed for the development of logic bases in the other engineering disciplines, and also in the fields of architecture, agriculture, facilities management, project management, medicine, law, finance and others. This could provide for interesting and valuable research.

6.6 CONCLUDING REMARKS

The sources of information and knowledge in the world are endless and expanding at an ever-increasing rate. Despite this, the practicing engineer still has to work out his or her own way of thinking and conceptualisation of complex systems and to solve problems in innovative ways. In this study a model was designed to support engineers in holistic and systematic thinking and problem-solving. This study restructures knowledge by designing and integrating ontologies with knowledge theories, and problem-solving to enhance knowledge acquisition, reuse and knowledge creation. This study will contribute to the enhancement and equipping of civil engineers to face the many civil engineering challenges of this century in a confident way and to produce holistic and innovative solutions. This study will contribute to knowledge management by having demonstrated how knowledge can be managed through the choice of suitable ontological structures and how knowledge can be acquired, reused and new knowledge can be created.

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APPENDICES

APPENDIX A The revised Cynefin Model

Note that the text that follows was freely transcribed and words were added or omitted by this researcher from “youtube” video material by Snowden (Snowden, 2013d).

The revised Cynefin Model starts on the left-hand side with the chaotic domain, on the left hand side of the diagram and then proceeds from left to right from the complex, through to the complicated and the simple domains.

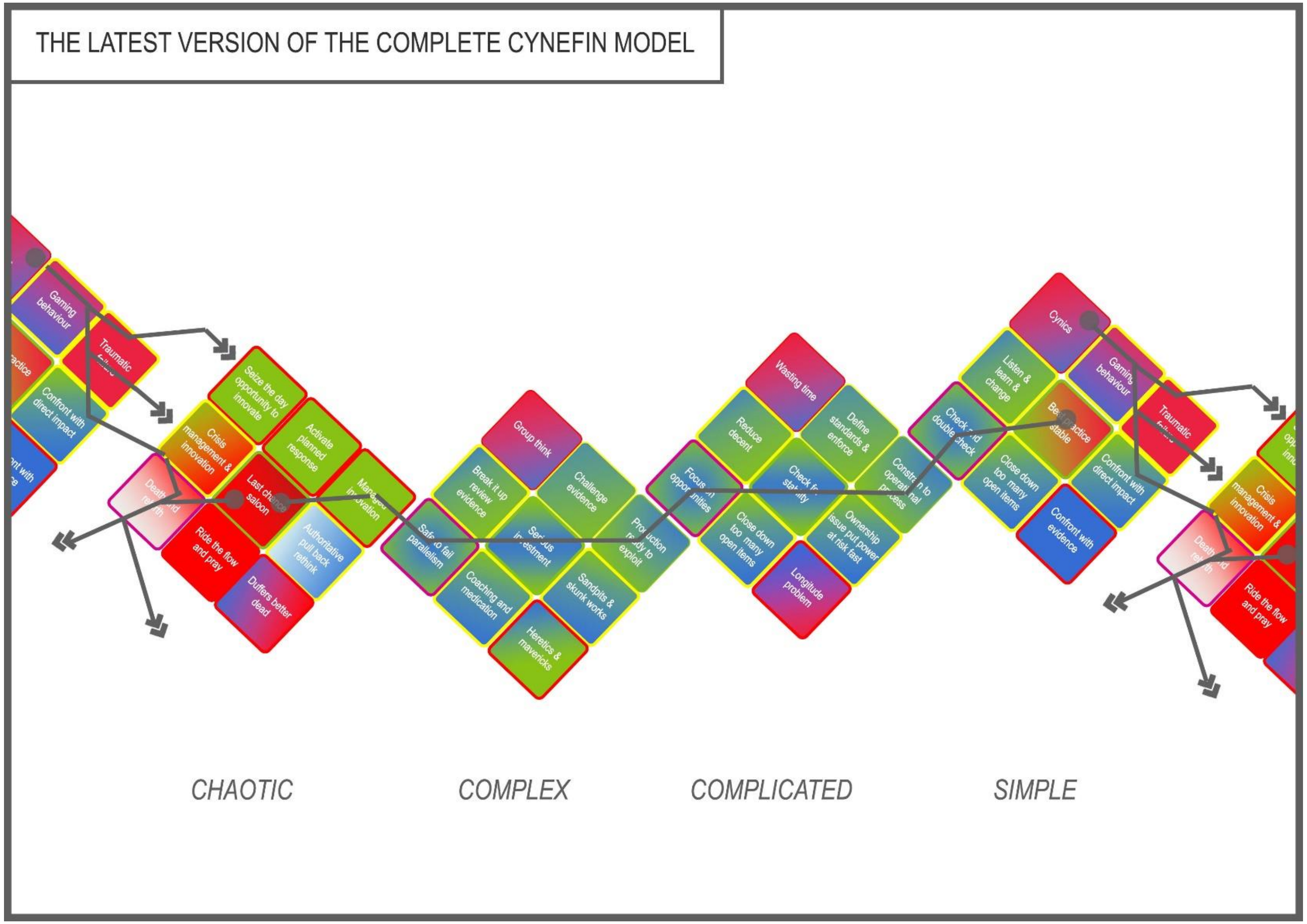

Figure A1 The latest version of the complete Cynefin Model (Snowden, 2013d)

The new version of the model is therefore considerably more elaborate than the earlier model. An important addition is the colour coding as shown in **Figure A1**. The red colour denotes “warning”, blue denotes “management action”, and green to say “use it, there could be something good in it” (Snowden, 2013d).

A diagonal line (white line in **Figure A1**) from the bottom left to the upper right or in the 45 degree version, from left to right) is called the “coherence line”. The idea is that in group workshop sessions participation of people can cause ideas and opinions to run in many directions, but in facilitating, one should be on the coherence line at all times and if it isn’t the case, steps should be taken to return to it. The important principle employed by Snowden is that two axes with scaled attributes are defined for the matrix. An ideal path (the diagonal line of coherence) is defined. Movement between the “boxes” or different states or conditions is moderated by the attributes defined on the axes. This model is a dynamic model and depending on the situation, the weights of the attributes can change at any time and therefore the situational state moves to other boxes within the domain or even into other domains. This movement from one state to another (or said to move from one box to another) can be seen against its relative position to the coherence line – which is the preferred place to be. Snowden explains this moderation to be analogous to, when a number of people sitting around a table and each holding a magnet of different strength and controlling the movements of a steel ball on the table. The influence of each magnet is different and the strengths of each magnet and proximity to the ball of each of the magnets would control where the ball would be rolling.

The discussion will follow the same sequence as that given in the above image, i.e., starting with the chaotic domain on the left-hand side of **Figure A2**. (Snowden, 2013a)

(The sections below were obtained from video lectures given by Snowden as referenced. There is a certain amount of overlap between videos. No comprehensive written text by Snowden was used in the descriptions given below, as it seems not to be available as yet.)

Brief discussion on the various domains

a) Chaotic domain

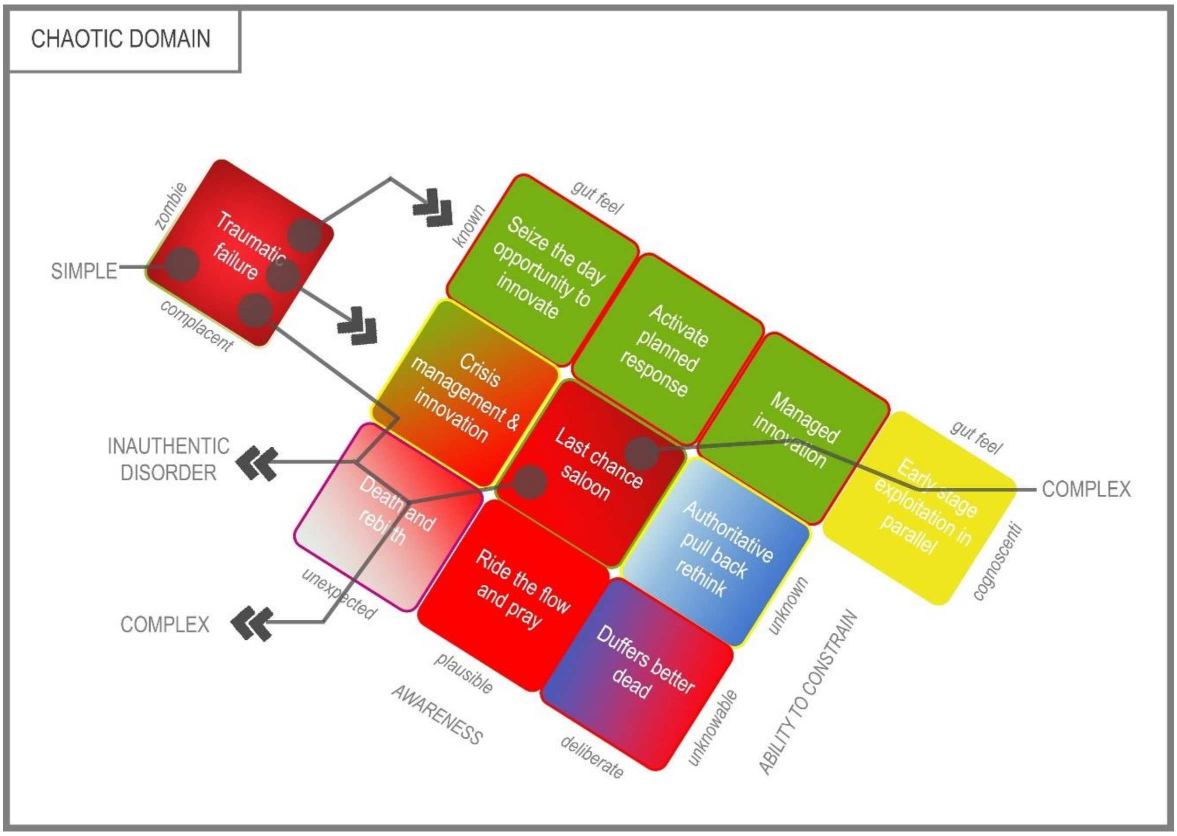

Figure A2 Chaotic Domain (reconstructed from images obtained from Cognitive-edge™ [Snowden, 2013a]**)**

b) Chaotic domain

In the chaotic domain, unlike the other domains, there are no visible relationships between causes and effects. The system is turbulent and there is no clear system identifiable. “The chaotic domain is in a very real sense uncanny, in that there is a potential for order, but few can see it – or if they can, they rarely do unless they have the courage to act. Regarding a decision model, it represents a space to act, quickly and decisively, to reduce turbulence; and then to sense immediately the reaction to that intervention so that one can respond accordingly” (Kurtz and Snowden, 2003, p.469).

There is a domain of disorder associated with this chaos domain and is described as “authentic disorder” on the diagram. (Also refer to **Figure 2.6**.) It represents a space where conflicts among individuals converge. Understanding situations that exist in the different domains also depend upon personal understanding and personality traits. Different opinions are expressed and can cause conflict. The reduction in the size of this domain is best done through consensual acts of collaboration among decision makers.

The 3 x 3 matrix of the chaos domain is depicted in **Figure A2.** A line of "coherence" runs diagonally, but is interrupted in the central block. The top of the diagonal moves into the complex domain and the bottom moves into inauthentic disorder – the centre of the main Cynefin framework (also refer to the original model shown in **Figure A1**). The vertical axis reflects the degree to which one can impose constraints. A chaotic domain is a domain without constraints. In the complex domain, there are partial constraints and the simple or ordered system is fully constrained. Snowden explains that there is an argument that one does not want to move or fall into chaos unless one can get off it. It is, however, a useful place to be in, if one can find time to spend in it.

The horizontal axis depicts the degree to what one knows what one is doing (awareness). The scale also depicts how one would view constraints. On the left-hand side, one did not expect things to go wrong (imposing constraints). In the middle, one could say that it is plausible that things could have gone wrong. And on the right-hand side, one deliberately chose to get rid of constraints. In the extreme left bottom box, it is impossible to setup constraints.

The top right-hand box is the only good position to be in, i.e., where one manages innovation. This is where all constraints are deliberately relaxed so that complete novelty can emerge. The action is taken when one is the bottom right-hand box is where one now "throws everything at it" and hope it works. The middle right-hand side is when one must pull back as fast as possible and get out of the situation. On the top left-hand box (one landed there unexpectedly), but knows that one can impose constraints and stimulate the teams. This is the situation when one builds resilient capacity such as social-network stimulation or narrative type research techniques and other things to see that one gets a response capability. That creates the opportunity to innovate. If one has a plan, such as a scenario plan or contingency plan ready, one can respond in a crisis by just activating it.

In the middle domain, one is not sure whether one can impose constraints or whether it is plausible. One is then in the "last chance saloon" and one needs to pull back. The coherence line is broken and one really wants to pull back from it. If one falls into the left hand extreme bottom box it is impossible to impose constraints. One has no idea of how one could have got there. If something does not now happen quickly, one can just as well give up. This box is named, “rebirth and die”. A practical example is that not enough people close businesses in time when things go wrong. People try and retrieve them and waste a huge amount of energy, but still do not succeed. If one unexpectedly starts to drop down towards this domain and if one thinks that one will be able to impose constraints, one moves into ruthless crisis control (for example, to save a business manager or owner, cut staff salaries and cancel supply contracts etc., to survive). One cannot be nice about it. Dictatorial people are needed to impose structure. On the other hand if one is in the bottom left and it is plausible to be there, but impossible to impose constraints, one can just “ride the flow and pray that things will work out”.

In summary, the chaos domain is a mixture of deliberate use for innovation and managing the fall. If one moves into that accidentally, there is a warning for moving deliberately without clear knowledge in advance of how one would impose controls to recover or to get back onto the coherence line.

c) The complex domain

The matrix for the complex domain is shown below. (Reconstructed from Snowden’s colour matrix.)

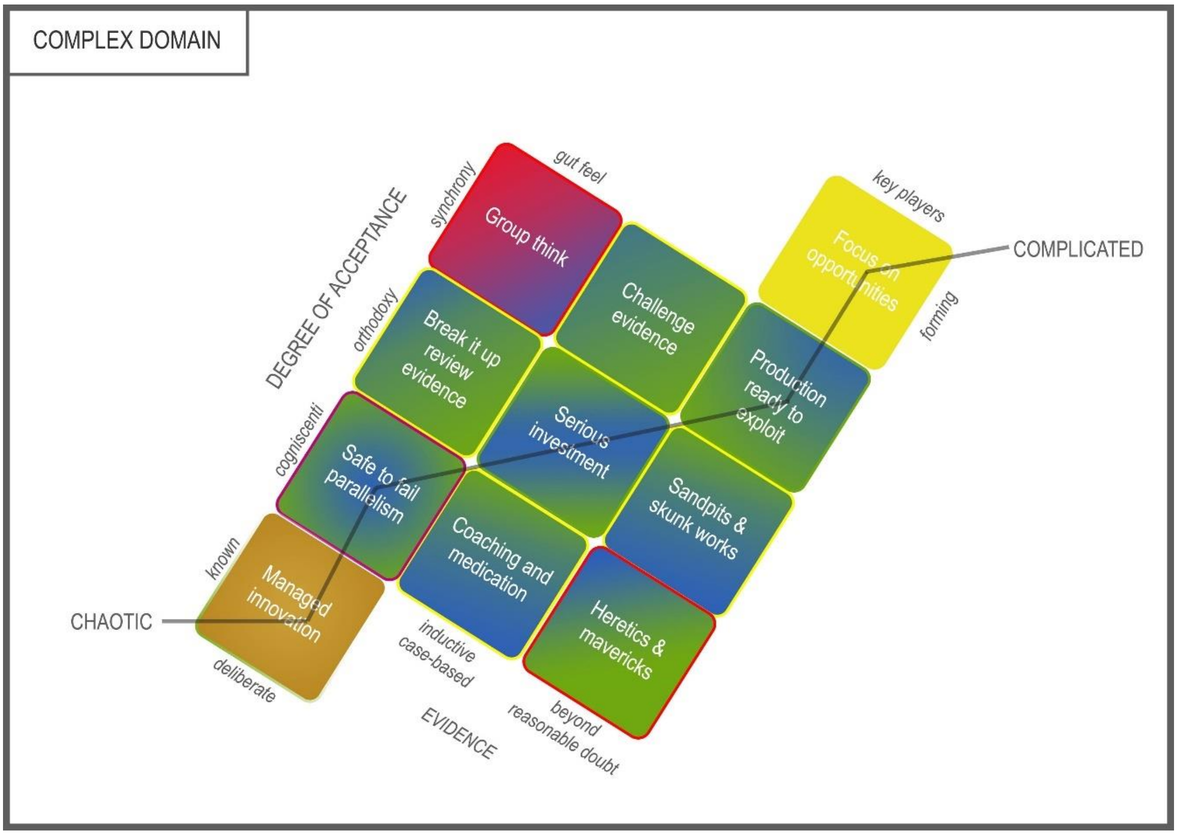

Figure A3 Complex Domain (reconstructed from images obtained from Cognitive-edge™[Snowden, 2013b])

On the vertical (left hand) axis is the degree of acceptance (also the degree of consensus or agreement of people in the organisation) and on the horizontal axis is the type of evidence. The line of coherence goes from the bottom left to the top right. One wants to stay on that line, and if not, get back onto the line as fast as possible.

On a situational assessment of what is going on, one moves from Cognoscenti – a small group of people believing in something of the orthodoxy. Orthodoxy is described as the dominant view of thinking. One then moves along the axis to synchrony that represents group thinking, where all people agree and everybody is in step and there is no descent.

The horizontal axis shows the types of evidence. This is not what people think they have, but that they must show actual evidence of evidence. On the right-hand side of the scale one asserts that a situation is true and it is beyond reasonable doubt. There is empirical evidence. Moving to the left, then, one can construct experiments and could falsify the experiments if the experiments had failed. One can use cases which could validate outcomes, but one doesn't know how universal these cases are. This represents a more inductive approach. Extreme left, it is gut feel and a belief. This means that there may be some evidence, but it is very difficult to harbour it. The way situations develop, for instance, are when new ideas come in from the bottom left. A small group of people will believe in something and gradually they should step up the diagonal to a point where most people believe in it. There is some evidence, and then everybody accepts it, and evidence is incontrovertible – at which point it moves into the complex domain. The top right is a more ordered domain, and the left is a less ordered domain. The reality is that most people slip to the sides. So, if one goes to the bottom right of the framework, one can see the area, "Heretics and mavericks". This is where a small group of people "know" they are right. The problem is, they then go on and tell everybody else that they are right, and when the other people do not accept it, they tell everybody else why they are wrong. And when this does not work, they insist that they are right and get very compelling about it, leading to rejection by everyone. This is, however, a very useful group, so the box is indicated in green, not red. The trouble is that one has to manage them differently and there are two strategies to approach it. One is effectively to move away from absolutism to something with more fluidity, and that's called coaching and mediation. This is a good use of retired employees. They know how things work. They can take a group of people with a wild new idea and help them to translate it so that other people can understand it. That is in effect a move back to the diagonal, losing some coherence for the sake of getting buy-in, which is a difficult thing to achieve. On the other hand, if it is of vital importance and one cannot afford to compromise, one must realise then that the energy cost is higher going back straight up to the diagonal, than moving across horizontally. The way this is done, is that one creates a sand pit or skunk-works project. One hides these people so that by the time they are finished with the development of their ideas, the concepts are so self-evident that nobody reasonably could deny it. So the two blue areas are strategies available for leaders. (Couching or skunk-works.)

One can then go to the other extreme on the top left. That's where everybody is agreed, but there is no evidence to support it. The sub-prime lending disaster in the USA is an example of this. It is called group thinking and is a major danger in organisations. One needs to monitor this, as ideas come out of the early-stage chaos domain – from the gut-feel cognoscenti. If they start to move up to the point where everyone agrees, but they haven't moved across horizontally at the same time, one needs to break things up fast. One needs to disrupt it. On the other hand, if they have moved up the diagonal successfully, they have veered off a little bit, one does not need to panic too much and only need to challenge things extensively. That deals with the extremes.

The reality is that most people start projects only when there is orthodoxy and there is a degree of evidence and that it is in the project-formation point. This is also true in the agile community, and it is also true in cultural-change programme strategy projects – in virtually everything. So one will start in the middle and move across into production and from there into the complicated. That actually means they miss a huge opportunity in the box in the left bottom which is “missing in action”. It is the space where one could rapidly reduce risks going downstream. There are strategies for managing in that space. One such strategy is “safe to fail” interventions. This is a Cognitive Edge™ technique. Instead of forming a project, which one iteratively works through to get it right. One creates a portfolio of safe-to-fail experiments which runs simultaneously. Some of the experiments need to be oblique, some of them need to be naïve, some need to be high risk and high return. One sees what happens to these experiments and the ones that succeed, or combine with others, move into project formation; others get killed. So this is a major de-risking activity. Even before that one can use Sensemaker® (Snowden, 2009) comprising software, utilising micro-narrative approach to gather huge amounts of fragmented, self-signified material which provides statistical data from larger populations, so that we can see coalescent patterns that come from those significations in order to identify areas where one should run safe-to-fail experiments in the first place. The complex argument is that one needs to start near chaos and explore more options and then gradually move up the diagonal and move into small projects, then into bigger projects before finally moving from exploration to exploitation and into the complicated domain.

The dynamic of this domain is that the line shows a trend in the development of sense-making. As more and more work is done, evidence accumulates and more people buy into the idea. Eventually, there is clear and nearly clear universal consensus. The evidence is there and one can shift from the complex to complicated domains. The block then links to the complicated domain.

The interesting point about this domain is that of conducting controlled safe-to-fail experiments to gain insight into the responses of complex issues. In this respect, Snowden developed the concept of a network of human sensors. This comprises a very large number of people (respondents) selected randomly, who provide simple feedback on a very regular basis of issues at grass roots level. In this way, a vast volume of data is collected and analysed automatically to arrive at status quo reports that actually reflect people’s perceptions in an unbiased way. Respondents provide regular feedback by way of narratives on certain issues or questions to gather valuable information in a short space of time and at high frequencies. This method is currently employed by Snowden in large studies for governments and authorities on, for example, infrastructure-related issues.

This technique suggests some similarity to A/B testing. A/B testing is a method to determine online what the best promotional and marketing strategies are for business. (It is also called split testing.) It is, in some cases, used almost continuously to compare two versions of a webpage against each other to determine which one performs better. By creating A and B versions of a webpage, one can validate new design changes, test hypothesis and improve the website conversion rate. Google, Amazon, Netflix and eBay are examples of such A/B testing to constantly improve their websites (Kissmetrics Blog, 2011).

d) The complicated domain (knowable domain)

This domain is known as the domain of "good practices" – it is also called the "knowable" domain. It describes the situation where cause-and-effect relationships are not fully known to all. Its characteristic is that one may have an idea of the known unknowns. One likely knows the questions that one needs to answer and how to obtain the answers.

Everything in this domain may, however, move to the "known" domain. It may require additional and/or specialist resources to help discover knowledge about a situation and move into the "known" domain. Systems thinking, learning organisation and adaptive enterprises are part of this domain. Also appropriate are experimentation, seeking expert opinions, fact finding and scenario planning. Regarding a decision model, incoming data is sensed and responded to in accordance with expert advice interpretation and analysis. Assumptions must be open to examination and challenge. This is an area where entrained patterns are at their most dangerous, "as a simple error in an assumption can lead to a false conclusion that is difficult to isolate and may not be seen" (Kurtz and Snowden, 2003, p.468). The approach in this domain is to sense the problem and analyse. Apply expert knowledge to assess the situation and determine a course of action and execute the plan (Webster, 2003).

Referring to known and knowable, does not necessarily refer to knowledge of individuals. It refers to knowledge held by organisations or knowledge that is obtainable from some source.

In the "unordered" quadrant, complex relationships exist. There are cause and effect between agents, but the number of agents and relationships makes it almost impossible to categorise and analyse these relationships. Patterns can be recognised in retrospect and seem to be logic. However, it cannot be sure that the patterns will prevail in time and space. "Patterns can be perceived, but not predicted; we call this phenomenon '*retrospective coherence*'" (Kurtz and Snowden, 2003, p.469).

Regarding a decision model, multiple perspectives are needed to gain an understanding of this space. "This is a time to 'stand still' (but pay attention) and gain new perspective on the situation rather than 'run for your life', relying on entrained patterns of past experience to determine response. The methods, tools, and techniques of the known and knowable domains do not work here. Narrative techniques are particularly powerful in this space" (Kurtz and Snowden, 2003, p.469).

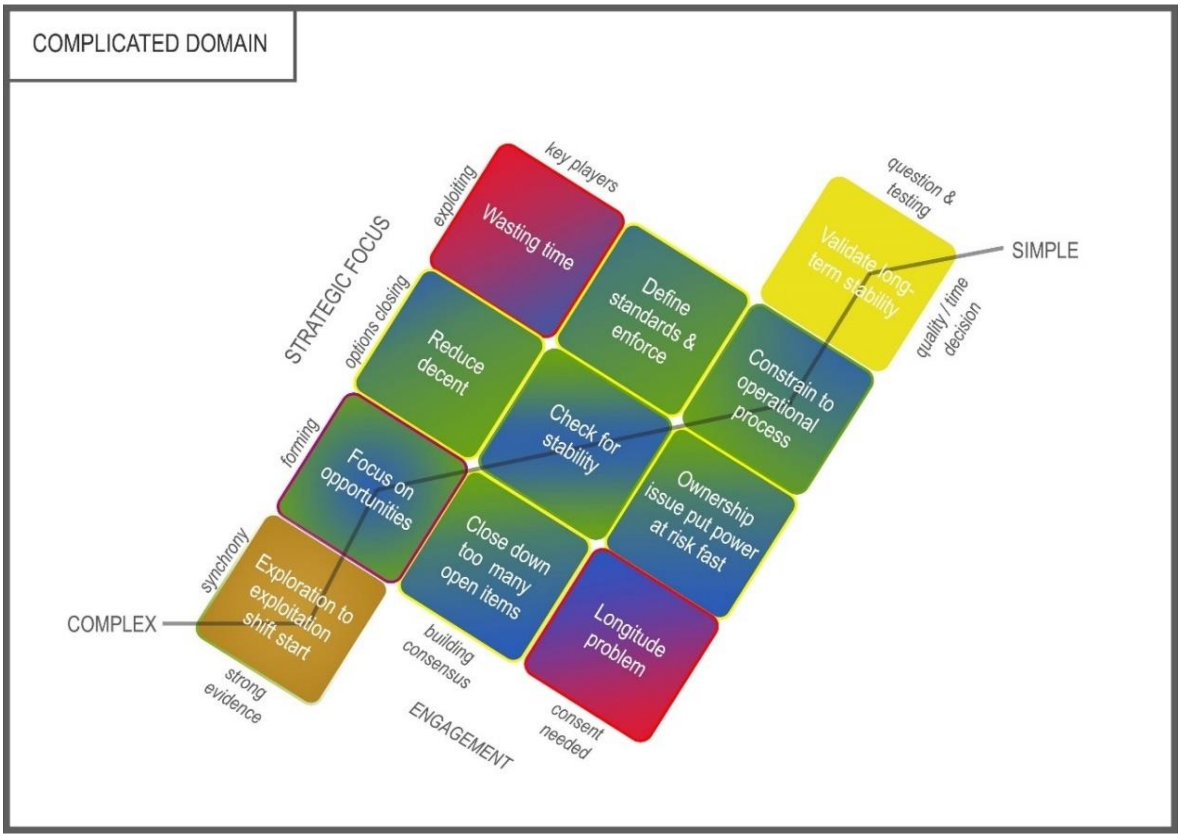

Figure A4 Complicated Domain (reconstructed from images obtained from Cognitive-Edge™ [Snowden, 2013c])

The coherence pathway runs through three stages from left to right in Snowden's diagram; **Figure A3** (refer to the text in *italics*).

e) Simple or obvious domain

The "known" quadrant indicates a full appreciation and understanding of a situation. This means that knowledge exists for most of the situation. In terms of a decision model, incoming data is sensed, categorised and responded to in accordance with predetermined practice. "Structured techniques are not only desirable but also mandatory in this space" (Kurtz and Snowden, 2003, p.468). In the updated model, Snowden calls this "known" domain as the "simple" domain and more recently renamed the domain to the "obvious" domain and describe the domain as the domain of "best practices". The characteristic of this domain is that problems are well understood, and solutions are evident. Minimal expertise is required to solve the problems. Snowden remarks that many issues can be addressed in this domain by help desks and written scripts. The approach that Snowden suggests is to sense the situation and categorise it into a "known bucket" and apply a well-known, potentially scripted solution.

The latest model is shown **Figure A5**

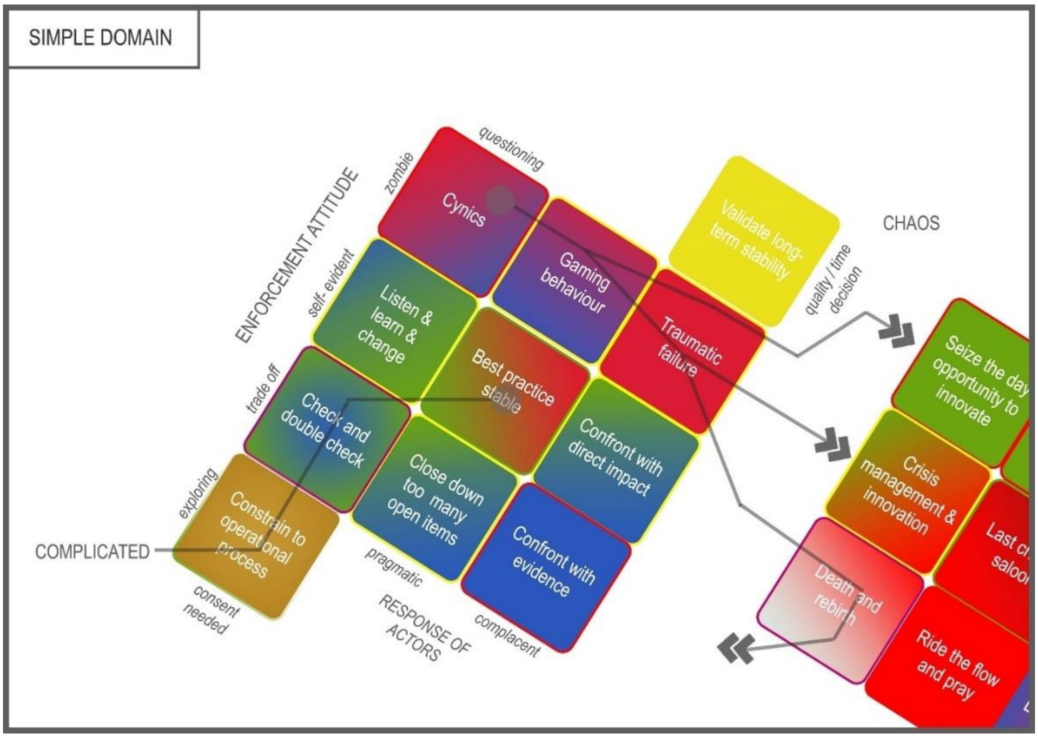

Figure A5 Simple Domain (reconstructed from images obtained from Cognitive-edge™ [Snowden, 2013e])

A pathway is shown through the elements of the matrix representing a so-called "coherent pathway" (see the sentences in *italics*).

APPENDIX B Problem-Solving Techniques

Table B1 A summary of problem-solving techniques, as well as creative-thinking methods

No	Problem-solving technique	Main attributes/description
1	• Morphological analysis / Morphological Forced Connections	• This is a group of methods having the same structure. These methods break down a system, product or process into essential sub-concepts. • The use of a matrix in creativity and innovation is described as a morphological technique. Various attributes are chosen to reflect the object or situation. For each attribute, as many alternatives are listed as possible. The alternatives are then randomly chosen and combined to form combinations that are then considered or analysed. The objective is to view the problem then from a multitude of different angles.
2	• Imitation	• This method primarily involves imitating the existing and improvising on it.
3	• Mind Maps	• Mind maps are based on association. A central idea is taken, and related ideas are developed around the central idea. This is normally done graphically.
4	• Story-boarding	• Own ideas and that of others are put up on a board while busy with a project or when solving a problem. The thought of others prompts further generation of ideas. This method is often applied to the film industry to do outlining of their scenes. This method can be used together with many other techniques, such as with brainstorming.
5	• Synectics	• This is a process of discovering the links between seemingly unrelated elements. It is the process of dismantling things and putting it together again, leading to new insights into a problem. It is usually used in small groups with people of diverse expertise.
6	• Metaphorical thinking	• The key to this method of thinking is to look for similarities. Metaphorical thinking is about connecting different worlds of meaning.
7	• Lotus Blossom	• This is a specific form of brainstorming. A central idea or theme or problem is built on by triggering new themes and problems or solutions. Central to this technique is to move away from processing

No	Problem-solving technique	Main attributes/description
		old information over and over again. A central subject or theme is chosen and sub-themes developed, each with a separate entry point. The connections made between themes and ideas bring about new properties. This can be illustrated by the parts of a car, when thrown on a heap, has no value. When classified according to function, patterns emerge and when continuing with the connections, the full functions of the car will emerge.
8	• Neuro-Linguistic Programming (NLP)	• This is referred to as the science of subjective experience where the subconscious plays an important role in finding solutions to problems. "In essence NLP is a form of modeling that offers potential for systematic and detailed understanding of people's subjective experience." The emergence of internal imagery and understanding significantly influences learning and thinking patterns.
9	• Assumption Smashing	• All assumptions relating to a problem are listed. The assumptions are then taken away and the resulting problems are analysed.
10	• Ask Questions	• The questions, What? Where? When? How? Why? and Who? are asked and ideas generated from the answers to these questions. The way questions are asked will determine the outcomes. Closed, open, leading, probing, funnel or rhetorical questions deliver different answers. This is also a very important subject when it comes to the design of questionnaires.
11	• DO IT	• Define, open, identify, transform. Define the problem, be open to any solution, identify the best solution and transform it into action.
12	• Unconscious Problem Solving	• This method relies on the unconscious mind that continuously process various inputs.
13	• Lateral Thinking	• Different points of entry to a problem are defined.
14	• Six Thinking Hats	• This represents 6 ways of thinking and promotes more input by more people. The hats are metaphorical hats the thinkers can put on and take off to indicate what type of thinking is being used. In summary the hats are as follows: • White hat – facts and figures. • Red hat – feelings intuition, emotions. • Black hat – judgement and caution.

No	Problem-solving technique	Main attributes/description
		• Yellow hat – logical and positive. • Green hat – creativity, alternatives, proposals, what is interesting, provocations and changes. • Blue hat – overview or process control.
15	• The Discontinuity Principle	• One gets used to a situation that lessens the stimulation for thinking. Disrupting thoughts stimulate new thinking.
16	• Checklists	The basic questions are asked and followed up by further questions, namely: (it includes standardised lists) Adapt? Modify? Substitute? Magnify/maximise? Minimise/eliminate? Rearrange? Reverse? Combine?
17	• Brainstorming	• Generating ideas from groups. This method can be combined with many of the above listed methods.
18	• Forced Analogy	• The problem is forcefully compared with something else that has little or nothing in common and gain new insights as a result.
19	• Attribute Listing	• The problems are broken down in smaller and smaller bits to see what can be learned from it. This method ensures that all aspects are being looked at.
20	• Problem reversal	• The point of departure is to view the world being full of opposites. E.g. for a leader to lead, there must be followers. See the world from the followers' perspectives. • New insights are obtained by seeing different angles of the problem.
21	• Trigger-word technique	• This is essentially a group technique. Potential solutions to a problem are presented which sparks off new ideas.
22	• Attribute-seeking technique	• This a qualitative technique, whereby the all the objects and their attributes and all the relationship between the objects including their attributes are investigated.
23	• Gordon technique/ Synectics	• This is closely related to brainstorming, except that it is more formalised and rigorous. The best known of the Synectics technique are the following trigger questions:

No	Problem-solving technique	Main attributes/description
		Subtract, add, transfer, empathize, animate, superimpose, change, scale, substitute, fragment, isolate, distort, disguise, contradict, parody, prevaricate, analogize, hybridize, metamorphose, symbolize, mythologize, fantasize, repeat, and combine.
24	• Associative thinking	• Reflection over a problem situation by focusing on unrelated perspectives. "During this process, a mapping of high order relations can be established between a source and a target situation."
25	• Work backwards	• The strategy of working backwards entails starting with the end results and reversing the steps you need to get those results, in order to figure out the answer to the problem.
26	• Weighted scoring	• Criteria are selected which would form the basis of decision making. A percentage weight is assigned to each criterion – adding up to 100%. Requirements are then given scores according to each criterion. The weighted score is then calculated by multiplying the score with the weight. The priority of a requirement is then decided according to the highest weighted score achieved.
27	• Pareto analysis	• This is a simple technique for prioritising aspects, scores, values etc. Also known as the 20/80 principle – helps to identify 20% of the aspects that would contribute 80% to the solution of a problem.
28	• Convergent and divergent thinking	• Convergent and divergent thinking are completely in contrast, but most effective if used in conjunction. Both methods are implemented to explore creativity and to find solutions to different problems. Convergent thinking focusses on a single outcome and a concrete solution to a problem. It also utilises previously tried-out techniques and reapplying them. • Divergent thinking explores multiple possible options to generate creative ideas. Different and new directions are explored, opening the mind to spontaneous idea generation and free-flowing. The most plausible solutions are then selected for implementation.
29	• Root-Cause Analysis (RCA)	• Root-Cause Analysis is a structured way to evaluate a systems response. It is essentially a causes and effects analysis, studying what, how and why a detrimental event happened and establishing what remedial should be taken to prevent the repeat of detrimental events. It is often used after the occurrence of an unwanted event,

No	Problem-solving technique	Main attributes/description
		typically in occupational safety to prevent injuries to people on duty or to eliminate losses.

APPENDIX C Abstracts from published literature

Project title	Key aspects	Types of knowledge	Reference
• Franki showing their mettle in Sandton.	• Large Basement excavations. Meeting challenges for large excavations in a short period of time.	• Performance reporting. • Applications of techniques.	• Anon., 2014c, pp.9-11.
• Repairing a failing rail embankment.	• As little as possible interference with rail traffic. Worked in close proximity of rail.	• Measurement/monitoring. • Special techniques and planning.	• Norris, 2014, pp.25-27.
• A brief comparison of geotechnical soil classification standards and limitations of “factual” soil descriptions.	• Comparison of South African standards for soil profiling is compares with Australian, European and American standards.	• Standards. • Heuristics. • Characterising parameters.	• Owens-Collins, 2014, pp.28-30.
• Working smarter.	• Using mobile technology to assess slope stability.	• Techniques. • Software tools.	• O’Brian, 2014, pp.33-34.
• Dolomite seminar, 2014	• Discussions on a proposed new standard for construction in dolomite areas.	• Development of standard.	• Day, 2014, pp.40.
• Managing flood risks on the Orange River.	• Hydraulic modelling and management.	• Systems modelling. • Performance reporting.	• Dunsmore and Ramsbottom, 2014, pp.46-50.
• Working as a resident engineer in South Africa.	• Sharing of amusing anecdotes.	• Knowledge sharing.	• Wyatt, 2014, pp.51-54.

Project title	Key aspects	Types of knowledge	Reference
• Sika solves bridge widening problem.	• Use of carbon fibre reinforced polymer (CFRP) laminates to strengthen a bridge.	• Application of new techniques/technology.	• Anon., 2014d, pp.58-59.
• Polyurea comes to the fore in SA construction industry.	• New industrial coating is introduced in RSA.	• Techniques/Products.	• The Concrete Institute, 2014, pp.65.
• Impact of the Gautrain on property development around station precincts.	• Investigations showed accelerated property development and increased mixed use.	• Systems analysis and reporting.	• Mushongahande, Cloete & Venter, 2014, pp.2-10.
• Factors predicting the intention to accept treated wastewater reuse for non-potable uses amongst domestic and non-domestic respondents.	• Several metrics representing possible factors playing a role in public acceptance of a new regime were tested using questionnaires and software to make predictions.	• System response tests.	• Adewumi, Ilemobade & van Zyl, 2014, pp.11-19.
• The management of constructability knowledge in the building industry through lessons learnt programmes.	• The factors affecting constructability were investigated.	• Systems behavior. • Sharing of knowledge.	• Kuo, & Wiium, 2014, pp.20-22.
• Evaluation of the strength behaviour of unpaved road material treated	• The importance of the time factor in the strength development of non-traditional treated materials was highlighted as well as the variability in results.	• System performance. • Measurements / monitoring.	• Molosane & Visser, 2014, pp.28-39.

Project title	Key aspects	Types of knowledge	Reference
with electrochemical-based non-traditional soil stabilisation additives.			
• The status of basic design ground motion provisions in seismic design codes of sub-Saharan African countries.	• Comparisons were made among codes for provision of earthquakes. It was found that the codes of certain African countries are insufficient and need immediate updating.	• Standards. • System performance parameters.	• Worku, 2014a, pp.40-53.
• Soil-structure interaction provisions. – A potential tool to consider for economical seismic design of buildings?	• The damping effect of soft soils may be taken into account to reduce the design forces on buildings.	• Systems performance. • Characterisation of parameters. • Application of theory.	• Worku, 2014b, pp.54-62.
• Proposed guideline for modelling water demand by suburb.	• The factors affecting water demand in suburbs were investigated and new, more comprehensive design envelopes are proposed.	• System performance. • Development of system/ Design Parameters (DPs).	• Griffioen & van Zyl, 2014, pp.63-68.
• Accounting for moment-rotation behaviour of connections in portal frames.	• Current calculations are conservative. New analysis could be carried out to optimise and save costs of steel members, but the analysis of complicated and not available in a cost effective way to the average consulting practices. Further research is proposed.	• Development of techniques for analysis. • Development of theory.	• Albertyn, Haas & Dunaiski, 2014, pp.69-76.

Project title	Key aspects	Types of knowledge	Reference
• Towards a systems thinking approach in allocating infrastructure budgets in local government.	• A combination of models is required to enhance decision making for reasons of the complexity of the municipal finance environment.	• Systems analysis and performance. • Measurement (validation surveys).	• Kaiser & Smallwood, 2014, pp.93-99.
• Analysing delay and queue length using microscopic simulation of the unconventional intersection design superstreet.	• Evaluation and comparisons of operational efficiency of various intersection types.	• Systems analysis and performance. • Simulation and determining Design Parameters (DPs).	• Naghawi & Idewu, 2014, pp.100-107.

APPENDIX D TRIZ Principles and parameters

The following table summarises the 40 inventive principles applied by TRIZ.

Table D1 The 40 inventive principles applied by TRIZ

1. Segmentation	16. Partial or excessive actions	31. Porous materials
2. Taking out / Separation	17. Another dimension	32. Colour changes
3. Local quality	18. Mechanic vibration	33. Homogeneity
4. Asymmetry (Change)	19. Periodic action	34. Discarding and recovering
5. Merging	20. Continuity of useful action	35. Parameter changes
6. Universality	21. Skipping	36. Phase transitions
7. “Nested doll”	22. “Blessing in disguise”	37. Thermal expansion
8. Anti-weight	23. Feedback	38. Strong oxidants
9. Preliminary anti-action	24. Intermediary	39. Inert atmosphere
10. Preliminary action	25. Self-service	40. Composite materials
11. Beforehand cushioning	26. Copying	
12. Equipotential	27. Cheap short-living objects	
13. “The other way around”	28. Mechanics substitution	
14. Curvature	29. Pneumatics and hydraulics	
15. Dynamization	30. Flexible shells and thin films	

Mann, D. L. (2009) developed 42 corollaries or combined/special principles. These are shown in **Table D2**.

Note: The numbering in **Table D2** follows in sequence from the numbering in **Table D1.**

Table D2 The 42 most important Combined / Special Principles

(Mann, 2009, pp.144-150)

Principle	**Principle**	**Principle**
41. Reduce the weight (Size) of individual parts.	56. Compensate for / utilize losses.	71. Localize and / or locally weaken a harmful effect.
42. Divide into heavy (large) and light (small) parts.	57. Reduce stages of energy transformation.	72. Mask defects.
43. Apply support.	58. Postpone action.	73. Facilitate detection.
44. Change and object’s shape for transportation.	59. Field transformation.	74. Reduce contamination.
45. Change conditions for transportation and/ or storage.	60. Introduce a second field.	75. Create a shape conforming to expected wear.
46. Apply counter-balance.	61. Adapt a tool to a person.	76. Reduce human errors.
47. Introduce and element with stored energy.	62. Shape transformation for strength.	77. Block dangerous actions.
48. Partial preliminary action.	63. Transform an object micro-structure.	78. Exploit non-linearities.
49. Concentrate energy.	64. Isolation / insulation.	79. Exploit false assumptions.
50. Field substitution.	65.Counteract an undesired action.	80. Emotional factors.
51. Create standards for comparison.	66. Change an undesired action.	81. Smart materials.
52. Retain information for later use.	67. Remove or modify the source of harm.	82. Meta-materials.
53. Integration into a pol-system.	68. Modifier substitute.	
54. Specialization.	69. Increase the system’s resistance to the harmful effect.	
55. Reduce scattering.	70. Parallel restoration	

The parameters used by TRIZ are grouped into the following categories:

Appendix D3_The 50 Parameters of TRI

NOTE:

- The different categories are shown in different colours.

- The classification **“-ility”** refers to parameters mainly ending with “ility”.

APPENDIX E Generic set of goals

(Also referred to as *ideation ideas*; adapted from Verbeek, 1992.)

- Improve efficiency.
- Reduce energy usage.
- Reduce amount/level of resources
- Improve handling
- Reduce conflict
- Reduce delays/Meet schedules
- Improve quality
- Reduce project duration
- Promote health
- Promote safety
- Enable construction
- Improve performance
- Enhance maintainability
- Increase productivity
- Reduce project cost
- Reduce complexity
- Eliminate unnecessary activity
- Enhance repeatability
- Reduce physical job stress
- Improve profits
- Standardise
- Use up-to-date standards
- Use up-to-date specifications
- Employ industry-best practice
- Ensure accessibility
- Optimise life-cycle costs
- Increase redundancy
- Improve skills
- Ensure continuity in staff and knowledge

APPENDIX F Analysis of Case studies

A small random selection of case studies is analysed to establish the fit between case studies and the various topics as described in Chapter 4, **Table 4.1**.
The analysis of the case studies is shown in the attached table, **Table E1.**

Discussion on Appendix F

From the analysis of the case studies it was possible to readily group all the cases' topics into the various classes as shown in **Table 4.1**. The random sample of case studies represent each of the main types of case studies, i.e. descriptive, exploratory and explanatory. Some case studies have elements of both explanatory and exploratory. This can be seen in case study no. 11 where elements of both explanatory and exploratory types are present. Many case studies contain drawings, sketches and/or photographs. For succinct purposes these are not shown in Table F1.
When considering cases such as no. 5 (rehabilitation of the Pietermartizburg Airport), no. 7 (essentials for appropriate substrate preparation), no. 8 (mechanical properties of self-compacting concrete), and no. 12 (stadiums failure [stands]) prior knowledge of the technical details should be known to understand the case better. The technology employed is embedded in the case studies. An example would be in case no. 11 (failure of septic tank system), the reader should have prior knowledge of what a septic tank is. In the same case study, knowledge of potential root causes of the problems of apparent tank failure was important in the analysis of the case. In this example, the root cause was discovered only later, after all the legal claims were instituted against the professionals. The root cause in this case turned out to have had nothing to do with the engineering design and construction as originally alleged by the owner, but was due to the damage caused by a landscaping contractor. The first lesson from this case is that the root cause of the problem lied outside the immediate technical aspects relating to the septic tank itself. A holistic approach from the beginning of the investigation could have made it possible to identify the correct root cause at an earlier stage, i.e., it was a landscape contractor that caused the damage. The second lesson is that if the root cause been discovered earlier, hardship and blaming of the professional team could have been avoided. Root-Cause Analysis (RCA) would require all the factual data of a system and full knowledge of operations. This includes matters outside the strict technical field such as resources (human resources, financial, legal, materials and equipment). It is therefore essential to incorporate these into the heading “processes and analysis and causal paths”.

The question now arises if the topics of case studies as indicated in **Table 4.1** can also form the elements of an ontology? **Table 4.1** contains a classification typical of case studies. An ontology provides the structure (“scaffolding” refer to Gavrilova and Gladkova, 2014) to organise knowledge contained in the logic base. Knowledge from case studies can then be “packaged” into the various ontological elements or components.

The principles for extrapolation and replication were found in the sample of case studies. This is an important component of the logic base. The outcomes of a case study and the principles for extrapolation and replication (and lessons learned) represent knowledge that needs to be taken up in the logic base. The way it should be done is to investigate the logic underlying the lessons learned and to incorporate that into the logic base. This would address the fundamental reasons for learning the lessons and should therefore be taken up in the logic to enhance replication.

By careful analysis and studying of problem-solving techniques used in a case study one can account for the logic underlying any conclusions in case studies. This can be part of the logic base to enable replication.

By selecting and analysing a small random sample of case studies, it can be concluded that the selected topics of case studies (forming the ontology) fully meets the goal of using these as a basis for the design of the logic base.

APPENDIX F Analysis of a random sample of case Studies

Appendix F Analysis
of Case Studies.pdf

APPENDIX G Example of Relationship Matrix

Appendix G
_Example of Relatior

APPENDIX G

EXAMPLE OF A RELATIONSHIP MATRIX

	No.	
Introduction and Scope		Purpose
	2	User requirements
	3	Content/System components
	4	Sub-components/ Work content
DESIGN	5	Evaluation & Current status
	6	Study/design/conceptualisation
	7	Science and laws/discipline technology
	8	Research
	9	Desgn development
	10	Design criteria
	11	Choice of parameters
	12	Analysis/calculations/simulations
	13	Configuration/design drawings/standard details/specifications/cost analysis
	14	Operational principles
	15	How does it work/processes/ description of behaviour
	16	Executable design
	17	Attributes
	18	Element database
	19	Rules and legal requirements/Stakeholder agreements
	20	Functionality/operability/maintainability/Monitoring
Construction and or manufacturing	21	Site management / Finances
	22	Human resources
	23	Materials
	24	Plant and equipment
	25	Procurement/costing
	26	Contracts/legal agreements
	27	Project Execution
	28	Scheduling
	29	Methods and techniques
	30	Quality assurance
	31	Final product
	32	Operations
	33	Maintenance
	34	Health
	35	Safety
Setting and context	36	Organisational structure
	37	Management
	38	Physical assets
	39	Legal / regualtory framework
	40	People. Roles and responsibilities
	41	Administration
	42	Communication
	43	Stakeholders / Interested and affected parties
	44	Social aspects
Sequence of events	45	Changes in circumstances
	46	Triggering/ initiating actions /events
	47	Eevents/ mobilisation
	48	System response
	49	Measurement and controls
	50	Consequences
Investigation	51	Issues and analysis thereof
	52	Risk analysis
	53	Unwanted events
	54	System response
	55	Root causes
	56	Problems / constraints / issues
	57	Influencing factors
	58	Phases of development
	59	Environment
	60	Evidence
Operations and maintenance	61	Asset and componnet definition and records
	62	Operational philosophies and strategies
	63	Performance monitoring
	64	Maintenance strategies
	65	Maintenance logistics
	66	Cost engineering

APPENDIX G
EXAMPLE OF RELATIONSHIP MATRIX

APPENDIX H Summary of research layout (Contextualisation)

1. Summary and discussion of research layout

In this appendix, summaries are given to indicate the “roadmap” of this study. First of all Figure H1 gives a diagrammatic layout of the research and in Table H, a summary is given of all the research questions and indications of where the various questions were answered in the text.

The diagram in Figure H1 depicts the layout of the study.

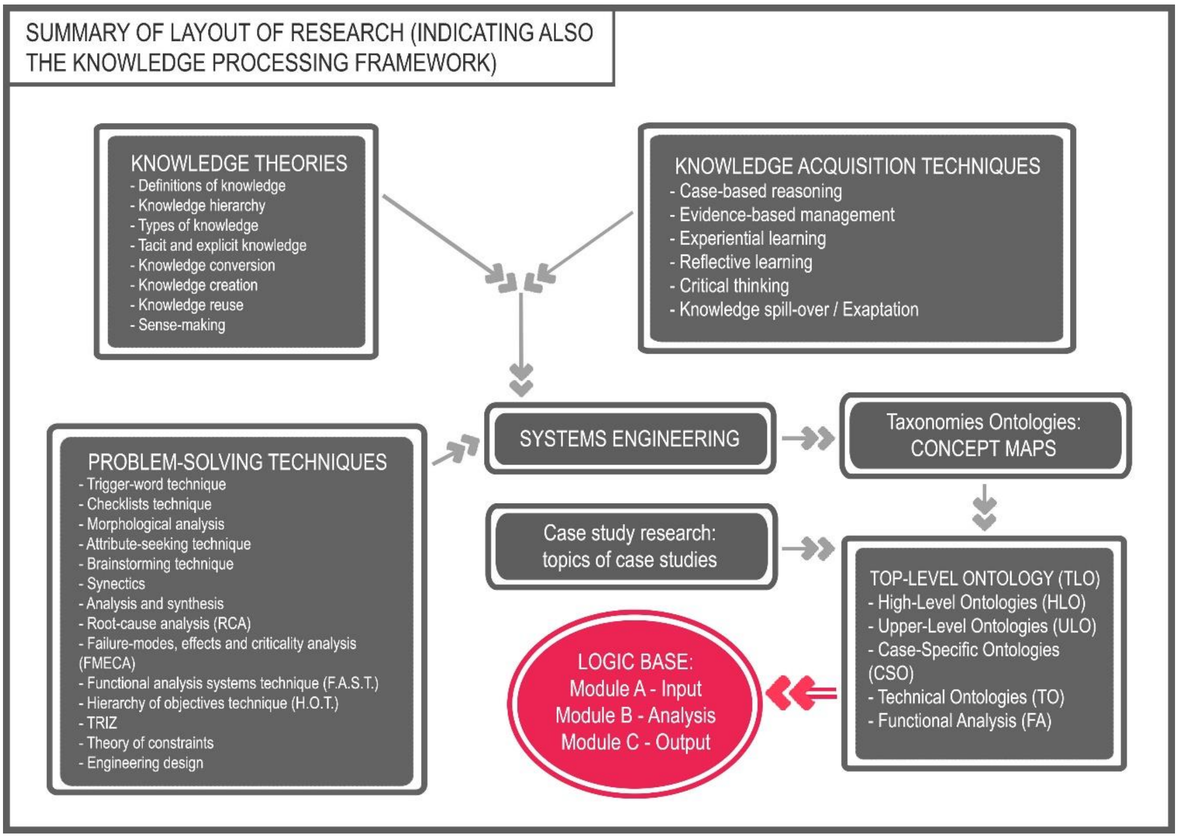

Figure H1 Summary of layout of research – The knowledge processing framework

Figure H1 depicts a summary of the layout of research in this study. Figure H1 lists the various knowledge theories and knowledge acquisitions techniques that were researched and how these are integrated through a systems-engineering point of view to from a holistic approach. (Refer to Chapter 2 of this study.)

From a more practical approach, the following tables show how the various knowledge theories and knowledge acquisition techniques can be put into practice. Table H1 shows the approach to integrate knowledge theories.

Table H1 The integration of knowledge theories

KNOWLEDGE THEORY	COMMENTS
Cognition	Visualise the case and make sketches to ensure proper understanding of the geometry and configuration.
Knowledge hierarchy	Is what is known, data, information or knowledge?
Types of knowledge	What is known about the procedural, declarative, heuristic, common-sense, inexact, uncertain and ontological issues?
Knowledge conversion	How are design philosophies structured, documented and communicated? Is there a central repository for documenting design details?
Redundancy	Is there any spill-over of information from other disciplines?
Sense-making	Is everything that is needed to be known currently in the “known” domain? Are there complex issues that need to be handled?

On the left-hand side of the table the various knowledge theories are listed with appropriate questions to be asked and answered in consideration of the case in hand.

Table H2 The integration of knowledge acquisition techniques

KNOWLEDGE ACQUISITION TECHNIQUE	**COMMENTS**
Case-based reasoning	Consider previous successful designs in relation to the current. What can be learned from the previous cases?
Evidence-based	What can be deduced from the physical evidence?
Experiential	Reflect on previous experience and how these experiences relate to the case in hand?
Reflective	Reflect on design methods and procedures, including available construction methods and constructability issues.
Critical thinking	Critical thinking is required during a design process to ensure that all factors are considered.
Knowledge spill-over/exaptation	Ask the question if the beam is in fact necessary. Speak to the owners of the building or plant to see if all alternatives were considered.

On the left-hand side of **Table H2**, the various knowledge acquisition techniques are listed and the appropriate actions are shown.

The integration of knowledge theories and knowledge acquisition techniques lead a user to explore and analyse the case at hand. (A "case" can be any civil engineering issue that needs to be investigated or that are in hand for resolution. It can also be existing case studies that are analysed for abstraction of knowledge.) In the analysis of case facts, not only are the case facts recorded, but the application of knowledge theories and knowledge acquisition techniques as described above in Tables H1 and H2 are essential. In a process referred to as "contextualisation", the case at hand is dissected and analysed to identify knowledge units. The knowledge units are then reviewed to ensure that the knowledge is understood to be in the correct context. It may be necessary to review and sort the knowledge by discarding irrelevant and unimportant knowledge. The purpose of this contextualisation is to ensure that all the knowledge is mapped correctly to the logic base. This is done by mapping the knowledge to the desired attributes of the logic base. The desired attributes of the logic base are described in chapter 4 and, for convenience are repeated in the following section.

2. The desired attributes of the logic base

(From the **Table 2.4** in Chapter 2 of this study, a list of attributes of the proposed knowledge base is given. The following summary is compiled from **Table 2.4**. The summary is expanded and incorporates the list in **Table 2.4.** This list also serves as an outline for the logic base (not necessarily in a particular order):

- Classifications and hierarchies are required (topical and/or functional).
- Integration of organisational strategies, policies, cultures and supporting technologies.
- All phases of projects as well as operations, maintenance and retirement should be included.
- Uncertainties must be addressed. (Also, involving sense-making such as the Cynefin framework, if required.) (Refer to Chapter 2.)
- All significant external influences on the system should be evaluated.
- Assumptions must be challenged.
- Attributes of elements and relationships among them must be identified.
- Causes and effects of actions must be identified, where possible.
- Root causes must be identified.
- Issues must be explored.
- Clear purpose and goal setting (idealisation) is required.
- Appropriate Functional Requirements (FRs) and Design Parameters (DPs) must be defined.
- Processes must be in place to identify attributes and establish the relationships between them.
- Analysis of contradictions and constraints is required.

- Risks are to be identified. (Including all kinds of risks, such as the risks of failure, health, safety, financial, time, resources risks and business risks.)
- Expansion of knowledge to cover wider fields is needed.
- Analogies are made and context provided.
- Prompting, triggers and metaphors are to be used.
- Action is required through systematic analysis using HOT/FAST methodologies. (Refer to Chapter 2, Section 2.7.10 and 2.7.11.)
- Checklists can be generated as actionable items.
- Patterns and standard solutions must form part of the logic base (refer to the 40 “innovative principles” offered by TRIZ). (Mann, 2007a.)
- Evidence and experiences must update knowledge.
- Recording or sharing of experience. (Where applicable, by way of media support such as video clips.)
- It must be adaptable and modifiable.

The purpose is to take the above desired attributes and used it for the integration of knowledge theories and knowledge acquisition techniques (contextualisation process). From the above list, at least the following are needed to commence with the drafting of concept maps:

- Establish a clear purpose
- Uncertainties must be addressed.
- Identify all risks
- Challenge assumptions
- All significant external influences on the system should be evaluated.
- Issues must be explored.
- All phases of projects as well as operations, maintenance and retirement should be included.
- Causes and effects of actions must be identified, where possible.
- Consider organisational integration (strategies, policies, cultures and supporting technologies).

The above contextualisation will enable the user to start with the drafting of concept maps. The drafting of concept maps is mostly an iterative process. After the first iteration, reference can be made to the complete list of desired attributes (as described above) to ensure that as many as possible of the appropriate attributes can be addressed through the analysis of the concept maps.

Research was carried out on concept mapping which relates back to the principles of cognition and how knowledge is represented in the human mind. The methods of drawing concept maps were researched. With this background, concept maps are drawn. The concept maps are “packaged” onto the appropriate ontologies. The various levels of ontologies were designed. The concept maps therefore integrate knowledge theories, knowledge acquisition and systems engineering. Once concepts maps are drawn, the interrelationships among the concepts can be identified and analysed. Various problem-solving techniques were researched. The researched showed that most problem-solving techniques involve analysis of relationships The problem-solving methods are then applied to the various ontologies, problems and constraints are identified and solutions identified for execution. The logic base integrates the various components as shown in Figure G1 and comprises a input module, (Module A), an analysis module (Module B) and an output module (Module C). In the output module, the concept maps are shown and the results of the analysis, including the solutions to the various problems and constraints

APPENDIX I Summary of research questions

Summary of research questions

There are several research questions, sub-research questions and sub-sub research questions. **Table I1** provides an overall summary of all these questions and also where the answers to the various questions can be found.

Table I1 Summary of research questions

MAIN RESEARCH QUESTION
What are the key characteristics of a model (termed a "logic base" in this study) for the acquisition, reuse and the creation of knowledge in a civil engineering environment?

SUB-RESEARCH QUESTION	SUB-SUB RESEARCH QUESTION	CHAPTERS WHERE RESEARCH QUESTIONS ARE DISCUSSED
a) What are the most appropriate knowledge elements to be considered for inclusion in the proposed logic base?	i) What are the most applicable definitions of knowledge for this model?	Chapter 2 Section 2.3.1
	ii) In what way is knowledge represented in the human mind and how does this relate to the logic base?	Chapter 2 Section 2.3.2
	iii) What types of knowledge can be identified in the civil engineering environment?	Chapter 2 Section 2.3.5; section 2.5
	iv) What methods are there for transferring knowledge to individuals, and how would these methods apply to civil engineering?	Chapter 2: Section 2.4
b) What sources of existing knowledge are available and how does this knowledge relate to the proposed logic base?	i) In what form or structure is existing knowledge available?	Chapter 2 Sections 2.5; section 2.9
	ii) How usable is existing knowledge to the practising engineer?	Chapter 2.5; section 2.9

SUB-RESEARCH QUESTION	SUB-SUB RESEARCH QUESTION	CHAPTERS WHERE RESEARCH QUESTIONS ARE DISCUSSED
c) How can existing engineering knowledge be reused?	i) What methods and processes are there for transferring knowledge to individuals for reuse?	Chapter 2. Section 2.
	ii) What methods and processes are there for transferring knowledge to individuals for reuse?	Chapter 2 Section 2.4
d) How can knowledge be created?	i) What stimulates thought processes to create engineering knowledge?	Chapter 2 Section 2.4.4; section 2.6
	ii) What processes would enhance knowledge acquisition and knowledge creation?	Chapter 2
e) What research methodologies are most applicable for the discovery and application of engineering knowledge?		Chapter 3 Section 3.8
f) What components are required for the logic base?	i) How can knowledge acquisition, reuse and knowledge creation be translated into components of a logic base?	Chapter 4 Sections 4.1 to 4.4.2
	ii) What are the relationships among the various components and how would the components contribute to the functioning of the logic base?	Chapter 4 Sections 4.5 and 4.6 Chapter 5 Section 5.2
	iii) What criteria are required to provide the functionality of knowledge acquisition, reuse and knowledge creation and how can the criteria be satisfied?	Chapter 4 Section 4.6.2; Section 4.8.2
g) What is an appropriate architecture of a logic base to fulfil the Functional Requirements (FRs) for the acquisition, reuse and the creation of knowledge?	i) What ontology and taxonomy can form the basis of the design of a logic base?	Chapter 4 Section 4.4 to 4.6 Chapter 5 Section 5.2, Section 5.7
	ii) How sensitive are the ontologies for different applications?	Chapter 4 Section 4.10
h) How can one formulate an integrated model, i.e., the logic base, to function as a suitable tool for practical application, incorporating elements of knowledge acquisition, reuse and the creation of knowledge?	i) How would all the components comprising the logic base interact to provide the required functionality regarding knowledge acquisition, reuse and creation of knowledge?	Chapter 5.8 and 5.9

SUB-RESEARCH QUESTION	SUB-SUB RESEARCH QUESTION	CHAPTERS WHERE RESEARCH QUESTIONS ARE DISCUSSED
	ii) What would be the inputs and outputs of the logic base?	Chapter 5 Section 5.8
	iii) What knowledge is required to interact with the logic base?	Chapter 6
	iv) Who would be the target users of the logic base?	Chapter 6