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LIST OF EQUATIONS

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LIST OF ABBREVIATIONS

BPR	:	Business Process Re-engineering
c.	:	*circa* - about, approximately (used in the references)
ED	:	event-driven
eq.	:	equation
ERM	:	Entity-represent-module
et al.	:	*et alii*, *et alia* - and others
etc.	:	*et cetera* (also *etcetera*) - and the rest; and similar things or people
EUROSIS	:	European Simulation Society
FC	:	Fraction-comparison
FMCG	:	Fast-moving Consumer Goods
GTL	:	Gas-to-liquids
i.e.	:	*id est* - that is to say
INT	:	Integer function that drops the fractional portion of a variable to return its integer value
ITI	:	iteration time interval
LP	:	Linear Programming
Ltd.	:	Limited
m^3/h	:	cubic metres per hour (used for the liquid phase)
MBA	:	Master of Business Administration
MTBF	:	Mean Time Between Failure
MTTR	:	Mean Time To Repair
MW	:	megawatt
nm^3/h	:	normalised cubic metres per hour (used for the gas phase)
No.	:	number
no.	:	number (used in the references)
OR	:	Operations Research
Pty.	:	Proprietary
p.	:	page (used in the references)
RAM	:	Random Access Memory

LIST OF ABBREVIATIONS
(CONTINUE)

Sapref	:	South African Petroleum Refinery
S.l.	:	*sine loco* - without a place (used in the references)
sic	:	used, spelt, *etc.*, exactly as written in the work that is quoted
SPD	:	Slurry Phase Distillate
ton/h	:	tons per hour (used for the solid phase)
VBA	:	Visual Basic for Applications
VL	:	Visual Logic (the logic building environment of Simul8)
vol.	:	volume (used in the references)
WSSD	:	World Summit on Sustainable Development

* * * * *

INTRODUCTION

The key objective of this research is to develop a generic simulation modelling methodology that can be used to model stochastic continuous systems effectively. Simulation models that are developed with the generic methodology have the following characteristics: short development and maintenance times, user-friendliness, short simulation runtimes, compact size, robustness, accuracy and a single software application.

The first chapter provides detail about the origins of, and the motivation behind, the research that is presented in this document. The origins of the research can be traced back to the development of a simulation model of the Sasol East plant. The simulation modelling method of this simulation model, which is the subject matter of a *Magister* dissertation, is used as the point of departure for the development of a generic simulation modelling methodology. A system description of an imaginary continuous process plant is developed. This plant represents the Sasol East plant, is referred to as the Synthetic Fuel plant and is used to demonstrate the generic methodology. The role of simulation modelling as a decision support tool is considered and the shortcomings of the original simulation modelling method are analysed. The key objective, importance and limitations of the research are also discussed.

The generic simulation modelling methodology is conceptualised in the second chapter. The key characteristics of stochastic continuous systems are identified and discussed. Seven methods and techniques are developed to solve the unique simulation modelling problems that are posed by these characteristics. The seven methods and techniques are integrated into, and form the "toolbox" of, the generic methodology. In Chapter 3 the two simulation models that are developed with the generic methodology are enhanced and another method is developed and integrated into the generic methodology. Therefore, the "toolbox" of the generic methodology contains the following eight methods and techniques: the variables technique, the iteration time interval (ITI) evaluation method, the event-driven (ED) evaluation method, the Entity-represent-module (ERM) method, the Fraction-comparison (FC) method, the iterative-loop technique, the time "bottleneck" identification technique and the production lost "bottleneck" identification technique. The generic methodology is divided into two separate parts, namely: an iterative-loop

technique part (that determines the governing parameters) and a simulation model part. The simulation model itself is divided into a "virtual" part (represented by the logic engine high-level building block) and a "real" part (represented by the four different high-level building blocks of the ERM method). The five high-level building blocks can be used to construct simulation models of stochastic continuous systems.

In the third chapter the generic simulation modelling methodology is demonstrated and validated by the development of two simulation models. Different simulation software packages are evaluated and a simulation model breakdown is derived from the system description of the Synthetic Fuel plant. The five high-level building blocks are used to construct two identical simulation models of the Synthetic Fuel plant in two different simulation software packages, namely: Arena and Simul8. An iteration time interval and minimum sufficient sample sizes are determined and the simulation models are verified, validated, enhanced (by the inclusion of an additional evaluation method option) and compared. The strengths and weaknesses of Arena and Simul8 are discussed.

In the fourth chapter the two simulation models are used to evaluate two alternative scenarios. The scenarios are used to identify the "bottlenecks" and to determine how additional capacity impacts on the throughput of the Synthetic Fuel plant. The results of the scenarios are compared and conclusions are presented.

The last chapter provides a synopsis of the research. The factors that motivated the research are identified and discussed. The process that was followed is detailed and a concise summary of the generic simulation modelling methodology is provided. The original simulation modelling method and the generic methodology are compared and the strengths and weaknesses of the generic methodology are discussed. The contribution to knowledge is explained and possible future developments are proposed. The possible range of application and three different usage perspectives are identified. To conclude, a few of the lessons learnt and reinforced during the completion of the research are presented.

* * * * *

CHAPTER 1

PROBLEM EXPOSITION

INTRODUCTION

The term "exposition" means an explanatory statement or account, and that is exactly what this chapter aims to achieve. It provides some detail about the origins of, and the rationale behind, the research that is presented in this document.

The first section indicates that the origins of the research that is presented in this document can be traced back to the development of a simulation model of the Sasol East plant. The original simulation model of the Sasol East plant was developed, refined, expanded and maintained over a 3-year time period from 1994 to 1996. The final 1996 simulation model includes the whole Sasol Synfuels complex and makes provision for the investigation of various scenarios. An investigation into the viability to update the final 1996 simulation model, led to an opportunity to use the original simulation modelling method as a point of departure for the development of a generic simulation modelling methodology.

A system description breakdown is provided in the first part of the second section and it is then used to describe the type of system that is considered in this document. To describe a system the physical and functional aspects of the system must be addressed. The physical aspect consists of the system configuration and the characteristics of the elements. The functional aspect consists of the process flow and the process logic. The second part of the section provides the system description of the Synthetic Fuel plant, an imaginary continuous process plant that represents the Sasol East plant.

The third section details the role of simulation modelling as a decision support tool. Simulations are compared to other decision support tools. A simulation model can provide knowledge about past and present system behaviour as well as insight into probable future system behaviour. Managers strive to achieve the maximum possible rate of production or throughput and consequently also the maximum possible profitability. Simulation modelling is a cost-effective way of managing the risk that is associated with decisions.

The shortcomings of the original simulation modelling method are addressed by the fourth section. Some background information is provided on a *Magister* dissertation that is based on the development of the original simulation model. The reasons why a FORTRAN subroutine was included into the original simulation model and the weaknesses of the original method are presented and discussed. These shortcomings were the catalysts that initiated the development of the generic simulation modelling methodology.

The fifth section indicates that the key objective of this research is to develop a generic simulation modelling methodology that can be used to model any generic variant of a stochastic continuous system effectively.   The generic methodology renders simulation models that exhibit the following characteristics: short development and maintenance times, user-friendliness, short simulation runtimes, compact size, robustness, accuracy and a single software application.

The importance of the research that is presented in this document is highlighted in the sixth section. The principal range of possible application of the generic simulation modelling methodology falls within the petrochemical industry, but the generic methodology is not restricted to the petrochemical industry alone. Any system that displays the same characteristics as the system that is detailed by the system description in the second section can readily be accommodated by the generic methodology. The majority of simulation software packages cannot adequately accommodate such systems because they focus primarily on the modelling of discrete-event systems.

The last section clarifies the limitations of the generic simulation modelling methodology. Simulation models of the class or type of system that is considered in this document are classified as dynamic, combined, stochastic simulation models. Continuous state change behaviour or transient behaviour is usually represented with state and differential equations. The generic methodology does not accommodate transient behaviour but this is not necessarily a limitation because it simplifies the generic methodology significantly.

* * * * *

1.1   BACKGROUND INFORMATION

The origins of the research that is presented in this document can be traced back to the development of a simulation model of the Sasol East plant. The Sasol East plant was formerly known as Sasol 3 and it forms part of the Sasol Synfuels (Pty.) Ltd. company. The company will hereafter be referred to simply as Sasol Synfuels. The massive Sasol Synfuels industrial complex is situated at Secunda, South Africa. The following quotation describes the main business activity of Sasol Synfuels (Sasol Synfuels (Proprietary) Limited, 2003):

> "*The company operates the world's only commercial coal-based synfuels manufacturing facility at Secunda. It uses unique Sasol Fischer-Tropsch technology to manufacture synthesis gas from low-grade coal and to convert this into a large range of petrochemical products, including synthetic liquid fuels, industrial pipeline gas and chemical feedstock. These latter products - including ethylene and propylene, ammonia, phenolics, solvents and olefins - form most of the building blocks for the South African chemical and polymer industries.*"

Sasol Synfuels is part of the Sasol group of companies. The Sasol group is the largest publicly listed group in Africa (West, 2003:12).

The need for a simulation model of the Sasol East plant originally arose because the plant management identified the necessity for a decision support tool on a strategic level (Owen, 1994:15,17). In this instance a strategic level is regarded as the level on which decisions of greater possible impact are handled. For example, the decision to move from a 24-month preventive maintenance cycle to a 36-month preventive maintenance cycle may have a pronounced effect on the production and the maintenance of the plant. It is therefore regarded as a strategic level decision. This can be compared to the decision whether to use corrosion prevention surface treatment A or B. Such a decision is regarded as a detail level decision.

In a plant of this size and complexity it is extremely difficult to predict what the effect of a proposed change is going to be on the operation of the plant. The complex interrelationships of the plant, chronological events such as services and random events such as failures can be handled by a simulation model. The simulation model can be used to identify problem areas ("bottlenecks") in the plant and to study the effect of proposed scenarios on the plant. Proposed scenarios may include added capacity at "bottlenecks", changes in the maintenance strategy, *etc.*

The original simulation model of the Sasol East plant was developed, refined, expanded and maintained over a 3-year time period from 1994 to 1996. This relates closely to a comment from Crowe *et al.* (1971:5) to the effect that it may take a few man-years to supply answers to complex problems with a simulation model.

> "*At the other extreme is a very accurate simulation for answering technically sophisticated problems. A simulation to supply such answers may take two to four man-years.*"

The final 1996 simulation model includes both the Sasol East and Sasol West plants as well as some existing and proposed interconnection lines between the two plants. Sasol West was previously known as Sasol 2 and together with Sasol East makes up the bulk of the Sasol Synfuels complex. The interconnection lines are used to channel the production from one plant to the other if required. The final 1996 simulation model makes provision for the evaluation of existing and proposed interconnection lines. It also affords the modeller the opportunity to study the effect of two opposing proposed maintenance strategies on the operation of the Sasol Synfuels complex.

A "phase" service strategy can be compared to a "block" service strategy with the final 1996 simulation model. A "phase" constitutes one half of either of the Sasol East or Sasol West plants, if split lengthwise from the beginning to the end of the process. All in all, there are thus four "phases" in the Sasol Synfuels complex, two "phases" in each of the Sasol East and Sasol West plants. A "block" constitutes any logical subdivision of a "phase". A "phase" service will therefore cause one quarter of the Sasol Synfuels complex to be decommissioned for the duration of the service, while a "block" service will cause one eighth, one sixteenth, *etc.* of the complex to be decommissioned.

From 1996 to 1999 the final 1996 simulation model was in continuous use as a decision support tool. It was used for the evaluation of several different proposed scenarios. During 1999 a concern developed that the final 1996 simulation model (constructed according to a system description or model definition that reflected the 1996 status of the Sasol Synfuels complex) may not accurately reflect the 1999 status of the complex. It was decided to explore the feasibility of updating the final 1996 simulation model to the 1999 status of the Sasol Synfuels complex.

A preliminary feasibility study found that comprehensive changes were needed. Parts of both the Sasol East and Sasol West plants have been dismantled and new additional parts have also been added to both plants. One part of the Sasol West plant was actually destroyed by an explosion

and it was prudently decided to redesign the appropriate process. Some of the original feedback-loops have also been moved and new ones added to accommodate new chemical processes that were introduced to increase efficiency and to align product supply with client demand.

The changes that are outlined in the previous paragraph cannot readily be incorporated into the final 1996 simulation model, because the simulation modelling method that is used is not very accommodating when changes of this magnitude are encountered. The simulation modelling method that is used by both the original simulation model of the Sasol East plant and the final 1996 simulation model will be referred to as the original simulation modelling method in the rest of this document. The comprehensive changes that were needed necessitated the proposal of a lengthy and costly process to update the final 1996 simulation model to a 1999 system description or model definition of the Sasol Synfuels complex and consequently the project was cancelled.

Even though the project was shelved, the whole exercise led to a unique opportunity to do something more than just an update of the final 1996 simulation model. It presented a chance to use the original simulation modelling method as a point of departure for the development of a generic simulation modelling methodology. The term "generic" implies that the generic methodology is applicable to an entire class or type that includes all plants or similar systems that exhibit the same characteristics as the Sasol East plant. The generic methodology also effectively addresses the shortcomings of the original method. The investigation into the viability to update the final 1996 simulation model of the Sasol Synfuels complex gave rise to the development of the generic methodology and thus triggered the research that is presented in this document.

In this document the term "method" is used in conjunction with the original simulation modelling method while the term "methodology" is used in conjunction with the generic simulation modelling methodology. In many instances these two terms are perceived to be interchangeable but in the context of this document the term "method" is perceived to be indicative of a lower order terminology, while the term "methodology" is perceived to be indicative of a higher order terminology. Van Dyk (2001:2-4) postulates that the hierarchy of terminologies that is used in Industrial Engineering proceeds along a continuum. The hierarchy that is suggested is as follows: tool, technique, method, approach and philosophy (arranged from lower to higher order). It is suggested that the transition within this hierarchy occurs continually. Even though van Dyk does not make a distinction between the term "method" and the term "methodology", in this document the term "method" is perceived to imply a less elegant, less accomplished procedure with a more restricted range of application, while the term "methodology" is perceived to imply a more elegant, more accomplished procedure with a broader range of application.

Furthermore, the following conventions, regarding the use of the terms "original simulation modelling method" and "generic simulation modelling methodology", are followed:

a)   The first reference in a paragraph to the original simulation modelling method uses the term "original simulation modelling method", while subsequent references only use the term "original method".

b)   The first reference in a paragraph to the generic simulation modelling methodology uses the term "generic simulation modelling methodology", while subsequent references only use the term "generic methodology".

The aforementioned distinction is necessary to clearly distinguish when the term "method" is used in conjunction with another method that is addressed and when the original simulation modelling method or generic simulation modelling methodology is addressed.

Summary

This section indicates that the origins of this research can be traced back to the development of a simulation model of the Sasol East plant. This simulation model was developed, refined, expanded and maintained over a 3-year time period from 1994 to 1996. The final 1996 simulation model includes the whole Sasol Synfuels complex. In 1999 a concern developed that the final 1996 simulation model may not accurately reflect the 1999 status of the complex. An investigation into the viability to update the final 1996 simulation model, highlighted the shortcomings of the original simulation modelling method and gave rise to the development of the generic simulation modelling methodology.

* * * * *

1.2   SYSTEM DESCRIPTION

The following exposition of the Sasol East plant gives an indication of the type of system that is considered in this document. A concise definition of a system is provided by Pegden *et al.* (1995:3).

> "*By a* **system** *we mean a group or collection of interrelated elements that cooperate to accomplish some stated objective.*"

The "*... a group or collection of interrelated elements ...*" part of the definition refers to the physical aspect of a system while the "*... cooperate to accomplish some stated objective ...*" part of the definition refers to the functional aspect of a system. Both the physical and functional aspects of a system have to be addressed when the system is described.

The physical aspect of a system is described by the configuration of the system and the characteristics of the elements. *The Oxford Compact English Dictionary* (1996:204) describes the term "configuration" as "*an arrangement of parts or elements in a particular form or figure.*" The configuration of the system thus identifies the elements and describes the way that they are arranged and connected. If the system under consideration is a plant, the elements are characterised by their capacities, service schedules and failure characteristics.

The functional aspect of a system is described by the process flow and the process logic of the system. The process flow describes the manner in which "commodities" like data, electrical currents, entities, solids, liquids, gases, *etc.* move or flow through the system. The process part of the process flow describes the processes that the "commodities" are subjected to while the flow part describes the path and the sequence or direction that the "commodities" follow. The process logic describes the rules of operation of the system. For example, if the process flow indicates that coal is supplied by Element(I) to both Element(II) and Element(III), then the rule of operation could stipulate that Element(III) will only be supplied with coal once the capacity of Element(II) is surpassed.

A schematic representation of the system description breakdown that is outlined above is shown in Figure 1.1: *System Description Breakdown*. This approach corresponds with the view of Harrell and Tumay (1999:1) who state that a system consists of resources, activities and controls. The "resources" are the physical aspect of the system, the "activities" are the process flow and the "controls" are the process logic (see the graphical representation of this view in Figure 1.1).

System Description Breakdown

Figure content:
- System
  - Physical Aspect
    - Configuration
      * Identify Elements
      * Element Arrangement
      * Element Connections
    - Element Characteristics
      * Capacities
      * Service Schedules
      * Failure Characteristics
  - Functional Aspect
    - Process Flow
      * Processes
      * Path and Sequence
        or Direction
    - Process Logic
      * Rules of Operation

Harrell and Tumay View

|← Resources →|← Activities →|← Controls →|

Figure 1.1: System Description Breakdown

The Sasol East plant is a continuous process plant (*i.e.* a system) that produces chemical products from coal. The physical and functional aspects of the plant are detailed in the rest of this section. A simplified schematic representation of the plant is shown in Figure 1.2: *Synthetic Fuel Plant*.

For the purpose of this document some changes to the original data pertaining to the Sasol East plant are incorporated to create the imaginary continuous process plant that is represented in Figure 1.2. The imaginary continuous process plant is used to demonstrate the generic simulation modelling methodology and will hereafter be referred to as the Synthetic Fuel plant.

The reasons for the changes to the original data are the following:
a) It protects the client confidentiality of Sasol Synfuels because the company would prefer not to disclose sensitive operational information, such as the capacity of the plant, to their competition.
b) It makes the representation more generic and representative of any continuous process plant. (Section 1.6 details the possible range of application of the generic simulation modelling methodology in the petrochemical and other industries.)

Synthetic Fuel Plant
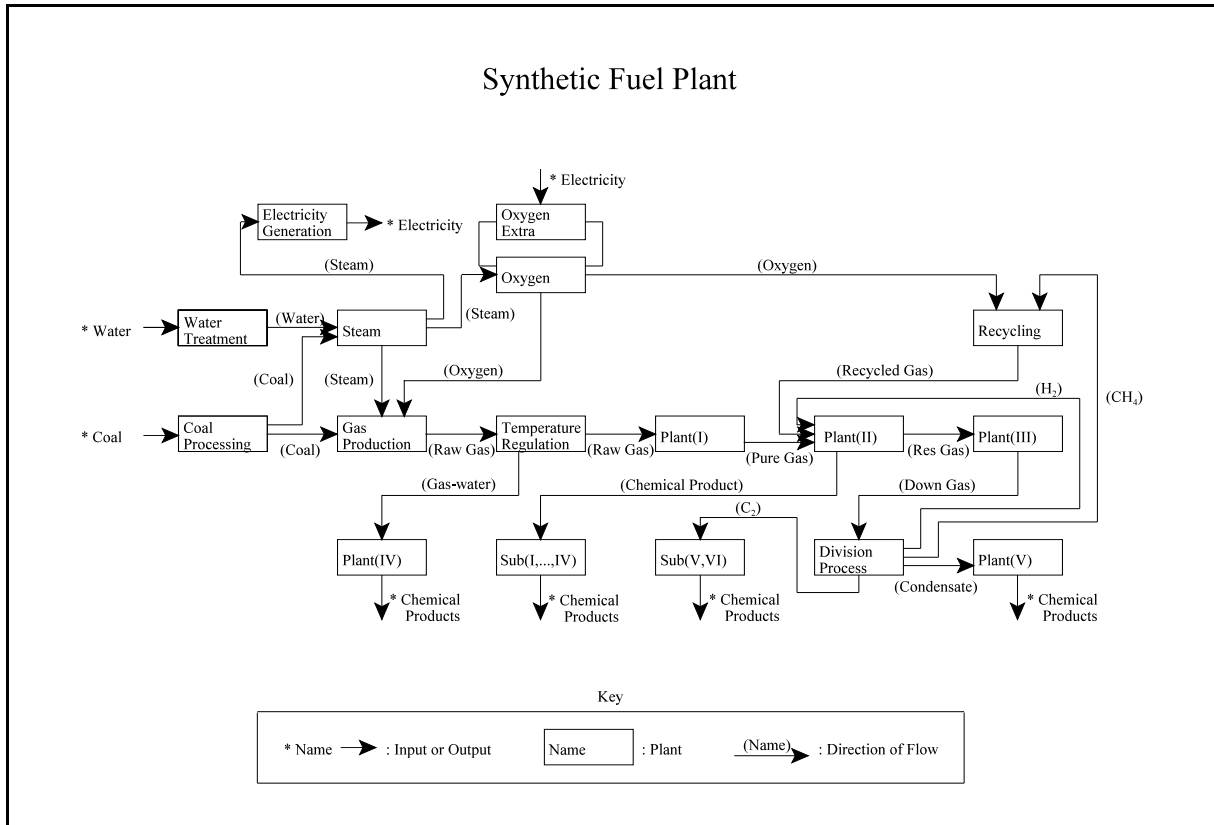
Figure 1.2: Synthetic Fuel Plant

The most obvious change is the change of the name of the plant from the Sasol East Plant to the Synthetic Fuel plant to clearly indicate the move from the specific to the generic. The other changes that are incorporated are the changing of some of the names (of the smaller plants) and the adjustment of all the capacities. For example, the Oxygen plant retains its name *verbatim* because the name is made up of common language words. Proprietary process specific names, on the other hand, are changed to more generic variants like Plant(I), Sub(I), *etc.* The capacities are adjusted by a constant scale factor, implying that the Synthetic Fuel plant is actually a "scale model" of the real Sasol East plant. This gives the added advantage that during the verification and validation of simulation models of the Synthetic Fuel plant the actual results from the Sasol East plant can be adjusted with the same scale factor to create a set of data for verification and validation purposes.

It is important to realise that the term "plant" as used in this document can denote either the Synthetic Fuel plant or one of the smaller plants that make up the Synthetic Fuel plant, depending on the context where it is used. For example, the total Synthetic Fuel plant comprises a number of smaller plants like the Coal Processing plant, the Water Treatment plant, the Steam plant, *etc.*

The configuration of the Synthetic Fuel plant that is represented in Figure 1.2 is exactly the same as that of the Sasol East plant, except for some of the names. The arrangement of the smaller plants and the connections between them are exactly the same as that of the Sasol East plant. The service schedules and failure characteristics, the process flow and the process logic are also not changed. If anything in the system description of the Synthetic Fuel plant is changed, except for the names and the capacities, then the Synthetic Fuel plant will no longer be a "scale model" of the real Sasol East plant.

To summarise, some names and all the capacities are changed, while the arrangement and connections of the smaller plants, the service schedules and failure characteristics, the process flow and the process logic are not changed.

The term "resolution of a model" refers to the level of detail addressed by the model. The level of detail that is required should be chosen in accordance with the objectives of the model. Enough detail should be included to validate any inferences drawn from the use of the model, without making the model cumbersome by the inclusion of unnecessary trivia. Pegden *et al.* (1995:15-16) stress the importance of this approach.

> "*Therefore, the model must include only those aspects of the system relevant to the study objectives.*
>
> *One should always design the model to answer the relevant questions and not to imitate the real system precisely. According to Pareto's law, in every group or collection of entities there exist a vital few and a trivial many. In fact, 80 percent of system behaviour can be explained by the action of 20 percent of its components.*"

The problem is to ensure that the few vital components are identified and included. Crowe *et al.* (1971:177) also warn against the inclusion of unnecessary detail.

> "*The long, detailed computer program has a place in a plant simulation only if meaningless results are generated without it.*"

For the purpose of this document, the Synthetic Fuel plant is considered to consist of 20 smaller plants (some of whom are grouped together for the sake of simplicity in Figure 1.2). The 20 smaller plants are made up of a total of 147 modules. A module can be defined as a grouping of

components that has a specific function. For example, in the Gas Production plant the coal is gasified by 40 gasifiers, each consisting of many components. For the resolution that is required in this instance, it is assumed that each individual gasifier represents a module. The Gas Production plant thus has 40 modules. The capacities, services and failures of the gasifier (*i.e.* the module) as an entity are described, not those of the separate components that make up the gasifier. This simplification can be justified by the fact that the requirement is for a decision support tool on a strategic level, not a detail level (see the explanation of strategic versus detail level in the previous section).

In terms of the definition of a system that is provided in the first paragraphs of this section, both the modules and the smaller plants can be considered as elements of the system, just on different levels of resolution. For the purpose of this document the 147 modules are considered as the "lower" level elements of the system and the 20 smaller plants are considered as the "higher" level elements of the system.

The names of the smaller plants are indicated in Figure 1.2 and Column 2 of Table A1: *Number of Modules and Capacities* (see Appendix A: *Synthetic Fuel Plant Detail*). The number of modules in each of the smaller plants is indicated in Column 3 of Table A1.

Some of the smaller plants consist of groupings of different types of modules. The Oxygen plant, for example, consists of three groupings of different types of modules. There are six air turbine and compressor sets, six cold boxes and seven oxygen turbine and compressor sets. For the sake of simplicity the three groupings are referred to as Oxygen-A, -B and -C respectively. The same logic applies to Plant(II) and Plant(IV).

A schematic representation of the Oxygen plant is shown in Figure 1.3: *Oxygen Plant*. It should be clear from the figure that the Oxygen plant actually consists of six parallel lines, each one containing an air turbine and compressor set, a cold box and an oxygen turbine and compressor set. Such a serial, parallel line within a smaller plant is sometimes referred to as a "train". In this instance the seventh oxygen turbine and compressor set in reality represents a reserve capacity and it was introduced because of the high failure rate of the oxygen turbine and compressor sets.

Oxygen Plant

Oxygen-A
Air Turbine and
Compressor Set

Oxygen-B
Cold Box

Oxygen-C
Oxygen Turbine and
Compressor Set

Number 1   Number 1   Number 1

Number 2   Number 2   Number 2

Number 3   Number 3   Number 3

* Steam   Number 4   Number 4   Number 4   * Oxygen

Number 5   Number 5   Number 5

Number 6   Number 6   Number 6

Number 7

Key

* Name   : Input or Output   Number   : Module   : Direction of Flow
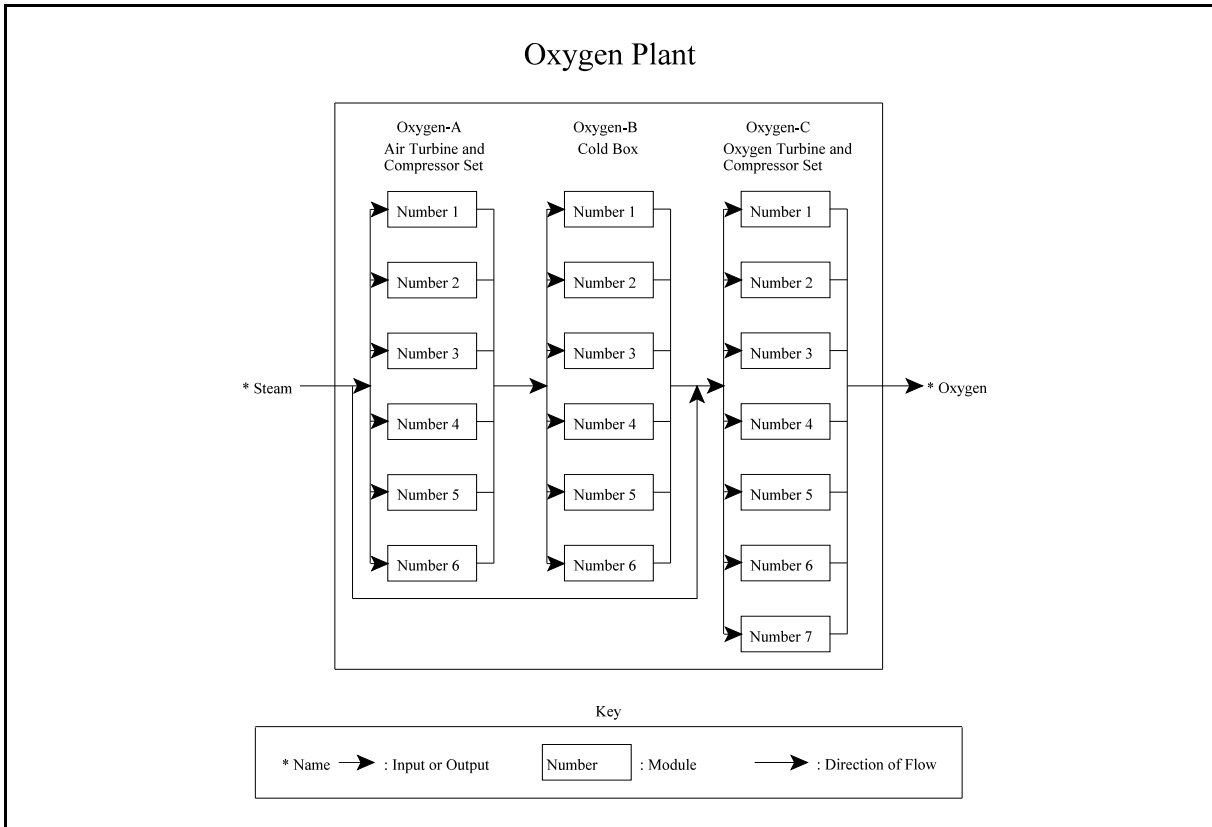
Figure 1.3: Oxygen Plant

The smaller plants have complex switching capabilities. This implies that if one of the modules in a "train" is unavailable (due to service or failure), the whole "train" is not necessarily rendered inoperative. If a module of the same type in another "train" is available, but not in use, it may be incorporated temporarily into the "train" with the unavailable module. Thus an operative "train" may be created from modules that are not positioned in the same geographical parallel line.

The way that the smaller plants are arranged and connected can be derived from Figure 1.2 and Table A1. For example, the Temperature Regulation plant is situated between the Gas Production plant and Plant(I) and connected to the Gas Production plant, Plant(I) and Plant(IV).

That concludes the description of the configuration (element identification, arrangement and connection) of the Synthetic Fuel plant.

The modules are characterised by their capacities, service schedules and failure characteristics. The input and output capacities of the modules are indicated in Columns 4 and 5 respectively of Table A1. The capacities are given as hourly rates of flow for a single module. For example, if

the output capacity of each individual module in the Steam plant is 378 ton/h, then the maximum possible output capacity of the Steam plant is 3402 ton/h (nine times 378 ton/h). The coal, water and steam capacities are given in tons per hour (ton/h), the liquid capacities are given in cubic metres per hour (m^3/h) and the gas capacities are given in normalised cubic metres per hour (nm^3/h). Because the temperatures and pressures (and therefore the volumes) of gases differ at different points in the process, the volumes of gases are represented as volumes that are numerically normalised to a standard temperature and pressure. This normalisation makes it possible to compare the volumes of gases at different points in the process.

To summarise, solid phase capacities are given in ton/h (except for water and steam where traditionally the capacities are always given in ton/h), liquid phase capacities are given in m^3/h and gas phase capacities are given in nm^3/h.

The service schedules of the modules are indicated in Table A2: *Service Schedules and Failure Characteristics* (see Appendix A). The services of the modules are strictly chronological events and are characterised by the service cycles of the modules. The service cycles are described by the start times, cycle times and service times (*i.e.* the length of time or duration of the services) of the modules. The cycle times and service times of the modules are indicated in Columns 3 and 4 respectively of Table A2. For example, the modules in the Steam plant are subject to a cycle time of eight weeks (1344 hours) and each service takes 34 hours to complete. The services of the individual modules in the Steam plant are of course staggered in time to minimise the impact of the services on steam production.

Some of the service schedules consist of more than one service cycle. Such an occurrence is referred to as a multiple service cycle. For example, the modules in both the Coal Processing plant and Plant(II)-A have three service cycles that are superimposed on one another. The "phase" services, are services that are conducted on a yearly basis. (A "phase" constitutes one half of the Synthetic Fuel plant, if split lengthwise from the beginning to the end of the process.) There is also a two-yearly shutdown during which routine (mostly statutory) maintenance work is completed.

The failure characteristics of the modules are also indicated in Table A2. The failures of the modules are random (*i.e.* stochastic) events and are characterised by the failure characteristics of the modules. The failure characteristics are described by the failure rates and repair times of the modules.

Various authors indicate that the behaviour of random phenomena can be represented in a model with the help of theoretical probability distributions or empirical (user-defined) distributions (Harrell and Tumay, 1999:83; Kelton *et al.*, 1998:35; Pegden *et al.*, 1995:17; *Simul8®: Manual and Simulation Guide*, 1999:110). The following quotation from Harrell and Tumay (1999:83) clearly illustrates this:

> "*Random phenomena must be either fit to some theoretical distribution or described using an empirical distribution ...*"

Pegden *et al.* (1995:17-18) provide the following reasons why it is desirable to use a theoretical probability distribution rather than an empirical distribution to represent random behaviour:

a)   Using raw empirical data implies that only the past (with its idiosyncrasies) is represented and the only events possible are those that transpired during the period of time when the data were gathered. This is different from the assumption that the basic form of the theoretical probability distribution that represents the data will remain unchanged.

b)   It is much easier to change certain aspects of the random behaviour if theoretical probability distributions are used, implying greater flexibility.

c)   It is highly desirable to test the sensitivity of the system that is under scrutiny to changes in the random behaviour. This is much easier with theoretical probability distributions than with empirical distributions because of the flexibility of the theoretical probability distributions.

According to Pegden *et al.* (1995:45) the exponential distribution can be used to represent the failure rates of the modules.

> "*The **exponential** function is widely used for times between independent events such as interarrival times, and lifetimes for devices with a constant hazard rate (when describing the time to failure of a system's component).*"

> "*When the exponential random variable represents time, the distribution possesses the unique property of forgetfulness or lack of memory. Given that **T** is the time period since the occurrence of the last event, the remaining time, **t**, until the next event is independent of **T**. Therefore, events for which interarrival times can be represented by the exponential* [distribution] *are said to be completely random.*"

The only value that is needed to describe the exponential distribution is the mean. The mean values of the exponential distributions that represent the failure rates of the modules are indicated in Column 5 of Table A2. These mean values are derived from the failure histories of the modules. The failure histories of the modules are available from the maintenance division of the plant. The mean value of the exponential distribution that represents the failure rate of a module is in fact the Mean Time Between Failure (MTBF) value of the module. The actual failure rate of a module is the reciprocal (*i.e.* the inverse) of the MTBF of the module. For example, the MTBF of the modules in the Steam plant is 2880 hours. It implies that, on average, there will be one failure every four months for each module (*i.e.* every 2880 hours - assume a 30-day month). An exponential distribution with a mean value of 2880 hours can thus be used to represent the failure rate of the modules. The actual failure rate of the modules is the reciprocal of 2880 hours and that is 0,000347 (3,47E-04) failures per hour.

Different theoretical probability distributions can be used to represent the failure rates of components. For example, the best mathematical approximation of the failure rate of a specific component may be a Weibull distribution. Pegden *et al.* (1995:38) indicate that the MTBF of electronic components generally follows a Weibull distribution. Ideally the failure history of each specific component should be subjected to thorough statistical analysis to determine the theoretical probability distribution that provides the best approximation of the failure rate of that specific component. The degree of precision with which the identified theoretical probability distribution approaches the real-world situation, depends largely on the availability and quality of the failure history of that specific component. Harrell and Tumay (1999:83) also stress this point.

> "*To define a distribution using a theoretical distribution requires that the data,*
> *if available, be fit to an appropriate distribution that best describes the variable*
> *...*"

The resolution (level of detail) of a model affects the degree of precision required of the theoretical probability distributions that are used to represent the failure rates. The higher the resolution (finer level of detail) of the model, the more effort should be expended to find theoretical probability distributions that represent the failure rates with a high degree of precision.

For the resolution that is required in this instance, the failure rates of the components that make up the modules are not considered. The failure rates of the modules as entities are determined and the exponential distribution is used to represent the failure rates of the modules.

The reasons for this assumption are the following:

a)   The requirement is for a decision support tool on a strategic level, not a detail level (see the explanation of strategic versus detail level in the previous section).

b)   The quality of the data that make up the failure histories of the modules is suspect in some instances.

According to Pegden *et al.* (1995:45) the triangular distribution can be used to represent the repair times of the modules.

> "*This distribution is most often used when attempting to represent a process for which data are not easily obtained but for which bounds (minimum and maximum) and most likely value (mode) can be established based on knowledge of its characteristics.*"

The triangular distribution is defined by three values, namely: a minimum, a mode and a maximum. The mode is the most likely value or most often occurring value. The three values of the triangular distributions that represent the repair times of the modules are indicated in Columns 6, 7 and 8 of Table A2. These values are derived from the failure histories of the modules. The failure histories of the modules are available from the maintenance division of the plant. Even though the mode of the triangular distribution that represents the repair time of a module is defined as the most likely value of the repair time of the module, it can be likened to the Mean Time To Repair (MTTR) value of the module. In most practical instances, if the triangular distribution is used to represent the repair time of a module, then the MTTR of the module can be used to approximate the mode of the triangular distribution that is used to represent the repair time of the module. The assumption is made that the MTTR and the mode are approximately equal. For example, the minimum repair time of the modules in the Steam plant is 24 hours, the mode or most likely repair time is 120 hours and the maximum repair time is 168 hours.

The same argument applies for the assumption to use the triangular distribution to represent the repair times of the modules, as for the assumption to use the exponential distribution to represent the failure rates of the modules.

The probity of these assumptions is established in Sections 3.6, 3.7 and 4.3 by the verification and validation of the simulation models that use the system description presented in this section as their model definition.

The process flow or activities according to Harrell and Tumay (1999:1) of the Synthetic Fuel plant can be derived from Figure 1.2 and Table A1. For example, the input of the Coal Processing plant is coal from the mines and the output is coarse coal to the Gas Production plant and fine coal to the Steam plant. The previous statement describes the process and also the path and the sequence or direction of the flow in that part of the Synthetic Fuel plant. The process can be derived by comparing the input (singular or multiple) and the output (singular or multiple) that are indicated in Columns 4 and 5 respectively of Table A1. In the case of the Coal Processing plant the process is to separate the coal from the mines into coarse and fine coal with sieves. The path and the sequence or direction of the flow can be derived from Figure 1.2 and Table A1. The plant (or plants) from which input (singular or multiple) is received and the plant (or plants) to which output (singular or multiple) is sent are indicated in brackets in Columns 4 and 5 respectively of Table A1.

The presence of feedback-loops and the division of the output of both the Steam and Oxygen plants are of special significance. Crowe *et al.* (1971:14) refer to a feedback-loop as recycle and indicate that it is a common feature of chemical processes.

> "*Most chemical processes have recycle of either matter or heat. Recycle means that a stream leaving a process unit affects a steam entering that unit.*"

The output of Plant(II)-A progresses through Plant(II)-B and Plant(III) and eventually it ends up as the input of the Division Process plant. From the Division Process plant there is a direct feedback-loop to Plant(II)-A and there is also an indirect feedback-loop through the Recycling plant to Plant(II)-A. The output of the Steam plant is divided between three other plants. Steam is supplied to both the Gas Production and Oxygen plants, while any additional steam is sent to the Electricity Generation plant. The output of the Oxygen plant is divided between two other plants. Oxygen is supplied to both the Gas Production and Recycling plants. The ramifications of these phenomena on a simulation model are detailed in Sections 2.1, 2.2, 2.4, 2.5 and 2.7.

The process logic (rules of operation) or controls according to Harrell and Tumay (1999:1) of the Synthetic Fuel plant are presented in Appendix B: *Synthetic Fuel Plant Rules of Operation*. For example, one of the rules of operation states that steam will only be supplied to the Electricity Generation plant once the Gas Production and Oxygen plants have been supplied. The supply of steam to the Gas Production and Oxygen plants is therefore the primary function of the Steam plant while the supply of steam to the Electricity Generation plant is the secondary function of the Steam plant. These rules of operation, if complex, can have a severe impact on the

complexity of a simulation model.

That concludes the description of the system that is considered in this document, according to the system description breakdown that is developed in the first paragraphs of this section.

The process flow describes the processes and also the path and the sequence or direction that the "commodities" that move of flow through the system follow. The "commodities" themselves, however, also have to be described. These "commodities" can be as diverse as data, electrical currents, entities, solids, liquids, gases, *etc.* If the "commodities" are discrete entities the motion is referred to as move and if the "commodities" are fluid in nature the motion is referred to as flow. A scrutiny of Figure 1.2 and Table A1 indicates that, in this instance, the "commodities" are coal, various gases (steam, oxygen, raw gas, pure gas, residue gas, *etc.*) and various liquids (water, gas-water, condensate and chemical products). Even though the coal from the mines is in the solid phase, it is considered as a fluid because it consists of chunks that are moved along on conveyor belts. The same logic applies to the coarse coal that is supplied to the Gas Production plant while the fine coal that is supplied to the Steam plant is in the form of a slurry (a suspension of insoluble particles). The motion of the coal, gases and liquids in the Synthetic Fuel plant is therefore characterised as flow.

Summary

The system description that is provided in this section gives an indication of the type of system that is considered in this document and also provides an insight into the level of detail that is deemed necessary if a simulation model of the system for strategic decision support is considered. The system description is used as the model definition when a simulation model of the system is developed.

* * * * *

1.3   SIMULATION MODELLING AS A DECISION SUPPORT TOOL

> "*It must be remembered that there is nothing more difficult to plan, more doubtful of success, nor more dangerous to manage, than the creation of a new system.*"
>
> Niccolò Machiavelli

This statement, made approximately 500 years ago by Machiavelli (1469 - 1527), regarding the challenge of planning and managing political systems, is equally applicable to the design and operation of modern day manufacturing systems (Harrell and Tumay, 1999:1).

Management can be described as the art of making decisions without having all the relevant information available. There is a commonly held belief that by the time all the relevant information about a decision is available, it may not be important or even necessary to make the decision any more (*i.e.* the time window of opportunity or impact of that decision has already passed). Managers would therefore like to have a "toolbox" of decision support tools available to help them to make better decisions. The goal is to decrease the risk associated with a decision and consequently to increase the confidence level that the correct decision is made. Morris (1977:1) describes a decision aid as "*... a model, method, technique, or process designed to enhance the decision-making process.*"

Figure 1.4: *Decision Support Tool Confidence Level* (adapted from Kleinschmidt (1990)) gives an indication of the confidence levels that can be obtained with different decision support tools.

The vertical axis represents the confidence level that can be obtained that the determined value of an attribute of a system is correct. The attribute that is under scrutiny can be as diverse as the performance of an aircraft or the environmental impact of a chemical plant. The confidence level that the determined value of an attribute of a system is correct can vary between 0% and 100%. The horizontal axis represents different decision support tools that can be used to obtain a required confidence level.
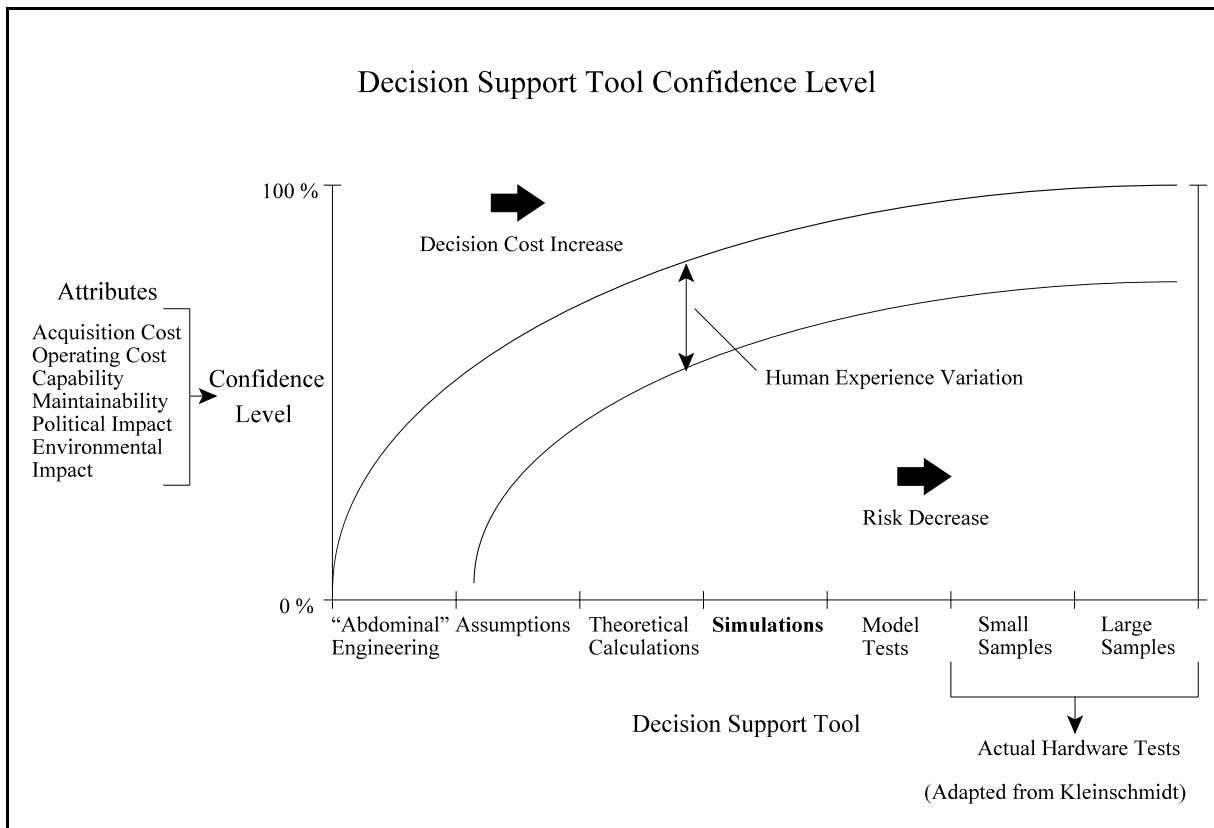
Figure 1.4: Decision Support Tool Confidence Level

"Gut feel" decisions or "abdominal" engineering features on the extreme left of the horizontal axis. This represents intuitive decisions, usually taken when there is very scant information or not enough time available to make a structured decision. Naturally the confidence level of an attribute value of a system that is determined with this decision support tool is not very high. Large samples are positioned on the extreme right of the horizontal axis. If a sample batch of a number of aircraft has been built and tested, the confidence level of the determined value of the performance attribute of the aircraft can be very high. The confidence level of an attribute value of a system that is determined with a large sample can approach 100%. There is a bandwidth of variation in the confidence level of the determined value of an attribute, depending on the experience level of the person involved. Obviously the "gut feel" decision of a very experienced person can be more accurate than the theoretical calculation of a novice in the field.

Simulations are found midway between "gut feel" decisions and large samples. Simulations are better than theoretical calculations because it generally uses stochastic methods to incorporate the effect of random events into the calculations. Theoretical calculations are usually deterministic (*i.e.* based on exact mathematical equations) and are therefore further removed from the real-

world situation than simulations that can incorporate random events.

In a grey area between theoretical calculations and simulations are mathematical models (not indicated in Figure 1.4), which are sometimes considered as either a subset of theoretical calculations or simulations, depending on personal preference. Taha (1987:12-13) compares mathematical models with simulation models.

> "*Simulation models, when compared with mathematical models, do offer greater flexibility in representing complex systems. The main reason for this flexibility is that simulation views the system from a basic elemental level. Mathematical modeling* [*sic*]*, on the other hand, tends to consider the system from a less detailed level of representation.*"

It is interesting to note that when Sasol Synfuels decided not to go ahead with the update of the final 1996 simulation model in 1999, they decided to develop a Linear Programming (LP) model as a decision support tool. Various handbooks on Operations Research (OR) explain the development and use of LP models, for example, Hadley (1975), Luenberger (1973:9-106) and Taha (1987:25-300). As a decision support tool an LP model is very powerful but it is limited in its range of application and some authors like Harrell and Tumay (1999:4) clearly indicate its shortcomings.

> "*Traditional methods, such as work analysis, flow charting, process mapping, **linear programming**, etc. are incapable of solving the complex integration problems of today. These tools have only limited application and are **unable** to provide a **reliable measure of expected system performance**.*" [Bold typeface added for emphasis]

Harrell and Tumay (1999:9) also indicate one of the major benefits of a simulation model that sets it apart from traditional methods such as LP programming.

> "*It also enables one to gain an overall understanding of the **system dynamics** that would otherwise be difficult to obtain.*" [Bold typeface added for emphasis]

Simulations are the last "soft" way of testing an idea before moving on to the real-world hardware of physical models and samples of the actual hardware. It can intuitively be judged that there will be an increase in the cost of decision support from left to right as one moves from "gut feel"

decisions to large samples. This increase in the cost of decision support goes hand in hand with a decrease in the risk that is associated with a decision. It is therefore evident that managers pay for their peace of mind. The question is how much are managers prepared to pay for their peace of mind? It seems as if simulation is a way of buying adequate peace of mind, without paying an excessively high cost penalty by moving on to physical model and actual hardware tests.

Morris (1977:1) describes decision-making behaviour as characterised along a continuum from random decision-making behaviour at one extreme, through inspirational decision-making behaviour, to systematic decision-making behaviour at the other extreme. This corresponds strongly with the aforementioned line of reasoning. The reference also indicates that systematic decision-making behaviour is preferable.

> "*There is a strong belief, and considerable evidence to support the belief, that systematic decision making increases the probability of achieving a good outcome.*"

The path to understanding the behaviour of a system can be characterised as progressing through four different levels, namely: data, information, knowledge and insight. When the data about the behaviour of the system are processed, it leads to information about the behaviour of the system. The information about the behaviour of the system is available to the managers, but to make truly inspired decisions, the managers need knowledge about and insight into the behaviour of the system. This is the domain where simulation modelling as a decision support tool really comes into its own right. A simulation model can provide knowledge about past and present system behaviour as well as insight into probable future system behaviour (within reasonable limits). For example, a simulation model can be used to identify the "bottlenecks" that currently exist in a system, thus providing knowledge about past and present system behaviour. The simulation model can alternatively also be used to predict system behaviour for different proposed strategies to alleviate the "bottlenecks", thus providing insight into probable future system behaviour. This is comparable to the view of Harrell and Tumay (1999:5) about the role of simulation modelling.

> "*Simulation itself does not solve problems, but it does clearly identify problems* [provides knowledge about past and present behaviour] *and quantitatively evaluate alternative solutions* [provides insight into future behaviour]."

It seems as if managers are becoming progressively more aware of the power of simulation modelling as a decision support tool. Owen (1994:15,17) indicates that large chemical plants are

making extensive use of modelling and simulation.

> "*... manager engineering, believes it is essential for large industrial companies to develop and implement a strategic approach to corporate maintenance philosophy and programmes to sustain competitive advantage.*"

> "*... uses sophisticated, computerised optimisation technology to assist with the more complex needs.*

> *These computerised techniques include ...* [various other techniques] *... and complete plant modelling and simulation.*"

The objective is to achieve the maximum possible rate of production and consequently also the maximum possible profitability. The manual of Extend™ (2000:E14) describes a common goal of business.

> "*In business, a common goal is to optimize a system such that it processes the most things using the least amount of resources and time.*"

From the first principles of economics it follows that the total cost of production can be divided into the fixed cost and the variable cost (Lipsey and Harbury, 1988:167).

$$Cost_{Total} = Cost_{Fixed} + Cost_{Variable} \quad (monetary\ unit) \qquad (Eq.:1.1)$$

The total cost of production is the cost of production at any given rate of production or throughput. Fixed cost does not vary with variation in the throughput while variable cost varies with variation in the throughput. Variable cost usually increases linearly with an increase in the throughput (*i.e.* variable cost is usually directly proportional to the throughput). This concept is graphically depicted in Figure 1.5: *Income versus Cost* (adapted from an example in Krajewski and Ritzman (1990:48)).

Income also usually increases linearly with an increase in the throughput (*i.e.* income is usually directly proportional to the throughput). From the first principles of economics it follows that the financial gain (profit) is the income minus the total cost.

-24-
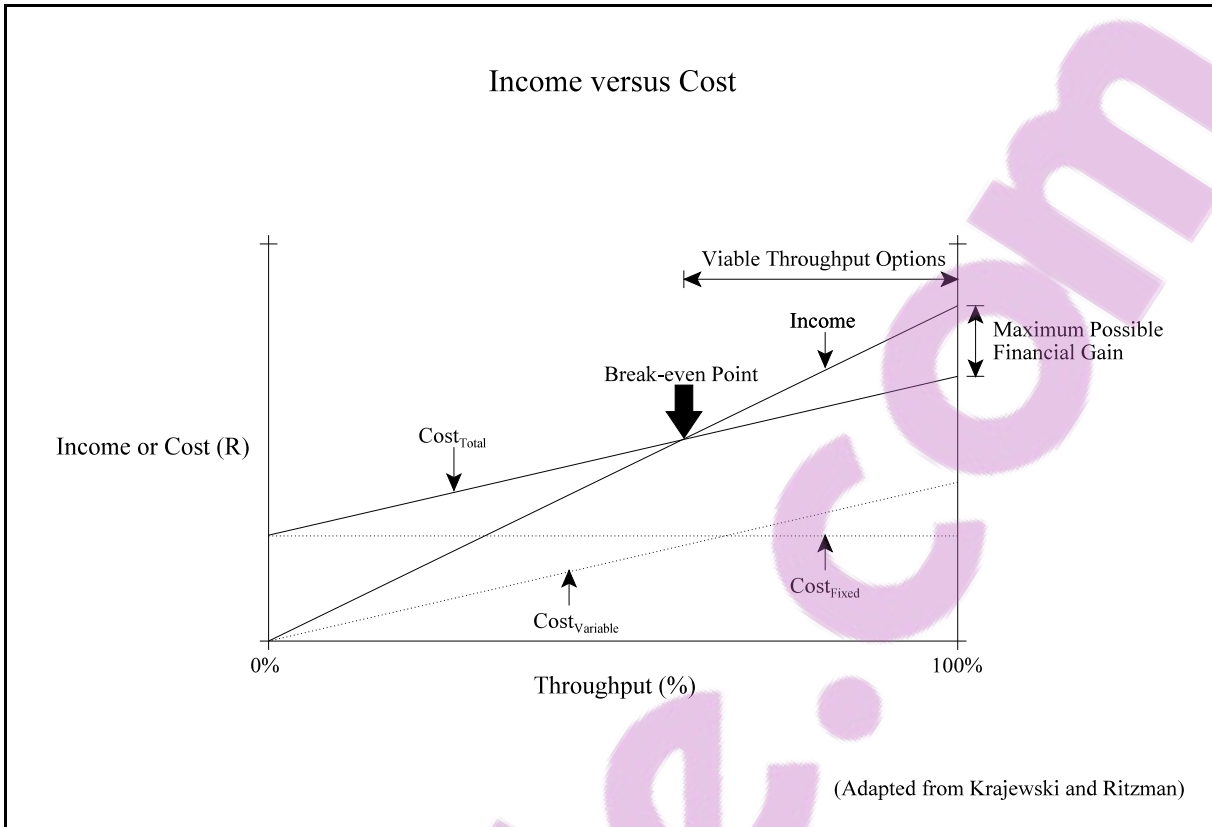
Figure 1.5: Income versus Cost

$$Gain_{Financial} = Income - Cost_{Total} \quad (monetary\ unit) \qquad (Eq.:1.2)$$

From Figure 1.5 it follows that the only viable throughput options are those that achieve better results than the one that achieves break-even results. The maximum possible financial gain is achieved with 100% throughput. The managers of a plant will therefore always strive towards maximisation of the throughput. (This assumption is only valid if it is assumed that there is an infinite market for the throughput of the plant, or at least "infinite" up to 100% of the throughput of the plant.) The aforementioned argument correlates closely with the optimisation principle that is supplied by Morris (1977:14).

> "*We would like to maximize some function of the benefits and costs, say the difference between benefit and cost, or the ratio of benefit to cost.*"

Taha (1987:5) advocates that a decision support model must include the following elements:

a)   Decision alternatives (probable scenarios) from which a selection is made.

b)   Restrictions for excluding infeasible alternatives.

c)   Criteria for evaluating and ranking alternatives.

All throughput options that achieve worse results than the one that achieves break-even results can be considered as infeasible alternatives (see Figure 1.5). In this instance the financial gain that is realised by each alternative is the criterion for evaluating and ranking alternatives.

Douglas (1972:7) supports this view in his discussion about the optimal control of process dynamics.

> "*Optimal control problems in the chemical and petroleum industries are similar to the preceding ones with the exception that the possibility of using profit as the performance criterion we wish to maximize must also be considered.*"

Summary

This section indicates how simulation modelling reduces the risk that is associated with decisions. Managers need decision support tools to achieve the maximum possible rate of production or throughput and consequently also the maximum possible profitability. Simulation modelling is a cost-effective way of attaining a high level of confidence in a decision. It is a low risk and a low cost decision support tool that managers can use to help them in the process of making better decisions. Harrell and Tumay (1999:9) provide a good synopsis of the role of simulation modelling in decision support.

> "*The key to sound management decisions lies in the ability to accurately predict the outcome of alternative courses of action. Simulation provides precisely that clarity of foresight.*"

* * * * *

1.4 SHORTCOMINGS OF THE ORIGINAL METHOD

The first section of this chapter refers to the original simulation model of the Sasol East plant that was developed from 1994 to 1996. The development of the original simulation model is the subject matter of a *Magister* dissertation (Albertyn, 1995). This section provides a very basic introduction to the original simulation model and details the shortcomings of the original simulation modelling method. The following abstract from a published article provides a short overview of the dissertation (Albertyn and Kruger, 1998:1):

> "*The key objective is to develop a method which can be utilised to model a stochastic continuous system. A system from the "real world" is used as the basis for the simulation modelling technique that is presented. The conceptualisation phase indicates that the model has to incorporate stochastic and deterministic elements. A method is developed that utilises the discrete simulation ability of a stochastic package (SIMAN), in conjunction with a deterministic package (FORTRAN), to model the continuous system. (Software packages tend to specialise in either stochastic or deterministic modelling.) The length of the iteration time interval is investigated and different methods are investigated and evaluated for the determination of adequate sample size. The method is authenticated with the verification and validation of the defined model. Two scenarios are modelled and the results are discussed. Conclusions are presented and strengths, weaknesses and further developments of this method are considered and discussed.*"

In the dissertation the original simulation model is used to identify the problem areas in the plant and to study the effect of a proposed change on the plant. The first scenario identifies the "bottlenecks" in the plant and the second scenario studies the effect of an extra oxygen "train" on the plant. Both the scenarios obviously use a *circa* 1995 system description or model definition of the plant. The first scenario thus provides knowledge about the then "past" and "present" behaviour of the plant and the second scenario provides insight into the then "future" behaviour of the plant. The addition of an extra oxygen "train" was chosen as a scenario because it was one of the real-world decision options that confronted the management of the plant at that time. The position of the extra oxygen "train" is indicated in Figure 1.2, the number of modules and their input and output capacities are indicated in Table A1 and the service schedules and failure characteristics of the modules are indicated in Table A2.

The original simulation model was developed in the SIMAN environment and it incorporates a Microsoft FORTRAN subroutine. SIMAN is a simulation software package from the now defunct Systems Modeling Corporation and Microsoft FORTRAN is a general scientific and engineering software package from the Microsoft Corporation. SIMAN has since been superseded by Arena. Arena is a simulation software package that started its life with the Systems Modeling Corporation but now forms part of the Rockwell Software Incorporated suite of software products. The original simulation model of the Sasol East plant was subject to further development, refinement, expansion and maintenance over the latter part of the 3-year time period from 1994 to 1996. During this process the final 1996 simulation model (that included the whole Sasol Synfuels complex) was upgraded to one of the first versions of Arena and it incorporates a WATCOM FORTRAN subroutine. WATCOM FORTRAN is a product of the WATCOM International Corporation.

SIMAN, Microsoft and Arena are registered trademarks and are usually denoted by SIMAN®, Microsoft® and Arena® respectively. However, for the sake of simplicity they will be written simply as SIMAN, Microsoft and Arena in this document. The same logic applies to WATCOM which is a trademark and usually denoted by WATCOM™.

The reasons why a FORTRAN subroutine was included into the original simulation model should be clear from the following quotation indicating the strengths of the original simulation modelling method, as detailed in the dissertation (Albertyn, 1995:106-107):

> "***Strengths of the method***
>
> ...
> i) *The method allows the modeller to incorporate complex decision-making processes into the model by virtue of the inclusion of FORTRAN. (The complex logic calculations associated with the determination of the number of modules to be switched on or off and the throughput, can readily be handled by FORTRAN, because it is a computer language designed for complex mathematical calculations.)* [The momentary "bottleneck" is also identified by the FORTRAN subroutine.]
> j) *FORTRAN poses virtually no restriction on the number of variables that can be addressed in the FORTRAN subroutine.*
> k) *Additional output files can be generated with ease from within the FORTRAN subroutine. (It allows the modeller more flexibility in terms of*

information that can be made available.)

l)   *"User-friendliness" is enhanced by the use of input files, because the input files allow the modeller to implement certain changes fast and without much effort.*

...

n)   *The incorporation of FORTRAN into the model to handle the complex mathematical calculations that are required assists in keeping simulation runtimes within acceptable limits. (FORTRAN is ideally suited to handle complex mathematical calculations in a <u>fast</u> and efficient way, whilst SIMAN would be <u>slow</u> and cumbersome if it were utilised to deal with the same calculations.)"*

The most important benefits of using a FORTRAN subroutine are the arguments that are stated under Points i) and n). The FORTRAN subroutine allows complex decision-making processes (*i.e.* the rules of operation of the plant) to be incorporated into the simulation model and it also helps to keep simulation runtimes within acceptable limits.

The weaknesses of the original simulation modelling method are also detailed in the dissertation (Albertyn, 1995:108) and they are presented in the following quotation:

"**<u>Weaknesses of the method</u>**

a)   *The fact that SIMAN does not have a sufficiently well developed graphics capability makes for more difficult debugging and also impacts adversely on client acceptance of the model.*

b)   *The inherent SIMAN restriction on the number of variables that can be addressed hampers model conceptualisation and development.   (It sometimes forces the modeller to revert to less elegant modelling techniques.)*

c)   *The FORTRAN subroutine has extremely complex structures and to a large extent it is not generic. (In fact, a small change in the model definition or conceptualisation can possibly lead to major changes in the FORTRAN subroutine.)*

d)   *The method gives rise to a very complicated structure, involving two different software packages and complex interfacing, compiling and linking.*

       e)   *The <u>complex structure</u> of the model complicates debugging. (It is sometimes difficult to assess whether a faulty event occurs in the SIMAN model, or in the FORTRAN subroutine.)*

       f)   *The <u>stochastic nature</u> of the model also complicates debugging. (Even though the modeller may provide for all possible combinations and permutations of feasible events, the stochastic nature of the model will result in the code not necessarily following a specific logic loop, until a certain sequence of events has taken place.)*"

The following exposition provides more detail about the weaknesses of the original simulation modelling method. The arguments of Points a) and b) are not valid anymore since SIMAN has been superseded by Arena. Arena has a good graphics capability and virtually no realistically achievable restriction on the number of variables that can be addressed. The arguments of Points c), d) and e) are the main concerns. The argument of Point f) is a universal problem that is characteristic of all stochastic simulation models.

Point c) of the weaknesses indicates that the FORTRAN subroutine has a complex structure and to a large extent it is not generic. This may lead to difficulty when changes in the system description or model definition of the plant need to be accommodated. The system description (see Section 1.2) of the plant is representative of the real plant and it is not static. The system description evolves over time as new chemical processes are introduced to increase efficiency and to align product supply with product demand.

The original simulation modelling method can easily accommodate the following changes in the system description of the plant through the manipulation of the input files:

a)   Changes in the number of modules in each of the smaller plants.

b)   Changes in the input and output capacities of the modules.

c)   Changes in the service schedules of the modules (*i.e.* the start times, cycle times and service times of the service cycles).

d)   Changes in the failure characteristics of the modules (*i.e.* the failure rates and repair times).

e)   The inclusion or exclusion of the extra oxygen "train".

However, the original simulation modelling method has difficulty in accommodating changes in the system description of the plant that concern the configuration, process flow or process logic. For example, if the plant configuration is changed by the addition of another smaller plant, it

cannot be accommodated by merely manipulating the input files. This is also true if the process flow or process logic is changed. For example, if feedback-loops are changed (*i.e.* moved, removed or added) or if the rules of operation of the plant are changed, it cannot be accommodated by the manipulation of the input files. None of the aforementioned changes can be accommodated without substantial changes in the FORTRAN subroutine.

Point d) of the weaknesses indicates that the original simulation modelling method leads to a complicated structure with two different software packages and therefore complex interfacing, compiling and linking. The whole process is time-consuming and it is easy to lose track of what is going on (Albertyn, 1995:58-63). The structure is much simpler if the whole simulation model resides as a single simulation model (without a subroutine) in one simulation software package. In such an instance there is no interfacing between different software packages and usually less complex compiling and linking.

Point e) of the weaknesses indicates that the complex structure of the original simulation model complicates "debugging" because it is sometimes difficult to determine whether a faulty event occurs in the SIMAN part of the original simulation model or in the FORTRAN subroutine. Once again it can intuitively be judged that "debugging" is easier if the whole simulation model resides as a single simulation model (without a subroutine) in one simulation software package.

Point f) of the weaknesses indicates that the inclusion of random behaviour complicates "debugging". Unfortunately it is an inherent problem of all stochastic simulation models.

The following two techniques can be used to counter this problem:

a)   Construct a small separate test simulation model that represents the required sequence of events to test the functioning of the specific logic loop that is under scrutiny. The disadvantage of this method is that it is time-consuming because once the test simulation model has been verified and validated, the code must be transferred into the real simulation model.

b)   Force the simulation model with external input to generate the required sequence of events to test the functioning of the specific logic loop that is under scrutiny. This is also time-consuming because the state of the simulation model at any given time is defined by a "state vector" that comprises all the variables of the simulation model. In order to force the process logic of the simulation model to consider a specific logic loop, input values that lead to that specific logic loop have to be supplied for every variable in the "state vector" (simulation model).

Summary

This section explains why a FORTRAN subroutine was included into the original simulation model and details the shortcomings of the original simulation modelling method. These shortcomings were the catalysts that initiated the development of the generic simulation modelling methodology that is presented in this document.

* * * * *

1.5   OBJECTIVE STATEMENT

Section 1.1 indicates that the 1999 investigation into the viability to update the final 1996 simulation model of the Sasol Synfuels complex concluded that comprehensive changes were needed. The reasons why the necessary changes cannot readily be accommodated by the original simulation modelling method are detailed in the previous section. The comprehensive changes that were needed and the inability of the original method to accommodate these changes easily, clearly indicated that there was substantial scope for further research in this area. From the outset it was envisioned that the research presented an opportunity to accomplish something more than just to solve the problem of how to accommodate the comprehensive changes that were needed for the update of the final 1996 simulation model. The research presented an opportunity to develop a generic simulation modelling methodology for a whole specific class or type of system. All systems that exhibit the same characteristics as the Sasol East plant can readily be accommodated by the generic methodology. These characteristics and their implications are discussed in detail in Sections 2.1 and 2.2. Systems of this class or type of system are described as stochastic continuous systems, thereby referring to their two most distinctive characteristics, namely: they are subject to random (stochastic) phenomena such as failures and characterised by continuous processes (flow).

The key objective of this research is to develop a generic simulation modelling methodology that can be used to model stochastic continuous systems effectively.

The generic simulation modelling methodology is able to accommodate any generic variant of a stochastic continuous system of approximately the same size and complexity, and to the same level of detail, as the system that is detailed by the system description in Section 1.2 (*i.e.* the Synthetic Fuel plant that represents the Sasol East plant). Of course, the generic methodology can

also easily accommodate any combination of stochastic continuous systems and the interrelationships between them (*i.e.* the whole Sasol Synfuels complex). The generic methodology renders simulation models that can be used as decision support tools on a strategic level of decision support (see Section 1.1).

The reasons why the generic simulation modelling methodology is effective can be attributed to a structured approach and the characteristics that are exhibited by simulation models that are developed with the generic methodology. The characteristics of the simulation models follow directly from the design criteria of the generic methodology. The design criteria are a combination of general best practise simulation modelling method design criteria and design criteria that originate from the shortcomings of the original simulation modelling method.

The characteristics (or alternatively the design criteria) of simulation models that are developed with the generic simulation modelling methodology, are the following:
a)   Short development time.
b)   Short maintenance times.
c)   User-friendliness as perceived from the development, maintenance and usage perspectives.
d)   Short simulation runtimes.
e)   Compact simulation model size.
f)   Robust modelling ability.
g)   Accurate modelling ability.
h)   Single software application.

The following points, on a one-to-one basis, provide more detail about the aforementioned characteristics of simulation models that are developed with the generic simulation modelling methodology:
a)   Section 1.1 indicates that the process to bring the final 1996 simulation model to fruition took approximately three years. This is not unusual for a technically sophisticated problem (Crowe *et al.*, 1971:5). A longer development time implies that larger resources of manpower and money must be committed from the outset to ensure probable success. It is also sometimes difficult to keep up enthusiasm for the project over a longer time span. Management always "needs the answer now". A shorter development time implies that fewer resources are needed as well as more enthusiasm and easier attainment of permission from management to proceed with the project.
b)   The previous section indicates that the original simulation modelling method placed

severe restrictions on the speedy implementation of comprehensive changes to the final 1996 simulation model. The same arguments as stated in the previous point are also valid in this instance and therefore it is obvious that great benefit can be derived if maintenance times are shorter.

c)   User-friendliness is a very important aspect of simulation models as far as acceptance and continued use are concerned (Bonnet, 1991:12-13).

> *"Even though less and less [sic] people are still intimidated by a computer and the actual answers of a simulation are what is of importance, user-friendliness still (unconsciously or otherwise) promotes the use of a program."*

The user-friendliness of the original simulation modelling method is listed as a strength because input files are used to manipulate the simulation model (Albertyn, 1995:107). Input files or spreadsheets greatly enhance the user-friendliness of simulation models. The use of graphics and animation can also benefit user-friendliness and help with simulation model "debugging" (Elder, 1992:3-4,72,277; Pegden *et al.*, 1990:305-308). Pegden *et al.* (1990:308) describe some of the benefits of animation.

> *"The animation also played an important role in model verification and validation. ... Consequently, management had high confidence in the model."*

There is a trend among the managers that use simulation modelling as a decision support tool to get more directly involved in the simulation modelling process. They do not only want the answers to a few preselected questions anymore. They want access to decision support on a continual basis. This implies a requirement for user-friendly simulation models that can be used directly by the managers themselves or by the industrial engineers that support them. Consequently the use of graphics and animation is becoming increasingly important. The results of a survey that probed the importance of graphics and animation in simulation models, as compared to purely statistical models, indicate the importance of graphics and animation. The majority of the respondents (81%) rated graphics and animation as "very important" (36%) or "important" (45%). Only a small percentage (19%) of the respondents rated graphics and animation as "somewhat important" (Simulation Fax Survey Results, 1993:10). Bonnet (1991:13) indicates that user-friendliness is even more important if the simulation model is going to be used by

someone else than the person who developed it.

> "*In conclusion, if the program is to be used only by the programmer, user-friendliness is very often not worth the trouble, since the programmer knows the program inside out. If the simulation is intended to be used by others, such as in this case, user-friendliness is an **essential prerequisite**.*"
> [Bold typeface added for emphasis]

d)   Short simulation runtimes for simulation models help to keep the development and maintenance times within acceptable limits. It is also advantageous during sensitivity analysis or scenario analysis.

e)   A compact simulation model size enhances the transportability of simulation models between different computers and over the Internet and it is an advantage when simulation models are stored on magnetic media. There is also an indirect advantage during the development and maintenance of simulation models, because it is easier to keep track of "what" is being done "where" in structured, compact simulation models than in less structured, dispersed simulation models.

f)   In this instance a robust modelling ability refers to the capacity of the generic simulation modelling methodology to facilitate the accommodation of any generic variant of a stochastic continuous system. It also indicates that comprehensive changes to simulation models can easily be handled by the generic methodology.

g)   The generic simulation modelling methodology renders simulation models that are very accurate when compared to acceptable industry standards. Accuracy is not compromised for the sake of any of the other characteristics or design criteria.

h)   The previous section clearly indicates the difficulties (*i.e.* the complex structure and difficult interfacing, compiling and linking) associated with a simulation modelling method that uses two different software packages to construct a simulation model. The generic simulation modelling methodology is structured to accommodate a simulation model in one simulation software package and therefore avoids these pitfalls.

Summary

To summarise this section, the key objective of this document is to present a generic simulation modelling methodology. The generic methodology can be used to model any generic variant of a stochastic continuous system. Simulation models that are developed with the generic methodology exhibit the following characteristics: short development and maintenance times,

user-friendliness, short simulation runtimes, compact size, robustness, accuracy and a single software application.

* * * * *

1.6   IMPORTANCE OF THE RESEARCH

Section 1.1 indicates that the comprehensive changes that were needed in 1999 to update the final 1996 simulation model of the Sasol Synfuels complex necessitated the proposal of a lengthy and therefore costly process. This can be ascribed to the shortcomings of the original simulation modelling method (see Section 1.4). The discussion of the characteristics of the generic simulation modelling methodology in the previous section indicates that the generic methodology successfully nullifies, circumvents or lessens the impact of the shortcomings of the original method. It can therefore be assumed that the project might have proceeded in 1999 if the generic methodology was available at that time.

Even though Sasol claims that the Sasol Synfuels complex is the only commercial coal-based synthetic fuel manufacturing facility in the world, an article in *Encyclopaedia Britannica* (2002) indicates that a similar plant exists in Japan. Omuta, Fukuoka Prefecture, Japan has been an important industrial city since 1917. The city is situated in a coal-mining area and is especially known for the manufacture of chemicals. Coke and synthetic petroleum are listed as commodities that are produced in Omuta. (Coke is the solid substance that is left after the gases have been extracted from coal.) It is obvious that a plant that manufactures coke and synthetic fuel is very similar to the Sasol Synfuels complex and therefore the generic simulation modelling methodology can also be used to easily construct a simulation model of such a plant.

From 1994 to 1995 a simulation model of a similar plant was developed by the same company that was responsible for the development of the final 1996 simulation model. The Kynoch plant at Modderfontein, South Africa is much smaller than the Sasol Synfuels complex but it uses basically the same processes. It also uses steam and oxygen to gasify coal and then extract chemical products from the gases. In the case of the Kynoch plant the main focus is on the production of ammonia from coal. Ammonia is one of the key ingredients of fertilisers. The two simulation models (the final 1996 simulation model and the Kynoch plant simulation model) were developed in parallel by two different project teams. The Kynoch plant simulation model is much simpler than the final 1996 simulation model and does not use the same simulation modelling

method. For example, the Kynoch plant simulation model only evaluates three points in the plant for the identification of the momentary "bottleneck", while the final 1996 simulation model evaluates 13 points in each of the Sasol East and Sasol West plants for the identification of their respective momentary "bottlenecks". The simulation modelling method that is used in the Kynoch plant simulation model, however, does not render very good results, because the system description or model definition of the plant was appreciably simplified to enable the entire simulation model to be accommodated in Arena. The project team of the Kynoch plant simulation model did not want to include a FORTRAN subroutine to handle the complex aspects of the simulation model. It stands to reason that the original simulation modelling method that was used for the final 1996 simulation model could also have been used for the Kynoch plant simulation model because of the degree of commonality between the Kynoch plant and the Sasol East and Sasol West plants. It can therefore be concluded that the Kynoch plant is also an excellent candidate for a system that could benefit tremendously from the advantages that are rendered by the generic simulation modelling methodology.

There are many crude oil refineries all over the world that exhibit the same characteristics as the Sasol Synfuels complex and the Kynoch plant. In the case of crude oil refineries the input of the process is crude oil rather than coal but in all other aspects the crude oil refineries are generic variants of the system that is detailed by the system description in Section 1.2 (*i.e.* the Synthetic Fuel plant that represents the Sasol East plant). It therefore stands to reason that the generic simulation modelling methodology can be used to great advantage when simulation models of crude oil refineries are required.

The Sasol Synfuels complex represents the oil-from-coal process but an equally important aspect which has developed recently is the gas-to-liquids (GTL) process. The following quotation provides some background on the subject (Sasol: Technologies & Processes, 2003):

> "*The Sasol Slurry Phase reactor at Sasolburg has been attracting international interest because of the world's abundant natural gas reserves and the mounting environmental lobby for cleaner burning fuels. The Slurry Phase reactor is at the heart of the tree-step SPD* [Slurry Phase Distillate] *process, which converts natural gas into high-quality low-emission diesel. The SPD diesel is more environmentally benign than the developed world's current and proposed generations of reformulated diesels.*"

Sasol is involved in GTL projects in South Africa, Qatar, Nigeria and Mozambique (Heckl,

2003:2; Fraser, 2002:1,14; Sasol's natural gas project surging ahead in Mozambique, 2002:7). Sasol expects its GTL investments to be producing five hundred thousand barrels of diesel a day in 10 years time (Fraser, 2002:1). Even though Sasol is considered as one of the leaders in this technology field, there are many other companies that are equally interested and active in the GTL environment. According to Bridge (2004:15) the PetroSA plant at Mossel Bay, South Africa is the largest commercial GTL plant in the world. (PetroSA was formed through the merger of Mossgas and Soekor in 2001.) Naturally, any GTL plant simulation model can easily be developed by applying the generic simulation modelling methodology.

The previous paragraphs clearly indicate the possible range of application of the generic simulation modelling methodology in the petrochemical industry. The oil-from-coal process, the classic crude oil refinement process and the GTL process can all be accommodated by the generic methodology without any difficulty. However, the possible range of application of the generic methodology is not restricted to the petrochemical industry. Any plant that exhibits the same characteristics as the Sasol East plant can readily be accommodated by the generic methodology. For example, a plant that manufactures paints obviously falls within this class or type of system. It thus stands to reason that the generic methodology can also be used to develop a simulation model of such a plant without great effort.

Traditionally the development of simulation software packages has focused primarily on the ability to model discrete-event systems. Harrell and Tumay (1999:34) indicate that this trend can be explained by the fact that most manufacturing and service systems are discrete-event systems. This leads to the phenomenon that most simulation software packages cannot adequately accommodate continuous systems. For example, Harrell and Tumay (1999) dedicate only approximately 3% of their book to the modelling of continuous systems (two pages to theory and seven pages to applications out of a total of 309 pages). Kelton *et al.* (1998) fare even worse and dedicate less than ½% of their book to the modelling of continuous systems (two pages out of a total of 547 pages). Pegden *et al.* (1998) dedicate a whole chapter to the modelling of continuous systems but this is still less than 6% of their book (33 pages out of a total of 600 pages). The *Simul8®: Manual and Simulation Guide* (1999) does not even address continuous systems. The closest reference to continuous systems is a description of batch modelling techniques that can be used for high volume applications like Business Process Re-engineering (BPR) and Fast-moving Consumer Goods (FMCG) applications.

Some authors propose that it is sometimes possible to model continuous phenomena using discrete-event modelling techniques (Harrell and Tumay, 1999:35; Kelton *et al.*, 1998:353).

Harrell and Tumay (1999:35) suggest the following technique as the first of two possible techniques that use discrete-event modelling techniques to deal with continuous phenomena:

> "*Often it is possible to model continuous phenomena using discrete-event logic, especially **if a high degree of precision is not important**. For example, continuous flowing substances such as liquids or granules can be converted, for purposes of simulation, into discrete units of measure such as gallons or pounds.*"
> [Bold typeface added for emphasis]

This technique can only be used if accuracy is not of paramount importance. It is therefore evident that this technique cannot be used by the generic simulation modelling methodology, as it clearly violates the design criterion that identifies accuracy as one of the required characteristics of simulation models that are developed with the generic methodology (see Point g) of the design criteria in Section 1.5). (Obviously this technique was also not used by the original simulation modelling method.)

Harrell and Tumay (1999:35) then proceed by indicating the second of two possible techniques that use discrete-event modelling techniques to deal with continuous phenomena.

> "*Another method is to simply update a variable at regular time intervals that accounts for a constant rate of change that occurred over the interval.*"

It is important to note that both the original simulation modelling method and the generic simulation modelling methodology use this technique (or a variation thereof) to determine the pertinent values of continuous phenomena as exact real numbers, thereby achieving very high accuracy. For example, the *Magister* dissertation (Albertyn, 1995:76) indicates that the original simulation model deviates less than 1% (0,59%) from the real-world situation for a known scenario. This technique is referred to as the variables technique and it is detailed in Sections 2.2 and 2.7.

The continuous modelling ability of Arena is described in its manual (Arena, 1998:145-148). Closer examination reveals that this modelling ability consists of the modelling of a container. It allows the modelling of the level and rate of change of a container that can be one of three possible types: a source, a transfer or a sink container. Containers or tanks are usually used as storage devices in continuous systems at the beginning (source containers) or the end (sink containers) of processes. Intermediate containers or tanks (transfer containers) are usually used

to buffer or dampen oscillations in the system that may result because of sudden changes in production capacity that are caused by services and failures. For example, a container or tank can be used to absorb the upstream production that cannot be processed by the "bottleneck" plant, until the "bottleneck" plant is restored to adequate capacity. This concept is more applicable to liquids than gases. In most cases it is impractical to store huge volumes of gases in containers or tanks (especially if the processes that are involved are temperature and pressure sensitive). For example, in the Synthetic Fuel plant there are no tanks in the part of the process where the products are in the gas phase. The only tank in the plant is situated directly in front of Plant(IV) where it is used to buffer the flow of gas-water (in the liquid phase) between the Temperature Regulation plant and Plant(IV). The tank is not indicated in Figure 1.2 for the sake of simplicity and because it is considered to be an integral part of Plant(IV). The minimum and maximum allowable volumes of gas-water in the tank are indicated in Columns 4 and 5 respectively of Table A1. It is obvious that the container modelling ability of Arena can only be used for a minuscule part (*i.e.* the single instance of a tank) of the simulation model if a simulation model of the Synthetic Fuel plant is developed.

Summary

This section indicates that the generic simulation modelling methodology has a huge range of possible application in the petrochemical industry, but it is by no means restricted to only the petrochemical industry. Any system that displays the same characteristics as the system that is detailed in the system description in Section 1.2 can readily be accommodated by the generic methodology. The majority of simulation software packages cannot accommodate such systems easily because they were originally developed with discrete-event systems in mind.

* * * * *

1.7   LIMITATIONS OF THE GENERIC METHODOLOGY

Section 1.5 indicates that the systems that are considered in this document belong to a specific class or type of system. These systems are referred to as stochastic continuous systems to clearly identify their two most distinctive characteristics. Section 1.2 provides some detail about the stochastic characteristic while this section focuses on the continuous characteristic of stochastic continuous systems.

It might be prudent to start off this section with an elementary introduction into the classification of simulation models. This is necessary to classify, and to provide a specific context for, simulation models that are developed with the generic simulation modelling methodology.

According to Kelton *et al.* (1998:9) a useful way to classify simulation models is along the following three dimensions:
a)   Static versus Dynamic.
b)   Discrete versus Continuous.
c)   Deterministic versus Stochastic.

The first dimension relates to the time period that is addressed by a simulation model. A simulation model that describes the behaviour of a system at a single point in time is called a static simulation model, while a simulation model that describes the behaviour of a system over a period of time is called a dynamic simulation model. This is analogous to a photograph (static) versus a movie (dynamic).

The second dimension relates to the way that a simulation model addresses the changes in the state of a system. The behaviour of a system over a period of time is usually characterised by changes in the state of the system. In a discrete simulation model the changes in the state of the system occur only at isolated (specific) points in time while in a continuous simulation model the changes in the state of the system occur continuously over time. A continuous simulation model usually uses algebraic, differential or difference equations to calculate the changes in the state of the system (Pegden *et al.*, 1995:6). Figure 1.6: *Discrete versus Continuous State Change* indicates the difference between a change in the state of the system at an isolated point in time and a continuous change in the state of the system that happens over a period of time.

Discrete versus Continuous State Change

Discrete State Change

State 1

Area A

State of System

Continuous State Change

Area B

State 2

Time Period A-C

Time 1   Time A   Time B   Time C   Time 2
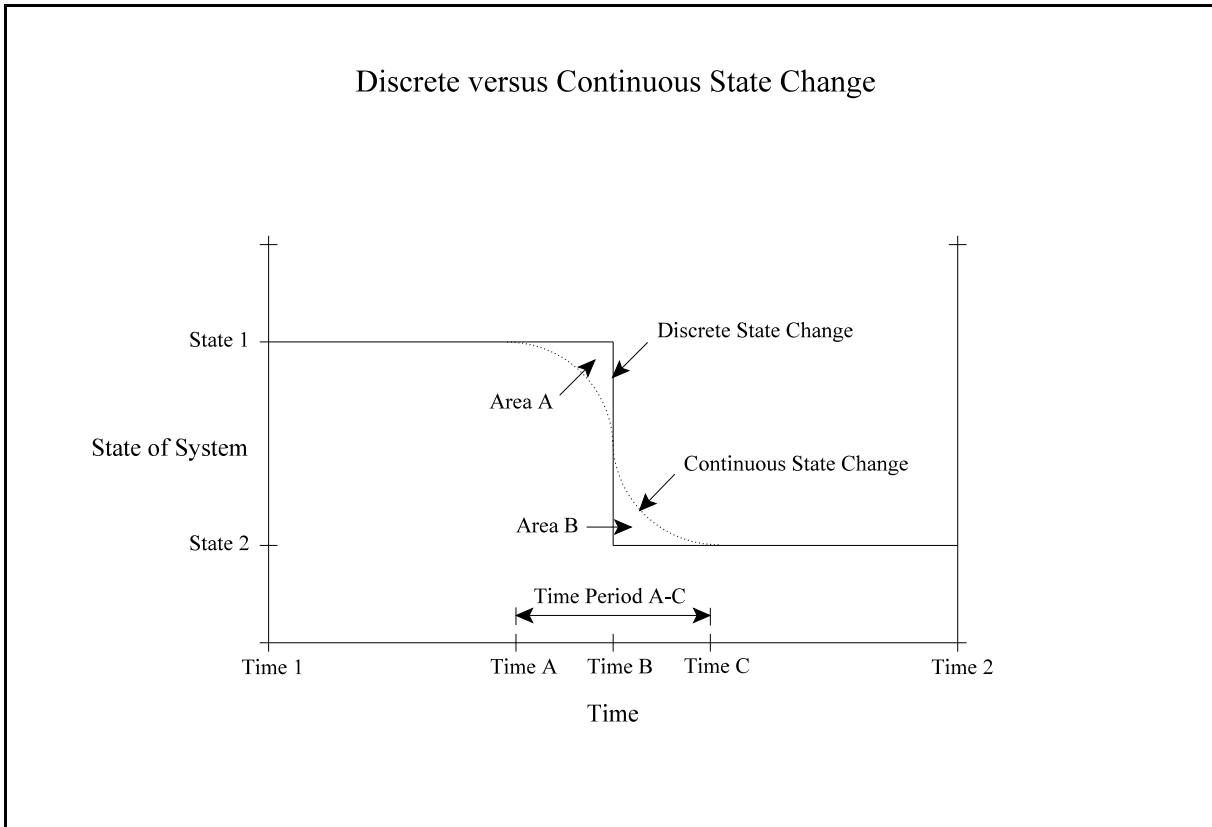
Time

Figure 1.6: Discrete versus Continuous State Change

In Figure 1.6 a discrete change in the state of the system is represented by the solid line and it occurs at an isolated (specific) point in time (Time B) while a continuous change in the state of the system is represented by the dotted line and it occurs over a period of time (Time Period A-C). Some systems exhibit both discrete and continuous state change behaviour. Simulation models of such systems are referred to as combined simulation models. It is obvious that the Synthetic Fuel plant that is described in Section 1.2 falls within this category. The plant is characterised by a continuous process and it is also subject to discrete events, like services and failures, that cause changes in the state of the plant. Kelton *et al.* (1998:9) specifically refer to refineries as examples of combined simulation models.

The final dimension indicates whether a simulation model makes provision for random variation in the system. According to Pegden *et al.* (1995:6) very few real-world systems are free from the influence of random variation. Deterministic simulation models ignore this randomness while stochastic simulation models make provision to accommodate the randomness of the system. The Synthetic Fuel plant displays random behaviour because of the failures of the modules.

From the exposition in the previous paragraphs, it follows that it is possible to classify a simulation model of the Synthetic Fuel plant as a dynamic, combined, stochastic simulation model. The simulation model describes the behaviour of the plant over a period of time, incorporates the continuous processes of the plant, accommodates discrete events like services and failures and makes provision for the randomness of the failures.

The classification of the simulation model as a dynamic, combined, stochastic simulation model should not be confused with the description of the class or type of system that is modelled. The class or type of system that is modelled is referred to as stochastic continuous systems to emphasise the most important characteristics of the systems.

The behaviour that is exhibited when the changes in the state of the system occur continuously over time is sometimes referred to as transient behaviour (see the behaviour of the Continuous State Change over Time Period A-C of Figure 1.6). Pegden *et al.* (1995:431-464) indicate that transient behaviour is usually represented with algebraic, differential or difference equations that describe the behaviour of the system in terms of states and rates. A state equation is a direct representation that describes the state of a variable over time as an algebraic equation. In most instances it is impossible to develop a direct representation of a variable, but it is possible to establish a relationship for the rate of change of the variable with respect to time. This is an indirect representation of the variable and it is known as a differential equation. The variables that describe the state of the system can therefore be described directly by means of state equations, or indirectly by means of differential equations. The behaviour of the system is obtained by solving the state and differential equations over time. State equations are usually easy to solve mathematically. Differential equations, by comparison, are very difficult to solve mathematically and elegant mathematical solutions are available for only a few rather simplistic differential equations. In the instances where mathematical solutions for differential equations are not available, numerical techniques (known as numerical integration) are used to obtain approximate numerical values for the state of the system over time. If a simulation model contains differential equations the simulation model cannot simply jump in time between events, but is advanced in time by a series of small time intervals between the normal discrete events (assuming that it is a combined simulation model that contains both discrete and continuous state change behaviour). The size of each small time interval is calculated separately and depends on the required accuracy.

To summarise, transient behaviour is described by states and rates. State equations are direct representations and differential equations are indirect representations of variables that describe

the state of the system. State equations are easy but differential equations difficult to solve and require numerical integration that involves the advancing of the simulation model time in small time intervals.

It is essential to note that simulation models that are developed with both the original simulation modelling method and the generic simulation modelling methodology do not make provision for transient behaviour. It is assumed that the changes in the state of the system occur at isolated points in time (see the behaviour of the Discrete State Change on Time B of Figure 1.6).

The reasons why this assumption is made are the following:

a)   Both the original simulation modelling method and the generic simulation modelling methodology provide decision support on a strategic level (see Section 1.1). Therefore the level of resolution (see Section 1.2) that is required excludes transient behaviour.

b)   The managers of plants usually strive towards the maximisation of the throughput and as a result the bandwidth of variation that occurs during changes in the state of the system is generally restricted to a small range (typically less than 10% of the total range of the state of the system). The small range of variation in the state of the system tends to negate the effect of transient behaviour.

c)   Integration is basically a process that determines the area underneath a function. For example, if the rate of production of a plant over a period of time is integrated, it yields the total production of the plant over that time period. Therefore, if the state of the system that is indicated in Figure 1.6 represents the rate of production of a plant, the area underneath the function or curve represents the total production. A scrutiny of Figure 1.6 reveals that Area A is taken into account when assuming a discrete state change in the rate of production and it results in a positive fault when the total production is calculated. In a similar fashion Area B is not taken into account when assuming a discrete state change in the rate of production and it results in a negative fault when the total production is calculated. It can intuitively be deducted that if the range of variation in the rate of production is small and many changes occur in the rate of production, then the sum of the positive Area A faults is counterbalanced by the sum of the negative Area B faults.

The integrity of the assumption not to include transient behaviour is borne out by the fact that the original simulation model deviates less than 1% (0,59%) from the real-world situation for a known scenario (Albertyn, 1995:76). The fact that both the original simulation modelling method and the generic simulation modelling methodology do not make provision for transient behaviour is perceived as a possible limitation in this section but, paradoxically, it can also be perceived as

a necessary and beneficial exclusion. The exclusion of transient behaviour reduces complexity and it is certainly beneficial in the attainment of the characteristics of the generic methodology that is detailed in Section 1.5.

To expand on the provision of a context for simulation models that are developed with the generic simulation modelling methodology, it might be useful to provide a very basic comparison with some other modelling methods and techniques. An LP model, for instance, is usually a static model that is strictly deterministic. The scenario that is under scrutiny in an LP model is represented as a "snapshot" of the behaviour of a system at an isolated point in time. An LP model finds the singular optimum solution to a governing set of equations and cannot investigate the behaviour of the system over a period of time or study the effect of random phenomena on the system. A detail simulation model is usually employed to investigate the dynamic behaviour of a system over a short period of time, typically in the order of milliseconds to hours. Such a simulation model is used as a decision support tool on the detail level of engineering. For example, the 3- and 6-degree-of-freedom simulation models that are used to investigate the performance of aircraft and missile systems fall within this category. A detail simulation model typically incorporates differential or difference equations and advances the simulation model in time with very small time increments, thereby achieving numerical integration of the differential or difference equations. Random phenomena are not included and a detail simulation model is therefore strictly deterministic. By comparison a simulation model that is developed with the generic methodology usually investigates the dynamic behaviour of a system over a longer period of time, typically in the order of hours to years. It is used as a decision support tool on a strategic level. Such a simulation model incorporates random phenomena and is therefore stochastic.

Summary

The simulation model classification framework that is provided in this section indicates that a simulation model of the class or type of system that is considered in this document can be classified as a dynamic, combined, stochastic simulation model. Continuous state change behaviour or transient behaviour is usually represented with state and differential equations. The generic simulation modelling methodology does not make provision for transient behaviour but this is not necessarily a limitation because it greatly simplifies the generic methodology.

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CHAPTER 2

METHODOLOGY CONCEPTUALISATION

INTRODUCTION

Simply stated, the purpose of this chapter is to conceptualise the generic simulation modelling methodology. It is imperative to have a clear understanding of precisely what has to be achieved and how it should be attained, before any attempt is made to begin with the physical process by which the desired goal has to be achieved.

A simulation modelling method or methodology is usually developed with a specific class or type of system in mind. Therefore the first section identifies the characteristics of the class or type of system that is considered in this document. The key characteristics of these systems are the following: continuous processes, two types of discrete events (*i.e.* the services and failures) and complex interrelationships.

In the second section the implications of these characteristics on a simulation model are explored. Different techniques are considered and two possible candidates emerge, namely: a technique that uses variables to represent the process flow in a simulation model and a technique that uses a fixed time interval to advance the simulation model in time. Equations are developed to determine the maximum possible throughput of the Synthetic Fuel plant, as a function of time, and also the number of modules that is switched on or off in each of the smaller plants to achieve that throughput, as a function of time. The determination of the maximum possible throughput is no arbitrary task because of the presence of feedback-loops, the division of the output of the Steam and Oxygen plants and the fact that the number of available modules in each of the smaller plants is a function of time.

The Entity-represent-module (ERM) method is described in the third section. The ERM method was originally developed as part of the *Magister* research and is used by both the original simulation modelling method and the generic simulation modelling methodology. It is an innovative method that determines the number of available modules in each of the smaller plants at any given moment in time. The concept of the ERM method is counter-intuitive because it uses entities to represent the modules rather than the cumbersome *Servers* or *Work Centers* that are usually used in simulation software packages. It leads to a compact simulation model size,

total control over all the aspects of the services and accuracy. Each of the smaller plants is represented by three separate parts (*i.e.* the Availability, Service and Failure parts) that are combined to form a high-level building block. Four types of smaller plants are represented in the ERM method by high-level building blocks (*i.e.* a smaller plant with a multiple service cycle and failures of the modules, a smaller plant with a service cycle and failures of the modules, a smaller plant with a service cycle of the modules and a smaller plant with failures of the modules). The advanced version of the ERM method (*i.e.* the one used by the generic methodology) is more compact and accurate than the original version (*i.e.* the one used by the original method).

The Fraction-comparison (FC) method is detailed in the fourth section. The FC method is the most important innovation of the generic simulation modelling methodology and can be considered as the "jewel in the crown" of the generic methodology. It is an elegant method that identifies the momentary "bottleneck" in a complex system at any given moment in time. The FC method is based on the fact that the actual output throughput values of the possible "bottleneck" points at any given moment in time are in fixed relations in terms of one another for all possible throughput options of the system that is under scrutiny. The fixed relations are expressed as the steady state actual output throughput values of the possible "bottleneck" points and are referred to as the FC method parameter set. The parameter set is unique for every specific system description of the system that is under scrutiny. The FC method provides a solution to one of the major problem areas of the generic methodology.

The determination of the governing parameters is detailed in the fifth section. The governing parameters are the gas-feedback-loop-fraction, steam-division-ratio, oxygen-division-ratio and the FC method parameter set. An iterative-loop technique is detailed that uses a FORTRAN software programme called PSCALC.FOR to determine the governing parameters of the Synthetic Fuel plant for the system description that is provided in Section 1.2.

The sixth section considers techniques to identify the "bottleneck" smaller plants in the system that is under scrutiny. The original simulation modelling method uses the throughput utilisation values of the smaller plants to identify the "bottleneck" smaller plants. A distinction is made between primary and secondary "bottlenecks". Two techniques are introduced to identify the primary "bottlenecks". The first technique identifies the primary "bottlenecks" based on the time that the smaller plant is the "bottleneck" and the second technique identifies the primary "bottlenecks" based on the production that is lost due to the smaller plant. Flared throughput indicates the existence of a secondary "bottleneck".

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The last section conceptualises the structure of the generic simulation modelling methodology. The seven methods and techniques that are developed in the previous sections are integrated to form the generic methodology. The generic methodology is divided into two separate parts. The iterative-loop technique part determines the governing parameters before the start of a simulation run and the simulation model part uses the six other methods and techniques continuously during the simulation run. The simulation model itself is divided into a "virtual" part that deals with the continuous processes and the functioning of the simulation model and a "real" part that deals with the behaviour of the modules. The "virtual" part is represented in the simulation model by the logic engine high-level building block and the "real" part is represented by the four different high-level building blocks of the ERM method. The five high-level building blocks can be used to construct simulation models of stochastic continuous systems. Simulation models that are developed with the generic methodology do not need a warm-up period and the advantages of this feature are also highlighted.

* * * * *

2.1 SYSTEM CHARACTERISTICS

In most instances a simulation modelling method or methodology is developed with a specific class or type of system in mind. The term "class" implies a collection of objects that share the same characteristics. A simulation modelling method or methodology therefore usually makes provision for systems with the same characteristics. This concept is also applicable to the generic simulation modelling methodology. It is therefore of cardinal importance to fully understand the characteristics of the Synthetic Fuel plant, as well as their impact on a simulation model, before a generic methodology can be conceptualised and developed.

Although the discussions in the rest of this chapter use the Synthetic Fuel plant as an example, it is important to realise that all the concepts are equally applicable to all systems of the class or type of system that is considered in this document.

From the system description of the Synthetic Fuel plant that is provided in Section 1.2, the following key characteristics of systems that belong to the class or type of system that is considered in this document, can be identified:
a) The systems are continuous process systems.
b) The systems are subject to two types of discrete events:
    i) Chronological events (services).
    ii) Stochastic events (failures).
c) The systems have complex interrelationships.

The following three paragraphs provide more detail about the characteristics of this class or type of system. Such systems are commonly referred to as stochastic continuous systems to accentuate their two most important characteristics.

Section 1.2 indicates that the motion of the "commodities" (coal, gases and liquids) in the Synthetic Fuel plant can be characterised as flow and therefore the process of the plant is characterised as continuous.

The Synthetic Fuel plant is subject to chronological and stochastic events. The services of the modules are strictly chronological events and are characterised by the service cycles of the modules (see Section 1.2 and Table A2). The failures of the modules are stochastic events and are characterised by the failure characteristics of the modules (see Section 1.2 and Table A2).

The complex interrelationships of the Synthetic Fuel plant are manifested in both the process flow and the process logic of the plant. The system description of the process flow indicates that there are several feedback-loops and that the output of both the Steam and Oxygen plants is divided (see Section 1.2 and Table A1). The process logic (rules of operation) of the plant indicates the complexity of the interrelationships between the smaller plants (see Section 1.2 and Appendix B). The continuous nature of the process of the plant implies that all 147 modules are, in a way, intrinsically interlinked as far as the effect of the service or failure of a module is concerned. Any breakdown in the processing capacity at one point because of the service or failure of a module, does have an immediate effect on upstream and downstream operations.

The fact that these characteristics have to be accommodated in a simulation model that conforms to the design criteria that are stated in Section 1.5 poses the main problem of the generic simulation modelling methodology.

The complexity of the main problem, when viewed in its entirety, seems overwhelming. This challenge, however, can be approached in a meaningful way by segregating the main problem into appropriate smaller manageable units or subproblems and then solving each of them individually. The rest of this chapter identifies the subproblems through the process of logical deduction and then identifies and develops methods and techniques that solve the various problems that are posed by the subproblems.

Leedy (1993:71) postulates that the main research problem usually consists of two to six subproblems and advocates that subproblems should not be confused with pseudo-subproblems. He defines pseudo-subproblems as procedural indecisions and indicates, for example, that the problem to determine the correct sample size is a pseudo-subproblem, because there are various techniques available to determine sample sizes and it is only necessary to identify the correct one to use for each specific application.

In this chapter the terms "method" and "technique" are also used in accordance with the convention that is explained in Section 1.1 concerning the hierarchy of terminologies that are proposed by van Dyk (2001:2-4). According to the convention the term "method" is perceived to be indicative of a higher order terminology, while the term "technique" is perceived to be indicative of a lower order terminology. Hence, the term "method" is used to indicate a "tool" that is used to solve a more complex subproblem and the term "technique" is used to indicate a "tool" that is used to solve a less complex subproblem.

Summary

The characteristics of the class or type of system that is considered in this document are identified in this section. The key characteristics of these systems are continuous processes, two types of discrete events (chronological and stochastic) and complex interrelationships.

* * * * *

2.2   IMPLICATIONS OF THE CHARACTERISTICS

Section 1.6 indicates that some authors propose that continuous phenomena can be accommodated by using discrete-event modelling techniques. Harrell and Tumay (1999:35) propose two possible techniques that both use discrete-event modelling techniques to deal with continuous phenomena. The first technique suggests that continuously flowing "commodities" can be converted into discrete entities or "packages" for the purpose of a simulation model. For example, the maximum possible raw gas output throughput of the Gas Production plant is 1596000 nm^3/h (40 modules with an output capacity of 39900 nm^3/h each). This can be converted into 100 discrete raw gas "packages" of 15960 nm^3 each for the purpose of a simulation model, if it is assumed that each raw gas "package" represents 1% of the maximum possible raw gas output throughput. If each raw gas "package" is delayed in a simulation model for 36 seconds (one hour divided by 100) as it leaves the Gas Production plant, then the simulation model simulates a raw gas output throughput of 1596000 nm^3/h (100 "packages" of 15960 nm^3 each leaves the Gas Production plant in one hour).

The following two major concerns immediately become apparent if the example that is mentioned in the previous paragraph is implemented in a simulation model:

a)   The first concern is that the maximum possible accuracy with which the raw gas output throughput of the Gas Production plant can be determined, has been reduced to the size of a raw gas "package" per hour (*i.e.* 15960 nm^3/h) or alternatively 1% of the maximum possible raw gas output throughput. The resolution of an answer that indicates the raw gas output throughput therefore cannot be any better than the size of a raw gas "package".

b)   The second concern is that 100 entities (raw gas "packages") leave the Gas Production plant during one hour of simulated time. This implies that 100 events (delays of raw gas "packages") occur at that point in the simulation model during one hour of simulated time. It also implies that over a simulated time period of one year a staggering 864000

events (assume an 8640-hour simulation model year - see Appendix L: *Synthetic Fuel Plant Simulation Model Year*) occur at that point in the simulation model.

The accuracy can obviously be improved by converting the maximum possible raw gas output throughput into more discrete "packages". For instance, a conversion into 200 discrete "packages" will result in an accuracy resolution of ½% of the maximum possible raw gas output throughput. Paradoxically, this implies that the number of events at that point in the simulation model now doubles. This clearly represents a Scylla and Charybdis situation where the choice lies between "*two dangers such that avoidance of one increases the risk from the other.*" (*The Oxford Compact English Dictionary*, 1996:917; Macrone, 1999:20-21).

Kelton *et al.* (1998:353) also propose a variation on this technique and they indicate that it is usually preferred because it results in fewer entities in the simulation model. The variation on the technique uses a single entity that is looped through a time delay and increases a variable that represents the raw gas output throughput with a fixed amount (*i.e.* the discrete "package" size) each time a loop is completed. The problem is that this variation on the technique does not address the accuracy and huge number of events in the simulation model concerns that are detailed in the previous paragraphs.

The diminished accuracy and huge number of events that characterise this technique clearly violate some of the design criteria of the generic simulation modelling methodology that is stated in Section 1.5. The concession on accuracy obviously impacts negatively on the accurate modelling ability design criterion. The huge number of events in a simulation model that uses this technique affects the short simulation runtime criterion directly and the short development and maintenance times criteria indirectly, because longer simulation runtimes impact negatively on simulation model development, maintenance and use. The violation of the design criteria leads to an untenable situation. It emphatically disqualifies this technique as a contender to feature in the generic methodology.

The second of the two techniques that are proposed by Harrell and Tumay (1999:35) holds more promise. The technique simply updates "*a variable* [like the raw gas output throughput of the Gas Production plant] *at regular time intervals that accounts for a constant rate of change that occurred over the interval.*" The second technique updates the variable with a real number amount as opposed to the first technique that updates the variable with an amount that is a multiple of the size of the discrete "package" that is used. It is therefore quite obvious that the second technique is much more accurate than the first one. With the second technique there is

also only one event every time interval to update the variable. That implies that if a time interval of one hour is used there are only 8640 events at that point in the simulation model over a simulated time period of one year. That is a hundredfold improvement on the 864000 events at that point in the simulation model if the first technique is used.

Pegden *et al.* (1995:431-464) indicate that continuous behaviour can also be represented in a simulation model by algebraic, differential and difference equations that describe the behaviour of the system in terms of states and rates (see Section 1.7). The behaviour of the system is obtained by solving these equations over time. Unfortunately differential equations are very difficult to solve mathematically and numerical techniques are usually used to obtain solutions. If a numerical technique is used, the simulation model is advanced in time by a series of small time intervals. The size of each small time interval is calculated individually and is determined by the required accuracy. The numerical technique actually divides the continuous behaviour of the system into behaviour at discrete points in time. The state of the system is calculated at each of these discrete points in time and the total behaviour of the system over a period of time follows from the summation of the behaviour at the discrete points in time.

An interesting variation on the numerical technique described in the previous paragraph uses a fixed time interval to advance in time. The size of the fixed time interval depends on the required accuracy and is usually chosen in accordance with the dynamic response characteristics of the system that is modelled. The advantage of this variation is that the size of each time interval does not have to be calculated and therefore a lot of processing time is saved during a simulation run. The simulation model is also simpler because some of the numerical techniques are rather cumbersome to implement in a simulation model. For example, the 3- and 6-degree-of-freedom simulation models that are used to investigate the performance of aircraft and missile systems use this technique. If the time interval is chosen prudently and correctly in relation to the dynamic response characteristics of the system that is modelled, the result that is obtained can be a very close approximation of the real-world situation that is modelled. This is also the technique that is used by Forrester (*c*.1961:73) in *Industrial Dynamics* where he describes the use of a fixed time interval and how its size is determined.

> "*The equations of the model are evaluated repeatedly to generate a sequence of steps equally spaced in time.*"

> "*The interval of time between solutions must be relatively short, determined by the dynamic characteristics of the real system that is being modeled* [*sic*]."

To summarise, the first part of this section clearly shows that the first of the two techniques that are proposed by Harrell and Tumay leads to low accuracy and a huge number of events and therefore the first technique disqualifies itself. The second technique leads to high accuracy and fewer events and therefore qualifies as an excellent possible candidate for further use. The part that follows indicates that differential equations in simulation models are solved with numerical techniques that advance in time with small time intervals. If a fixed time interval is used, the need to calculate the size of each time interval falls away but care should be taken to ensure that accuracy requirements are not violated.

Section 1.7 shows that the generic simulation modelling methodology does not use differential equations to represent continuous behaviour. The reasons for this omission are also discussed. Even though the generic methodology does not accommodate differential equations, it still stands to reason that the continuous processes of the Synthetic Fuel plant can also be modelled by a simulation model that uses a fixed time interval to advance in time. The size of the fixed time interval should be chosen in accordance with the dynamic response characteristics of the Synthetic Fuel plant.

The following two possible candidates thus emerge as techniques for inclusion into the generic simulation modelling methodology:
a)   The one technique proposes the use of variables to represent process flow, like the raw gas output throughput of the Gas Production plant, as real numbers. These variables are updated with real number amounts at regular time intervals to ensure high accuracy.
b)   The other technique proposes the use of a fixed time interval to advance the simulation model in time. The size of the fixed time interval depends on the required accuracy and dynamic response characteristics of the system that is modelled.

Section 2.1 indicates that the class or type of system that is considered in this document is subject to two types of discrete events, namely: services and failures. Section 1.6 explains that the development of simulation software packages has traditionally focused primarily on the ability to model discrete-event systems. This implies that there is a plethora of techniques available in various simulation software packages that allow the easy incorporation of discrete events into simulation models.

The complex interrelationship characteristic of the class or type of system that is considered poses a much more formidable problem. The complex interrelationship characteristic is manifested in both the process flow and the process logic. The system description of the Synthetic Fuel plant

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in Section 1.2 reveals that there are feedback-loops in the plant. Crowe *et al.* (1971:1) provide some insights into the problems that are posed by the recycling (*i.e.* the feedback-loops) of either heat or matter in chemical plants.

> "*... an evaluation can be anything but exiting when it involves the tedious task of long and repetitious calculations caused by the recycle of energy or material.*"

> "*Recycle occurs frequently in chemical plants to conserve material and to improve the overall efficiency. Such recycle, however, introduces calculational [sic] difficulties.*"

The feedback-loops in the Synthetic Fuel plant are detailed in Point k) of the rules of operation of the plant in Appendix B, but it is important to repeat it here *verbatim* for the sake of the continuity of the argument. Plant(II)-A receives input from three other plants. Plant(II)-A receives pure gas directly from Plant(I), H_2 from the Division Process plant and recycled gas from the Recycling plant. From the Division Process plant there is a direct feedback-loop to Plant(II)-A and there is also an indirect feedback-loop from the Division Process plant through the Recycling plant to Plant(II)-A. The primary input of Plant(II)-A is the pure gas from Plant(I) and it is supplemented by the secondary input that consists of the H_2 and recycled gas from the Division Process and Recycling plants respectively. The volumes of H_2 and recycled gas that are supplied to Plant(II)-A obviously depends on the volume of pure gas that is supplied to Plant(II)-A from Plant(I). The ratio of the pure gas to the pure gas plus the H_2 and the recycled gas is referred to as the gas-feedback-loop-fraction. The gas-feedback-loop-fraction assumes a fixed value for a specific system description.

The system description of the Synthetic Fuel plant also indicates that the output of both the Steam and Oxygen plants is divided. The division of the output of the Steam and Oxygen plants is detailed in Points g) and i) respectively of the rules of operation of the Synthetic Fuel plant in Appendix B. Once again these points are repeated here *verbatim* for the sake of the continuity of the argument.

The output of the Steam plant is divided between three of the smaller plants. Steam is supplied to the Gas Production, Oxygen and Electricity Generation plants. Steam will only be supplied to the Electricity Generation plant once the Gas Production and Oxygen plants have been supplied. The primary function of the Steam plant is to supply steam to the Gas Production and Oxygen plants and the secondary function is to supply steam to the Electricity Generation plant.

The ratio of steam that is supplied to the Gas Production plant to steam that is supplied to the Oxygen plant is referred to as the steam-division-ratio. The steam-division-ratio is a fixed ratio for a specific system description.

The output of the Oxygen plant is divided between two of the smaller plants. Oxygen is supplied to both the Gas Production and Recycling plants. The ratio of oxygen that is supplied to the Gas Production plant to oxygen that is supplied to the Recycling plant is referred to as the oxygen-division-ratio. The oxygen-division-ratio is a fixed ratio for a specific system description.

The previous paragraphs clearly indicate that the gas-feedback-loop-fraction, steam-division-ratio and oxygen-division-ratio assume fixed values for a specific system description. This aspect of the complex interrelationship characteristic therefore implies that a method has to be devised that can render the gas-feedback-loop-fraction, steam-division-ratio and oxygen-division-ratio for every specific system description.

The complex interrelationship characteristic also manifests itself in the operation of the Synthetic Fuel plant. The first rule of operation in Appendix B states that the Synthetic Fuel plant always strives to maintain the maximum possible rate of production or throughput. In their book *The Goal*, Goldratt and Cox (1992:294) stress the importance of the throughput as the definitive measurement of plant performance.

> "*But the important thing is that we, in our plant, have switched to **regard throughput as the most important measurement**. **Improvement** for us is not so much to reduce costs but **to increase throughput**.*" [Bold typeface added for emphasis]

The maximum possible throughput of the Synthetic Fuel plant varies over time (*i.e.* it is a function of time) because the modules in the smaller plants are subject to services and failures. It therefore follows that the maximum possible throughput of the Synthetic Fuel plant, as a function of time, needs to be determined by the simulation model. The maximum possible throughput of the total Synthetic Fuel plant, as a function of time, can only be determined once the maximum possible throughput of each of the smaller plants, as a function of time, has been determined.

The maximum possible throughput of each of the smaller plants is a function of time because the modules in the smaller plants are subject to services and failures. The maximum possible

throughput of each of the smaller plants, as a function of time, is the number of available modules in the smaller plant, as a function of time, multiplied by the capacity of a module in the smaller plant, as a constant.

$$Throughput_{PltMaxPos}(t) = (n_{PltModAvl}(t))(Capacity_{PltMod}) \quad (ton, m^3, nm^3/h) \qquad (Eq.:2.1)$$

Where:

$Throughput_{PltMaxPos}(t)$: The maximum possible throughput of the smaller plant, as a function of time, in ton/h, m^3/h or nm^3/h.

$n_{PltModAvl}(t)$: The number of available modules in the smaller plant, as a function of time.

$Capacity_{PltMod}$: The input or output capacity of a module in the smaller plant, as a constant, in ton/h, m^3/h or nm^3/h.

The input and output capacities of the modules in each of the smaller plants usually differ (*i.e.* usually the input to output ratios are not equal to one), depending on the chemical processes that are involved. The maximum possible throughput of each of the smaller plants can therefore be expressed as either a maximum possible input throughput (*i.e.* the maximum possible upstream throughput) that depends on the input capacity or a maximum possible output throughput (*i.e.* the maximum possible downstream throughput) that depends on the output capacity.

The number of available modules in each of the smaller plants is a function of time because the modules in the smaller plants are subject to services and failures, both of which display time-dependent behaviour.

$$n_{PltModAvl}(t) = f(Service(t), Failure(t)) \quad (number) \qquad (Eq.:2.2)$$

More specifically, the number of available modules in each of the smaller plants, as a function of time, is the number of modules in the smaller plant, as a constant, minus the number of modules in the smaller plant that is being serviced, as a function of time, and the number of modules in the smaller plant that is being repaired after failure, as a function of time.

$$n_{PltModAvl}(t) = n_{PltMod} - (n_{PltModServ}(t) + n_{PltModFail}(t)) \quad (number) \qquad (Eq.:2.3)$$

Where:

n_{PltMod} : The number of modules in the smaller plant, as a constant.

$n_{PltModServ}(t)$:   The number of modules in the smaller plant that is being serviced, as a function of time.

$n_{PltModFail}(t)$:   The number of modules in the smaller plant that is being repaired after failure, as a function of time.

The maximum possible throughput of the Synthetic Fuel plant is a function of the maximum possible throughput of each of the smaller plants and therefore also a function of time.

$$Throughput_{SFPltMaxPos}(t) = f(Throughput_{PltMaxPos}(t) \text{ for No.1 ... } n_{Plt}) \quad (ton, m^3, nm^3/h) \quad (Eq.:2.4)$$

Where:

$Throughput_{SFPltMaxPos}(t)$:   The maximum possible throughput of the Synthetic Fuel plant, as a function of time, in ton/h, m^3/h or nm^3/h.

n_{Plt} :   The number of smaller plants, as a constant.

The determination of the maximum possible throughput of the Synthetic Fuel plant, as a function of time, is no arbitrary task because of the presence of feedback-loops, the division of the output of the Steam and Oxygen plants and the fact that the number of available modules in each of the smaller plants is a function of time. There is one consolation though. The second rule of operation in Appendix B states that only the smaller plants that form part of the main-gas-cycle can act as "bottlenecks" that influence the maximum possible throughput of the Synthetic Fuel plant. There are 10 smaller plants in the main-gas-cycle and they are sometimes referred to as the "heart" of the Synthetic Fuel plant. Two of the 10 smaller plants consist of groupings of different types of modules. The Oxygen plant consists of three groupings of different types of modules and Plant(II) consists of two groupings of different types of modules. The 10 smaller plants of the main-gas-cycle therefore represent 13 possible separate points, any one of which can be the "bottleneck" that determines the maximum possible throughput of the Synthetic Fuel plant at any given moment in time. The 13 possible "bottleneck" points in the main-gas-cycle are the following: Coal Processing, Steam, Gas Production, Temperature Regulation, Oxygen-A, -B and -C, Plant(I), Plant(II)-A and -B, Plant(III), Division Process and Recycling. These 13 possible "bottleneck" points determine the maximum possible throughput of the Synthetic Fuel plant at any given moment in time. The possible "bottleneck" point that is the "bottleneck" in the main-gas-cycle of the Synthetic Fuel plant at a specific moment in time is referred to as the momentary "bottleneck". The throughput of the Synthetic Fuel plant at any given moment in time is adjusted to coincide with the maximum possible throughput of the momentary "bottleneck" at that specific moment in time.

More than one of the 13 possible "bottleneck" points can simultaneously be the "bottleneck" at any given moment in time. Such an occurrence is referred to as a multiple momentary "bottleneck". The effect of these multiple momentary "bottleneck" occurrences is taken into account when the "bottleneck" smaller plants in the Synthetic Fuel plant are identified (see Section 2.6). The identification of the momentary "bottleneck" should not be confused with the identification of the "bottleneck" smaller plants. The identification of the momentary "bottleneck" is necessary to determine the maximum possible throughput of the Synthetic Fuel plant at a specific moment in time, while the identification of the "bottleneck" smaller plants are necessary to determine which of the smaller plants are "bottlenecks" over a period of time, typically a year or more.

The maximum possible throughput of the Synthetic Fuel plant at any given moment in time is defined by a "throughput vector" that comprises the actual throughput of each of the smaller plants. The actual throughput of the momentary "bottleneck" at that specific moment in time is, of course, exactly the same as the maximum possible throughput of the momentary "bottleneck" because the Synthetic Fuel plant always strives to maintain the maximum possible throughput. The momentary "bottleneck" represents one of the 13 possible "bottleneck" points in the main-gas-cycle and from there the actual throughput of the other 12 possible "bottleneck" points in the main -gas-cycle at that specific moment in time can be determined, depending on the input and output capacities of the modules in the smaller plants and provided that the gas-feedback-loop-fraction, steam-division-ratio and oxygen-division-ratio are known for that specific system description. If the actual throughput of each of the 13 possible "bottleneck" points in the main-gas-cycle is known, the actual throughput of the rest of the Synthetic Fuel plant at that specific moment in time can be determined. Point c) of the rules of operation in Appendix B indicates that the Electricity Generation plant, Plant(IV), Plant(V) and Sub(I) to Sub(VI) do not form part of the main-gas-cycle and that they are referred to as the peripheral plants. The actual throughput of each of the peripheral plants depends on the rules of operation of that specific peripheral plant. For example, Point d) of the rules of operation states that if Plant(IV), Plant(V) and Sub(I) to Sub(VI) do not have the capacity to process the throughput at their respective positions in the Synthetic Fuel plant, then the portions of the throughput that cannot be processed are flared. This example indicates that the complex interrelationship characteristic is even manifested in the determination of the actual throughput of the peripheral plants.

It is a common convention to express the actual throughput of each of the smaller plants as the actual output throughput (*i.e.* the actual downstream throughput) and not as the actual input throughput (*i.e.* the actual upstream throughput). If this convention is followed, it is only

necessary to add the actual input throughput of the total Synthetic Fuel plant (*i.e.* the coal that is supplied to the Coal Processing plant and the water that is supplied to the Water Treatment plant from external sources) to give a complete description of the maximum possible throughput (*i.e.* the "throughput vector") of the Synthetic Fuel plant at any given moment in time.

To summarise, the previous paragraphs indicate that the determination of the maximum possible throughput of the Synthetic Fuel plant, as a function of time, primarily depends on the identification of the momentary "bottleneck" in the main-gas-cycle at any given moment in time. The identification of the momentary "bottleneck" at any given moment in time poses a significant challenge due to the presence of feedback-loops, the division of the output of the Steam and Oxygen plants and the fact that the number of available modules in each of the 13 possible "bottleneck" points is a function of time. This challenge represents one of the significant problem areas of the generic simulation modelling methodology. An elegant solution to this problem is detailed in Section 2.4.

The number of modules that is switched on or off in each of the smaller plants, as a function of time, also has to be determined by the simulation model. All the available modules in the momentary "bottleneck" are switched on and operating at 100% of the module capacity at any given moment in time because of the philosophy of operating the Synthetic Fuel plant at the maximum possible throughput. However, it may not be necessary to switch on all the available modules in the other 12 possible "bottleneck" points for that specific maximum possible throughput of the Synthetic Fuel plant at that specific moment in time.

The number of modules that is switched on in each of the smaller plants, as a function of time, is the actual output throughput of the smaller plant, as a function of time, divided by the output capacity of a module in the smaller plant, as a constant.

$$n_{PltModOn}(t) = (Throughput_{PltActOut}(t)) / (Capacity_{PltModOut}) \quad (number)$$

$$if \qquad (Throughput_{PltActOut}(t)) / (Capacity_{PltModOut}) = Integer \quad (number)$$

$$or \qquad\qquad\qquad\qquad (Eq.:2.5)$$

$$n_{PltModOn}(t) = Truncate((Throughput_{PltActOut}(t)) / (Capacity_{PltModOut})) + 1 \quad (number)$$

$$if \qquad (Throughput_{PltActOut}(t)) / (Capacity_{PltModOut}) = Real \quad (number)$$

Where:

$n_{PltModOn}(t)$: The number of modules that is switched on in the smaller plant, as a function of time.

$Throughput_{PltActOut}(t)$: The actual output throughput of the smaller plant , as a function of time, in ton/h, m^3/h or nm^3/h.

$Capacity_{PltModOut}$: The output capacity of a module in the smaller plant, as a constant, in ton/h, m^3/h or nm^3/h.

The number of modules that is switched off in each of the smaller plants, as a function of time, is the number of modules that is available in each of the smaller plants, as a function of time, minus the number of modules that is switched on in each of the smaller plants, as a function of time.

$$n_{PltModOff}(t) = n_{PltModAvl}(t) - n_{PltModOn}(t) \quad (number) \qquad\qquad (Eq.:2.6)$$

Where:

$n_{PltModOff}(t)$: The number of modules that is switched off in the smaller plant, as a function of time.

Even though Equations 2.1 to 2.6 use the term "smaller plant", they are equally applicable when the term "smaller plant" is replaced with the term "possible "bottleneck" point" to accommodate instances where some of the smaller plants consist of groupings of different types of modules.

The following example serves to illustrate what the impact of the complex interrelationship characteristic is on the operation of the Synthetic Fuel plant. Consider an imaginary two-plant system that only involves the Gas Production and Temperature Regulation plants at a specific moment in time. If two of the modules in the Gas Production plant are being repaired after failure and one module in the Temperature Regulation plant is being serviced, then the maximum possible raw gas output throughput of the Gas Production plant is 1516200 nm^3/h (38 of the 40 modules with a raw gas output capacity of 39900 nm^3/h each are available) and the maximum possible raw gas input throughput of the Temperature Regulation plant is 1470000 nm^3/h (seven of the eight modules with a raw gas input capacity of 210000 nm^3/h each are available). The smaller one of the maximum possible raw gas output throughput of the Gas Production plant and the maximum possible raw gas input throughput of the Temperature Regulation plant determines the maximum possible throughput of the imaginary two-plant system. It is obvious that the momentary "bottleneck" in the imaginary two-plant system is the Temperature Regulation plant

and that the maximum possible raw gas input throughput of the momentary "bottleneck" is 1470000 nm^3/h. (Assume that the imaginary two-plant system always strives to maintain the maximum possible throughput.)

The maximum possible throughput of the imaginary two-plant system at that specific moment in time, according to the convention previously described, is defined by a "throughput vector" that comprises the actual output throughput (*i.e.* the actual downstream throughput) of each of the two smaller plants as well as the actual input throughput of the imaginary two-plant system. The actual raw gas output throughput of the Gas Production plant is 1470000 nm^3/h. The actual output throughput of the Temperature Regulation plant consists of an actual raw gas output throughput and an actual gas-water output throughput. The actual raw gas output throughput is also 1470000 nm^3/h because the raw gas input and output capacities of the Temperature Regulation modules are identical (1470000 nm^3/h multiplied by the output to input ratio of the raw gas - 210000 nm^3/h divided by 210000 nm^3/h). The actual gas-water output throughput is 940,8 m^3/h (1470000 nm^3/h multiplied by the output to input ratio of the gas-water - 134,4 m^3/h divided by 210000 nm^3/h). The actual input throughput of the imaginary two-plant system is determined in a similar manner. The actual steam input throughput is 954,2 ton/h (1470000 nm^3/h multiplied by the input to output ratio of the steam - 25,9 ton/h divided by 39900 nm^3/h). The actual oxygen input throughput is 203736,8 nm^3/h (1470000 nm^3/h multiplied by the input to output ratio of the oxygen - 5530 nm^3/h divided by 39900 nm^3/h). The actual coarse coal input throughput is 937,6 ton/h (1470000 nm^3/h multiplied by the input to output ratio of the coarse coal - 25,45 ton/h divided by 39900 nm^3/h).

The number of modules that is switched on or off in each of the smaller plants at that specific moment in time depends on the actual output throughput of each of the smaller plants (see Equations 2.5 and 2.6). The Temperature Regulation plant is the momentary "bottleneck" and consequently all seven available modules in the Temperature Regulation plant are switched on and operating at 100% of the module capacity (all the available modules in the momentary "bottleneck" are switched on to ensure that the maximum possible throughput of the imaginary two-plant system is realised). Or alternatively, the actual raw gas output throughput of the Temperature Regulation plant, divided by the raw gas output capacity of a module in the Temperature Regulation plant, gives the number of modules that is switched on in the Temperature Regulation plant. That also gives exactly seven modules in the Temperature Regulation plant that are switched on (1470000 nm^3/h divided by 210000 nm^3/h). The number of modules that is switched on or off in the Gas Production plant is determined in a similar manner. The actual raw gas output throughput of the Gas Production plant, divided by the raw

gas output capacity of a module in the Gas Production plant, gives the number of modules that is switched on in the Gas Production plant. That gives an answer of 36,8 modules in the Gas Production plant that are switched on (1470000 nm^3/h divided by 39900 nm^3/h). It is, however, impossible to switch on 36,8 modules and therefore 37 of the 38 available modules in the Gas Production plant are switched on and one is switched off. In reality the workload (*i.e.* the actual raw gas output throughput of the Gas Production plant) is evenly distributed among the 37 modules in the Gas Production plant that are switched on. There will not be 36 modules operating at 100% of the raw gas output capacity of a module and one module operating at 80% of the raw gas output capacity of a module.

To summarise, the example shows that the operation of the imaginary two-plant system at that specific moment in time is described by the following:

a)   The number of available modules in each of the smaller plants is (use Equation 2.3):

      i)   Gas Production   : 38 modules of a possible 40 modules

      ii)   Temperature Regulation   : 7 modules of a possible 8 modules

b)   The maximum possible throughput (input or output) of each of the smaller plants is (use Equation 2.1):

      i)   Gas Production   : 1516200 nm^3/h raw gas (output)

      ii)   Temperature Regulation   : 1470000 nm^3/h raw gas (input)

c)   The momentary "bottleneck" of the two-plant system is:

      i)   Temperature Regulation

d)   The maximum possible throughput (*i.e.* the "throughput vector") of the two-plant system is (use Equation 2.4):

      i)   Actual input throughput:

          Steam   : 954,2 ton/h

          Oxygen   : 203736,8 nm^3/h

          Coarse coal   : 937,6 ton/h

      ii)   Actual output throughput of the Gas Production plant:

          Raw gas   : 1470000 nm^3/h

      iii)   Actual output throughput of the Temperature Regulation plant:

          Raw gas   : 1470000 nm^3/h

          Gas-water   : 940,8 m^3/h

e)   The number of modules that is switched on in each of the smaller plants is (use Equation 2.5):

      i)   Gas Production   : 37 modules of the 38 available modules

      ii)   Temperature Regulation   : 7 modules of the 7 available modules

f)   The number of modules that is switched off in each of the smaller plants is (use Equation 2.6):

    i)   Gas Production   : 1 module of the 38 available modules

    ii)   Temperature Regulation   : 0 modules of the 7 available modules

This example clearly illustrates the complexities that are involved to determine the maximum possible throughput (*i.e.* the "throughput vector") and the number of modules that is switched on or off to achieve that throughput, for a very simple imaginary two-plant system at a specific moment in time. Therefore, the determination of the maximum possible throughput and the number of modules that is switched on or off to accomplish that throughput, as functions of time, for the entire Synthetic Fuel plant is not a straightforward matter.

The maximum possible throughput (input or output) of each of the smaller plants and the maximum possible throughput of the system (that consists of the actual input throughput of the system and the actual output throughput of each of the smaller plants) are determined as real numbers. In contrast to this, the number of modules that is available in each of the smaller plants and the number of modules that is switched on or off in each of the smaller plants are determined as integer numbers. The representation of the maximum possible throughput of the smaller plants and the maximum possible throughput of the system as real numbers already presupposes the notion of representing continuous processes with variables (*i.e.* the variables technique). It is obvious that the variables technique is more accurate than the techniques that represent continuous processes by converting the continuously flowing "commodities" into discrete entities or "packages" (see the discussion in the first part of this section).

Summary

This section investigates the implications of the characteristics of stochastic continuous systems on a simulation model. The continuous process characteristic leads to two techniques that qualify for possible inclusion into the generic simulation modelling methodology, namely: the use of variables to represent processes and the use of a fixed time interval to advance the simulation model in time. The characteristic of the two types of discrete events (*i.e.* the services and failures) does not represent a significant problem. The complex interrelationship characteristic, however, poses a much more formidable problem. The gas-feedback-loop-fraction, steam-division-ratio and oxygen-division-ratio have to be determined for every specific system description. The complex interrelationship characteristic also influences the operation of the system and therefore the determination of the maximum possible throughput (*i.e.* the "throughput vector") of the

system and the number of modules that is switched on or off to achieve that throughput, is no arbitrary matter (as demonstrated by the imaginary two-plant system example).

This section also provides equations for the determination of the maximum possible throughput and the number of modules that is switched on or off to achieve that throughput. However, there are still a few outstanding issues that have to be resolved. In the simple imaginary two-plant system example the number of modules that is being serviced and the number of modules that is being repaired after failure in each of the smaller plants at that specific moment in time is assumed to be known and the identification of the momentary "bottleneck" is very easy with only two possible candidates to choose from. The same does not apply when the entire Synthetic Fuel plant is considered. The identification of the momentary "bottleneck" from the 13 possible "bottleneck" points is not easy because there are feedback-loops, the output of the Steam and Oxygen plants is divided and the number of available modules in each of the smaller plants is a function of time.

The outstanding issues that require further consideration are the following:

a)   The determination of the number of modules that is being serviced and the number of modules that is being repaired after failure in each of the smaller plants at any given moment in time. The services and failures are the discrete events and an innovative method to accommodate this characteristic is detailed in Section 2.3. This method is referred to as the Entity-represent-module (ERM) method.

b)   The identification of the momentary "bottleneck" from the 13 possible "bottleneck" points at any given moment in time. An elegant method that identifies the momentary "bottleneck" in a complex system is detailed in Section 2.4. This method is referred to as the Fraction-comparison (FC) method

c)   The determination of the governing parameters for every specific system description of the system that is under scrutiny. The governing parameters comprise the gas-feedback-loop-fraction, steam-division-ratio, oxygen-division-ratio and the FC method parameter set. The first three follows from the presence of feedback-loops and the fact that the output of the Steam and Oxygen plants is divided and the parameter set is necessary for the FC method to function. The determination of the governing parameters is detailed in Section 2.5.

* * * * *

2.3   THE ERM METHOD

The abbreviation ERM stands for Entity-represent-module. The ERM method is used by both the original simulation modelling method and the generic simulation modelling methodology. It was originally developed as part of the *Magister* work (Albertyn, 1995:42-47). However, the advanced version that is presented in this document, is considerably more refined than the original version. The ERM method is an innovative method that determines the state of the modules in the system that is under scrutiny at any given moment in time. The previous section indicates that the continuous processes can be represented by variables in a simulation model. However, the behaviour of the modules also has to be represented in the simulation model. The modules are subject to discrete events (*i.e.* the services and failures).   The differences between the representation of the continuous processes and the representation of the behaviour of the modules lead to a natural division of the simulation model into two parts. One part deals with the continuous processes and the other deals with the behaviour of the modules. The part of the simulation model that deals with the continuous processes is referred to as the "virtual" part of the simulation model, because the actual processes are represented by variables and logical equations (*i.e.* the process flow and process logic or rules of operation are represented by variables and logical equations). The part that deals with the behaviour of the modules is referred to as the "real" part of the simulation model, because the actual modules are represented by standard simulation software package building blocks. This section is primarily concerned with the "real" part of the simulation model that deals with the behaviour of the modules.

The modules in the smaller plants represent the physical processing resources of the Synthetic Fuel plant that actually process the "commodities" (*i.e.* the coal, gases and liquids) that flow through the plant. The modules are subject to two types of discrete events, namely: the services and the failures of the modules (see Section 1.2 and Table A2). The groupings of components that are referred to as modules in this document are usually represented in simulation models by high-level simulation software package building blocks. A high-level building block is a conglomerate of basic building blocks that model a specific concept that occurs frequently in simulation models. For example, a high-level building block can be developed that represents a lathe in a machine shop. Most simulation software packages provide basic building blocks that allow the modeller the freedom to include unique concepts and high-level building blocks that facilitate the use of standardised concepts. The high-level building blocks that represent modules are different in different simulation software packages.

In the Arena simulation software package a module is represented by the *Server* high-level

building block on the *Common* template. The *Server* high-level building block "... *defines a station corresponding to a physical or logical location where processing occurs.*" (according to the Arena help function). The *Server* high-level building block makes provision for services (called downtime) and failures. The services are defined by a cycle time and a service time, both of which can be defined by either constant values or theoretical probability distributions. A multiple service cycle can be accommodated, but the start time of a service cycle cannot be specified. The failures are defined by a failure rate and a repair time. The failure rate can be defined by either count (counting the number of occurrences of an event) or time (a constant value or a theoretical probability distribution). The repair time can be defined by a constant value or a theoretical probability distribution.

In the Simul8 simulation software package a module is represented by the *Work Center* high-level building block on the *Build Tools* template. "*A Work Center* [*sic*] *is a place where work takes place on Work Items.*" (according to the Simul8 help function). The *Work Center* high-level building block groups all unavailability (*i.e.* the services and failures) together under a single heading that is called *Efficiency*. The *Efficiency* is defined by a percentage value and an average repair time that is a constant value.

Simul8 is a registered trademark and is usually denoted by Simul8®. However, for the sake of simplicity it will be written simply as Simul8 in this document. Simul8 is a simulation software package from the Simul8 Corporation.

It is clear that the Arena representation of a module is more accomplished and that the Simul8 representation of a module is more basic. The Arena representation, however, still lacks the ability to specify the start time of a service cycle. It therefore seems as if none of the two simulation software packages can adequately represent a module. The services of the smaller plants are characterised by the service cycles of their modules (see Section 1.2 and Table A2). The start times of the service cycles are of critical importance, because the way that the different service cycles of the different smaller plants interact can have a pronounced effect on the throughput of the Synthetic Fuel plant. It is obvious that the two simulation software packages cannot accommodate all the required intricacies of the services.

This deficiency of the simulation software packages led to the development of the ERM method. The only logical solution is to use the basic simulation software package building blocks to develop a high-level building block that does accommodate all the required intricacies of the services. It also presents an opportunity to use the basic building blocks in an innovative manner.

A simulation model usually incorporates the processing resources and the "commodities" that are processed. In a discrete simulation modelling environment the processing resources are usually represented by *Servers* (Arena) or *Work Centers* (Simul8) and the "commodities", that move or flow through the system, are usually represented by entities. The word entity is "*... a generic term used to denote any person, object, or thing—whether real or abstract—whose movement through the system may cause changes in the state of the system.*" (according to the Arena help function). An entity is referred to as an *Entity* in Arena and as a *Work Item* in Simul8. Entities are usually created at specific points in a simulation model and then move or flow through the system while they are processed by various processing resources (*i.e.* the *Servers* or *Work Centers*).

The innovative aspect of the ERM method is that it uses entities to represent the modules. This is a counter-intuitive concept because *Servers* and *Work Centers* usually represent physical processing resources that are "fixed" in position, while the entities usually represent the "commodities" that move of flow through the system. All the relevant information about a module is stored in the attributes of the entity that represents the module. An attribute is referred to as an *Attribute* in Arena and as a *Label* in Simul8. For example, the relevant information about a module, such as the number of the smaller plant that the module belongs to, a grouping number (if the smaller plant consists of groupings of different types of modules), a module number that determines its position in the smaller plant, values that determine its next service and failure, *etc.* can all be stored in the attributes of the entity that represents the module.

The behaviour of a module is characterised by the following four different possible states:

a) On   :   Available (switched on)
b) Off   :   Available (switched off)
c) Service :   Unavailable (being serviced)
d) Failure :   Unavailable (failed and being repaired)

A module is either available or unavailable. An available module is either switched on or it is switched off. An unavailable module is either being serviced or it is being repaired after failure.

The four possible states of a module seem to imply that each of the smaller plants needs four separate parts to deal with the behaviour of the modules in that specific smaller plant. If the first two possible states are combined to form one part, the four separate parts are reduced to three separate parts. In such an instance the first part deals with all the available modules (irrespective of whether they are switched on or off) and the second and third parts deal with the modules that are being serviced and the modules that are being repaired after failure respectively.

The three separate parts of each of the smaller plants can easily be constructed from the basic building blocks of simulation software packages. The first part is very simplistic and consists of only a queue. All the available modules reside in the queue. The second and third parts are more complex and consist of queues, resources and other associated basic building blocks. The resources in the second and third parts represent the human resources of the Synthetic Fuel plant that are necessary to service and repair the modules. The human resources that service the modules are referred to as Service Teams and the human resources that repair the modules are referred to as Repair Teams. There is a dedicated Service Team for each of the smaller plants whose modules are subject to services and a dedicated Repair Team for each of the smaller plants whose modules are subject to failures.

It is important to note that in the ERM method of the original simulation modelling method each of the smaller plants consists of four separate parts, because the ERM method of the original method uses two separate queues to distinguish between the modules that are switched on and those that are switched off. The two queues provide statistics about the number of modules that is switched on or off in the smaller plant over a period of time. In the ERM method of the generic simulation modelling methodology, however, each of the smaller plants consists of only three separate parts because the two queues are combined to form one queue for the available modules. The statistics about the number of modules that is switched on or off in the smaller plant over a period of time is kept by variables. This change helps to support the compact simulation model size design criterion (see Point e) of the design criteria in Section 1.5) of the generic methodology by eliminating one of the queues that is used in each of the smaller plants in the ERM method of the original method. The ERM method of the original method uses four queues in each of the smaller plants, one in each of the four separate parts of each of the smaller plants while the ERM method of the generic methodology uses three queues in each of the smaller plants, one in each of the three separate parts of each of the smaller plants.

The aim of the ERM method is to determine the state of the modules in the system that is under scrutiny at any given moment in time. To reach that goal, it is necessary to construct three separate parts for each of the smaller plants. The first part is referred to as the Availability Part, the second as the Service Part and the third as the Failure Part.

Before the start of a simulation run, the first part (*i.e.* the Availability Part) of each of the smaller plants in the Synthetic Fuel plant is populated with the corresponding correct number of entities. The number of modules in each of the smaller plants is indicated in Column 3 of Table A1. The entities represent the modules in each of the smaller plants. Appropriate values are also assigned

to the attributes of each of the modules. Each of the modules is uniquely identified by the number of the smaller plant that the module belongs to, a grouping number (if the smaller plant consists of groupings of different types of modules) and a module number that determines its position in the smaller plant. Values are also assigned to the next-service and next-failure attributes.

The next-service attribute determines when the module is decommissioned for a service. The start time of the service cycle of each of the smaller plants determines when the first module in that specific smaller plant is decommissioned for a service. The other modules in that specific smaller plant are then decommissioned in sequence until the service cycle is completed. The services of the modules are staggered in time to minimise the impact of the services on production. Before the start of a simulation run, the next-service attribute of the first module in each of the smaller plants is assigned the start time value of the service cycle of that specific smaller plant. The next-service attributes of the other modules in that specific smaller plant are then assigned values that are progressively the service time apart to ensure that the services are staggered in time and do not overlap. The start time of the service cycle in each of the smaller plants only controls when the first service cycle starts, from that point the service cycles follow in a regular pattern, one service cycle apart. The cycle times and service times of the smaller plants are indicated in Columns 3 and 4 respectively of Table A2. The start times are not indicated in Table A2 because they can vary significantly from scenario to scenario. A multiple service cycle can easily be accommodated by using different next-service attributes for the different service cycles of the multiple service cycle. The start time values of each of the different service cycles are then assigned to the corresponding next-service attributes before the start of a simulation run.

The next-failure attribute determines when the module is going to fail. Before the start of a simulation run, the next-failure attribute of each of the modules is assigned a value that is sampled randomly from a theoretical probability distribution. The theoretical probability distributions that are used represent the failure rates of the modules in each of the smaller plants (see Section 1.2). The failure rates of the modules in each of the smaller plants are characterised in Column 5 of Table A2.

To summarise, before the start of a simulation run the first part of each of the smaller plants is populated with the correct number of modules and the attributes of the modules are assigned appropriate values for identification purposes, next service, next failure, *etc.*

During a simulation run, at any given moment in time, each of the smaller plants is evaluated to

determine the state of the modules in each of the smaller plants. The next-service attributes of all the modules in the first part (*i.e.* the Availability Part) of each of the smaller plants are first evaluated to determine if any of them are due for a service. If any of them are due for a service they are removed from the first part of the smaller plant and sent to the second part (*i.e.* the Service Part) of the smaller plant, provided that the Service Team of that specific smaller plant is available at that specific moment in time. To ensure the maximum possible throughput of the Synthetic Fuel plant a module will not be decommissioned for a service while another module is still being serviced. The services of the modules in each of the smaller plants do not overlap if they are assigned correctly, but this rule is necessary because if the service schedule of a smaller plant consist of a multiple service cycle, the services of the modules can overlap. The service cycles of a multiple service cycle are prioritised, with the service cycle having the longest service time, taking precedence. It is assumed that the service cycle with the longest service time is the most important service cycle. The next-failure attributes of all the modules in the first part (*i.e.* the Availability Part) of each of the smaller plants are then evaluated to determine if any of them have failed. If any of the modules in each of the smaller plants have failed, they are removed from the first part of the smaller plant and sent to the third part (*i.e.* the Failure Part) of the smaller plant. It is not necessary to determine if the Repair Team of that specific smaller plant is available at that specific moment in time because a failed module is immediately removed from the first part and placed in a queue to await repair if the Repair Team is still busy repairing another module at that specific moment in time.

Modules that arrive at the second part (*i.e.* the Service Part) of each of the smaller plants pass through a queue and are then delayed for a time period that is equal to the service time of that specific service. The service times of the services of each of the smaller plants are indicated in Column 4 of Table A2. The Service Team of that specific smaller plant is also engaged for that time period. Strictly speaking a queue is not necessary because a module is not removed from the first part if the Service Team is not available. However, the queue is advantageous because the statistics of the queue indicates whether modules had to wait in the queue for their services and therefore it can be used to verify that the simulation model works correctly. If modules had to wait in the queue for their services, the simulation model is obviously not working correctly. When the service is completed, the Service Team is disengaged, the number of services that is completed is incremented by one, the next-service attribute is assigned a value that corresponds to the cycle time of the appropriate service cycle, the next-failure attribute is assigned a value that is sampled randomly from the appropriate theoretical probability distribution and the module is returned to the first part of that smaller plant. The number of services that is completed is used for simulation model verification and validation purposes (see Section 3.6). The cycle times of

the service cycles of the smaller plants are indicated in Column 3 of Table A2. The next-failure attribute is assigned a new value because it is assumed that the module is restored to an "approximately as good as new" configuration by the preventive maintenance of the service.

Modules that arrive at the third part (*i.e.* the Failure Part) of each of the smaller plants are placed in a queue if the Repair Team of that specific smaller plant is engaged, or pass through the queue if the Repair Team is available. If the Repair Team is available, the modules are delayed for a time period that is sampled randomly from a theoretical probability distribution. The theoretical probability distributions that are used represent the repair times of the modules in each of the smaller plants and are characterised in Columns 6, 7 and 8 of Table A2 (see Section 1.2). The Repair Team of that specific smaller plant is also engaged for that time period. When the repair is completed, the Repair Team is disengaged, the number of failures that is repaired is incremented by one, the next-failure attribute is assigned a value that is sampled randomly from the appropriate theoretical probability distribution and the module is returned to the first part of that smaller plant. The number of failures that is repaired is used for simulation model verification and validation purposes (see Section 3.6).

To summarise, during a simulation run, at any given moment in time, the Availability Part of each of the smaller plants is evaluated to determine the state of the modules in each of the smaller plants. Modules that are due for a service are removed from the Availability Part, sent to the Service Part, delayed for the service time, assigned new values to the appropriate attributes and returned to the Availability Part. Modules that have failed are removed from the Availability Part, sent to the Failure Part, delayed for the repair time, assigned new values to the appropriate attributes and returned to the Availability Part.

The basic structure of the three separate parts of each of the smaller plants is graphically depicted in Figure 2.1: *Smaller Plant Parts*.

The three separate parts of each of the smaller plants therefore identify the number of modules that is available, being serviced, and being repaired after failure, in each of the smaller plants at any given moment in time. The number of modules that is available in each of the smaller plants at any given moment in time is of special importance, because it is used to determine the maximum possible throughput of the smaller plants and hence the maximum possible throughput of the system that is under scrutiny at any given moment in time.
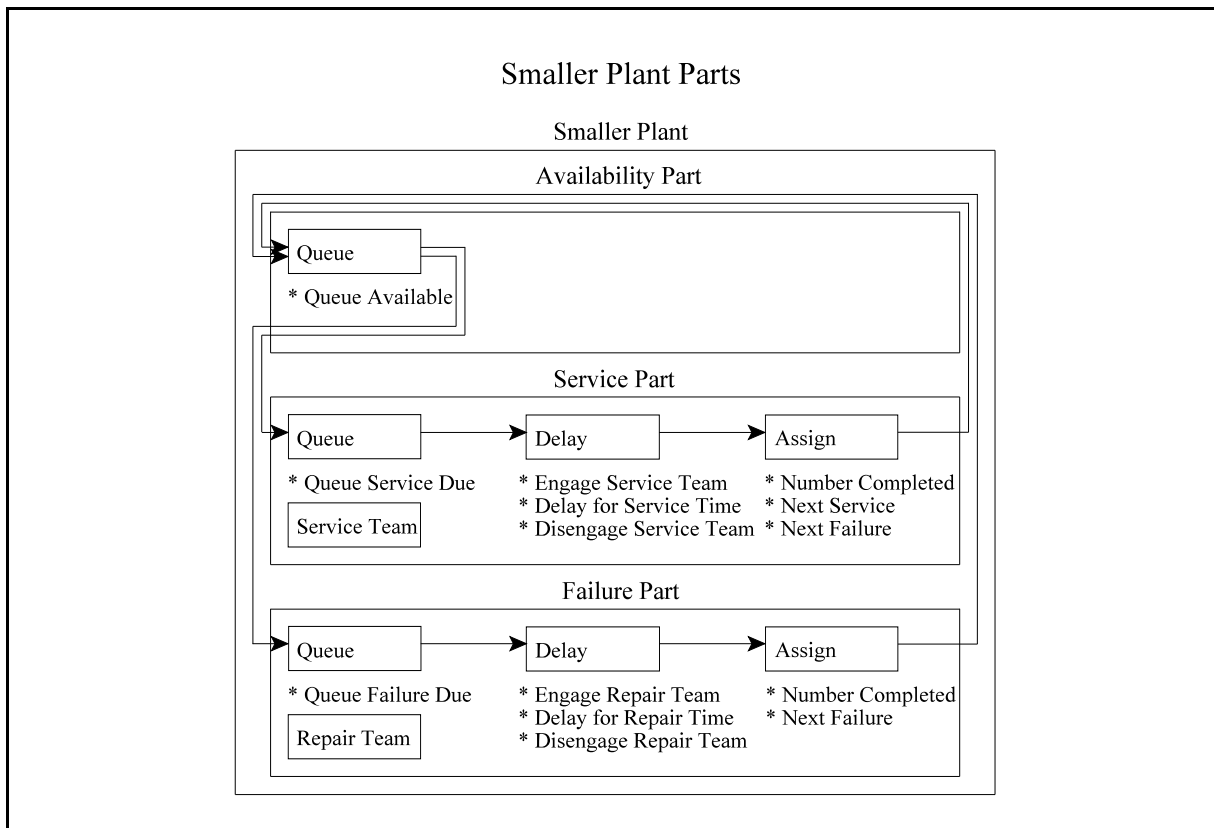
Figure 2.1: Smaller Plant Parts

It is important to realise that a module is in one of the three queues at any given moment in time. This leads to the interesting phenomenon that a module may be in the Failure Part of a smaller plant when its next service is due. It is obvious that the required service cannot start at the scheduled time because the module is still being repaired.

In such an instance one of the following options is applicable:

a)   The module is released from the Failure Part before the time that the service would have been completed and consequently the module is immediately sent to the Service Part for the remainder of the service time. Such an event is counted as a completed service and the next-service attribute is assigned a value that corresponds to the cycle time of the appropriate service cycle in exactly the same manner as a regular service. The next-failure attribute is also assigned a new value because the module has been restored to an "approximately as good as new" configuration.

b)   The module is released from the Failure Part after the time that the service would have been completed and consequently the module is sent to the Availability Part. Such an event is counted as a missed service and the next-service attribute is assigned a value that

ensures that the specific module is serviced next at exactly the right time to be in its original service sequence with respect to the other modules of that specific smaller plant. The next-failure attribute is not assigned a new value because a new value has already been assigned to the next-failure attribute when the module left the Failure Part.

In this instance the service is not really partially completed or missed in the real-world situation, because in the real-world situation the Service Team moves to the module that is stationary. In the real-world situation the Service and Repair Teams of a smaller plant can both be working on one module at the same time. The elaborate approximation that is described above is necessary because it is impossible to emulate the concept of both teams working on one module at the same time in the ERM method. In the ERM method the module is moved and it can only be in one part at any specific moment in time, either in the Availability, Service or Failure Part.

Another interesting phenomenon that occurs is that a module may be due for its next service while another module is still being serviced. This phenomenon can only occur in a smaller plant with a service schedule that consists of a multiple service cycle because the services of the different service cycles may overlap. In a smaller plant with a regular service cycle the services cannot overlap if they are assigned correctly. It is obvious that the required service cannot start at the scheduled time because another module is still being serviced.

In such an instance one of the following options is applicable:

a) The module that is being serviced is released from the Service Part and returned to the Availability Part before the time that the service of the module that is due for its next service would have been completed. Consequently the module that is due for its next service is immediately removed from the Availability Part and sent to the Service Part for the remainder of the service time of the specific service cycle, provided that another module is not due for its next service in a service cycle that has a higher priority than the service cycle of the original module that is due for its next service. Such an event is counted as a completed service of the specific service cycle and the next-service attribute of that specific service cycle is assigned a value that corresponds to the cycle time of that specific service cycle in exactly the same manner as a regular service of that specific service cycle. The next-failure attribute is also assigned a new value because the module has been restored to an "approximately as good as new" configuration.

b) The module that is being serviced is released from the Service Part and returned to the Availability Part after the time that the service of the module that is due for its next service would have been completed. Consequently the module that is due for its next

service is not removed from the Availability Part. Such an event is counted as a missed service and the next-service attribute of the specific service cycle is assigned a value that ensures that the specific module is serviced next at exactly the right time to be in its original service sequence with respect to the other modules of that specific smaller plant, as far as that specific service cycle is concerned. The next-failure attribute is not assigned a new value because the service has been missed and the module has not been restored to an "approximately as good as new" configuration.

Even though these phenomena do not occur very frequently, they disturb the service sequences of the modules in the smaller plants when they occur. The disturbances are more pronounced in longer simulation runs because once a service sequence is disturbed the effect is repeated every service cycle that follows from that point onward. A disturbed service sequence looks like a "row of teeth" with one or more of the "specimens" conspicuously missing when viewed graphically on a time graph of the Service Team utilisation. The number of services that is missed is used for simulation modelling verification and validation purposes.

The discussion in the previous paragraphs clearly illustrates the complexities that are involved when the services and the failures of the modules are modelled. Another compounding factor is that the values of the next-service attributes of the modules sometimes start to deviate from the correct values in longer simulation runs because of the accumulation of floating-point errors in the calculations. A floating-point error is a very small error that affects the value of a real variable in a digital computer when a multitude of calculations are done with that real variable because the computer, of necessity, has to approximate each real number with a fixed number of decimal digits. Therefore it is necessary to incorporate mechanisms that continuously test the values of the next-service attributes of the modules and immediately correct them if they start to deviate from the correct values.

To summarise, the following three phenomena can cause a disturbed service sequence:
a)   A module is in the Failure Part when its next service is due.
b)   A module is due for its next service while another module is still being serviced (overlapping service cycles of a multiple service cycle).
c)   The value of the next-service attribute of a module starts to deviate because of the accumulation of floating-point errors.

It is essential to note that the ERM method of the original simulation modelling method does not make provision for the occurrence of these phenomena and consequently the service sequences

of the modules in some of the smaller plants are disturbed during longer simulation runs. This leads to a minor inaccuracy as far as the effect of the services on the throughput of the Synthetic Fuel plant is concerned. The previous paragraphs indicate how this shortcoming is addressed in the ERM method of the generic simulation modelling methodology. Therefore the service sequences of the modules in all the smaller plants are always correct when the ERM method of the generic methodology is used, irrespective of the length of the simulation run.

The advantages of the ERM method are the following:

a)   The ERM method greatly reduces the size of the simulation model because the three separate parts of each of the smaller plants are constructed from basic simulation software package building blocks and no high-level building blocks are used. In the instance of the Synthetic Fuel plant 147 *Servers* or *Work Centers* (high-level building blocs) are needed to represent the modules if a conventional simulation modelling method is used. If the ERM method is used, 147 entities (which may be regarded as basic building blocks) are needed to represent the modules. Sometimes it is not even necessary to represent a module with an entity, depending on the type of smaller plant that is represented. This concept is clarified in the latter part of this section. Even though queues, resources and other associated basic building blocks are used in the three separate parts of each of the smaller plants, the size of an ERM method simulation model is significantly less than that of a conventional simulation model because no high-level building blocks are used in the ERM method. This aspect of the ERM method therefore supports the compact simulation model size criterion of the generic simulation modelling methodology (see Point e) of the design criteria in Section 1.5).

b)   The ERM method allows total control over all the relevant aspects of the services of the modules, namely: the start time, the cycle time and the service time. In most instances it is impossible to achieve this level of control or accuracy if the high-level building blocks of simulation software packages are used. This aspect of the ERM method therefore supports the accurate modelling ability criterion of the generic simulation modelling methodology (see Point g) of the design criteria in Section 1.5).

c)   The inclusion of techniques to handle the "disturbed service sequence" phenomena enhances the accuracy of the ERM method. Therefore it also supports the accurate modelling ability of the generic simulation modelling methodology (see Point g) of the design criteria in Section 1.5).

The three separate parts of each of the smaller plants can, of course, be combined to form an ERM method high-level building block for each of the smaller plants. A scrutiny of Table A2

indicates that all the smaller plants are not necessarily subjected to both services (with either a regular or a multiple service cycle) and failures.

The following five different types of smaller plants can be identified:
a)   A smaller plant with a multiple service cycle and failures of the modules.
b)   A smaller plant with a service cycle and failures of the modules.
c)   A smaller plant with a service cycle of the modules.
d)   A smaller plant with failures of the modules.
e)   A smaller plant with neither a service cycle nor failures of the modules.

It is obvious that all the types of smaller plants can be represented by one high-level building block if it includes a multiple service cycle and failures of the modules. It is also clear that the fifth type of smaller plant does not need to be represented by a high-level building block because all the modules in such a smaller plant are available all the time. That leaves two possible options, namely: use only one high-level building block to represent the first four types of smaller plants, or use four different high-level building blocks to represent the first four types of smaller plants. The first option supports the user-friendliness criterion (see Point c) of the design criteria in Section 1.5) of the generic simulation modelling methodology. It introduces simplicity because only one high-level building block is used, learnt and understood (*i.e.* a standardisation principle). However, the simulation model size suffers because unnecessary and unused options are included. The second option supports the compact simulation model size criterion (see Point e) of the design criteria in Section 1.5) of the generic methodology by not including any options that are unnecessary or unused. However, user-friendliness suffers a bit because four different high-level building blocks are used. This once again presents a Scylla and Charybdis situation where the avoidance of the problems of one option leads to the problems of the other. In this instance the compact simulation model size is deemed more important and therefore four different high-level building blocks (representing the first four types of smaller plants) are used in the ERM method. The fifth type of smaller plant is incorporated into the "virtual" part of the simulation model where the actual processes are represented by variables and logical equations only. The four different high-level building blocks are used to represent the first four types of smaller plants in the "real" part of the simulation model.

Summary

This section details an innovative method that determines the state of the modules in the system that is under scrutiny at any given moment in time. The ERM method uses entities to represent

the modules rather than the cumbersome *Servers* or *Work Centers* that are usually used in simulation software packages. The relevant information about a module is stored in the attributes of the entity that represents the module. Each of the smaller plants is represented by three separate parts, namely: the Availability, Service and Failure Parts. Before the start of a simulation run the Availability Part of each of the smaller plants is populated with the correct number of modules and the attributes of the modules are assigned appropriate values. During a simulation run, at any given moment in time, each of the smaller plants is evaluated to determine the state of the modules in the Availability Part. Modules that are due for a service are removed and sent to the Service Part while modules that have failed are removed and sent to the Failure Part. The services and failures are governed by complex rules. The main advantages of the ERM method are a compact simulation model size, total control over all the relevant aspects of the services and accuracy. The number of modules that is available in each of the smaller plants at any given moment in time is used to determine the maximum possible throughput of the smaller plants and hence the maximum possible throughput of the system at any given moment in time.

The three separate parts of each of the smaller plants are combined to form a high-level building block. Four types of smaller plants are represented in the ERM method by the following four different high-level building blocks: a smaller plant with a multiple service cycle and failures of the modules, a smaller plant with a service cycle and failures of the modules, a smaller plant with a service cycle of the modules and a smaller plant with failures of the modules. The four different high-level building blocks are used to represent all the smaller plants in the "real" part of the simulation model and the fifth type of smaller plant (with neither a service cycle nor failures of the modules) is incorporated into the "virtual" part of the simulation model, where the actual processes are represented by variables and logical equations only.

The ERM method of the generic simulation modelling methodology is more compact and accurate than the ERM method of the original simulation modelling method because it reduces the number of queues that is used in each of the smaller plants from four to three and it introduces techniques that address the "disturbed service sequence" phenomena. The ERM method of the generic methodology is referred to as the advanced version and the ERM method of the original method is referred to as the original version.

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2.4   THE FC METHOD

The abbreviation FC stands for Fraction-comparison. The FC method is the most important innovation of the generic simulation modelling methodology. It is an elegant method that identifies the momentary "bottleneck" in a complex system at any given moment in time. Section 2.2 indicates that the determination of the maximum possible throughput of the Synthetic Fuel plant, as a function of time, primarily depends on the identification of the momentary "bottleneck" in the main-gas-cycle at any given moment in time. The identification of the momentary "bottleneck" in the Synthetic Fuel plant at any given moment in time is no arbitrary exercise due to the presence of feedback-loops, the division of the output of the Steam and Oxygen plants and the fact that the number of available modules in each of the 13 possible "bottleneck" points is a function of time. This significant challenge represents one of the major problem areas that has to be addressed by the generic methodology.

The entire FC method is based on the simple fact that the actual output throughput values at any given moment in time of the 13 possible "bottleneck" points in the main-gas-cycle are in fixed relations in terms of one another for all possible throughput options of the Synthetic Fuel plant. Section 2.2 indicates that it is a common convention to express the actual throughput of each of the smaller plants as the actual output throughput (*i.e.* the actual downstream throughput). The statement concerning the 13 possible "bottleneck" points at the beginning of this paragraph is based on the assumption that the input to output ratios of all the smaller plants are constant for all possible throughput options of the Synthetic Fuel plant.

This assumption is not necessarily true for all chemical processes but it is a valid assumption in this instance, because of the following:
a)   It can be justified by the fact that the requirement is for a decision support tool on a strategic level, not a detail level (see the explanation of strategic versus detail level in Section 1.1).
b)   The managers of plants usually strive towards the maximisation of the throughput and therefore the bandwidth of variation in the maximum possible throughput of the Synthetic Fuel plant is generally restricted to a small range (typically less than 10% of the total range of the maximum possible throughput of the plant). The small range of variation in the maximum possible throughput of the Synthetic Fuel plant justifies the assumption that the input to output ratios of the smaller plants are constant over that range.

The validity of this assumption is proved in Sections 3.6, 3.7 and 4.3 by the verification and

validation of the Arena and Simul8 simulation models that are developed in Chapter 3.

The fixed relations of the actual output throughput values of the 13 possible "bottleneck" points in the main-gas-cycle depend on the specific system description of the Synthetic Fuel plant (see Section 2.2). The fixed relations are expressed as the actual output throughput values of the 13 possible "bottleneck" points when the Synthetic Fuel plant is operating at the steady state maximum possible throughput. The term "steady state" implies that the influence of time has been removed from the system. In this instance the steady state implies that all the modules in all the smaller plants are available. The influence of the time-dependent services and failures are disregarded. At the steady state the Synthetic Fuel plant operates at the maximum possible throughput of the steady state momentary "bottleneck" (or the steady state multiple momentary "bottleneck" if the steady state momentary "bottleneck" consists of more than one of the 13 possible "bottleneck" points). The steady state actual output throughput of the momentary "bottleneck" is, of course, the steady state maximum possible output throughput of the momentary "bottleneck". The steady state actual output throughput of each of the possible "bottleneck" points that do not qualify as the momentary "bottleneck", is less than the steady state maximum possible output throughput of the possible "bottleneck" point. Therefore the fixed relations of the actual output throughput values of the 13 possible "bottleneck" points are defined by the steady state actual output throughput values of the 13 possible "bottleneck" points. The 13 steady state actual output throughput values of the 13 possible "bottleneck" points are referred to as the FC method parameter set of the Synthetic Fuel plant. The FC method parameter set depends on the specific system description of the system that is under scrutiny.   The determination of the FC method parameter set of the Synthetic Fuel plant for the system description that is provided in Section 1.2 is detailed in the next section.

If the steady state actual output throughput values of the 13 possible "bottleneck" points in the main-gas-cycle are known, the momentary "bottleneck" at any given moment in time is easily identified. The maximum possible output throughput values of the 13 possible "bottleneck" points at any given moment in time can be determined if the number of available modules in the 13 possible "bottleneck" points at any given moment in time is known. The previous section indicates how the number of available modules in each of the smaller plants is determined.

The maximum possible output throughput of each of the 13 possible "bottleneck" points, as a function of time, is the number of available modules in the possible "bottleneck" point, as a function of time, multiplied by the output capacity of a module in the possible "bottleneck" point, as a constant (see the maximum possible output throughput option of Equation 2.1).

The maximum possible output throughput of each of the 13 possible "bottleneck" points, as a function of time, divided by the steady state actual output throughput of the possible "bottleneck" point, as a constant, gives a fraction value for the possible "bottleneck" point, as a function of time.

$$Fraction_{Plt}(t) = (Throughput_{PltMaxPosOut}(t)) / (Throughput_{PltSSActOut}) \quad (number) \quad (Eq.:2.7)$$

Where:

$Fraction_{Plt}(t)$: The fraction value of the smaller plant, as a function of time.

$Throughput_{PltMaxPosOut}(t)$: The maximum possible output throughput of the smaller plant, as a function of time, in ton/h, m^3/h or nm^3/h.

$Throughput_{PltSSActOut}$: The steady state actual output throughput of the smaller plant, as a constant, in ton/h, m^3/h or nm^3/h.

Even though the discussions in this section use the term "possible "bottleneck" point" to make provision for instances where some of the smaller plants consist of groupings of different types of modules, Equations 2.7 to 2.9 use the term "smaller plant" to maintain commonality with the nomenclature of Equations 2.1 to 2.6.

The fraction value of each of the possible "bottleneck" points at any given moment in time indicates the level of compliance of the possible "bottleneck" point, in terms of the steady state actual output throughput of the possible "bottleneck" point. A fraction value of more than one indicates that the maximum possible output throughput of the possible "bottleneck" point is more than the steady state actual output throughput of the possible "bottleneck" point, a fraction value of one that it is equal to and a fraction value of less than one that it is less.

The fraction values of the 13 possible "bottleneck" points in the main-gas-cycle at any given moment in time can be compared because they are normalised by the division process. The effect of the relative sizes of the maximum possible output throughput values of the 13 possible "bottleneck" points is negated by the normalisation process that turns the relative sizes into dimensionless fraction values. The possible "bottleneck" point with the smallest fraction value is the momentary "bottleneck" (or the multiple momentary "bottleneck" if the smallest fraction value consists of the fraction values of more than one of the possible "bottleneck" points). The smallest fraction value is referred to as the Benben value in reference to the "magical" squat obelisk found in the Egyptian temples of antiquity, because this value is the "magical" value that

determines the maximum possible throughput of the Synthetic Fuel plant at any given moment in time. The Benben value is a function of time and it can only assume values that are equal to, or smaller than one.

$$Benben(t) = Smallest(Fraction_{Plt}(t)) \quad (number) \qquad (Eq.:2.8)$$

Where:

$Benben(t)$: The Benben value is the smallest fraction value, as a function of time.

The actual output throughput of the momentary "bottleneck" at any given moment in time is, of course, the maximum possible output throughput of the momentary "bottleneck". The actual output throughput of each of the possible "bottleneck" points, as a function of time, is the Benben value (*i.e.* the smallest fraction value that is also the fraction value of the momentary "bottleneck"), as a function of time, multiplied by the steady state actual output throughput of the possible "bottleneck" point, as a constant.

$$Throughput_{PltActOut}(t) = (Benben(t))(Throughput_{PltSSActOut}) \quad (ton, m^3, nm^3/h) \quad (Eq.:2.9)$$

Where:

$Throughput_{PltActOut}(t)$: The actual output throughput of the smaller plant, as a function of time, in ton/h, m^3/h or nm^3/h.

The actual output throughput of each of the smaller plants, as a function of time, is used in Equation 2.5 to determine the number of modules that is switched on in each of the smaller plants, as a function of time.

For example, consider the imaginary two-plant system that is used in Section 2.2 to illustrate the impact of the complex interrelationship characteristic on the operation of the Synthetic Fuel plant and revisit it using the FC method to determine the momentary "bottleneck" and the maximum possible throughput.

The imaginary two-plant system consists of the Gas Production and Temperature Regulation plants. The steady state maximum possible output throughput of the Gas Production plant is 1596000 nm^3/h (all 40 modules with an output capacity of 39900 nm^3/h each are available) and the steady state maximum possible output throughput of the Temperature Regulation plant is

1680000 nm^3/h (all eight modules with an output capacity of 210000 nm^3/h each are available). It is obvious that the steady state momentary "bottleneck" is the Gas Production plant. The steady state actual output throughput of the Gas Production plant is therefore equal to the steady state maximum possible output throughput of the Gas Production plant and that is 1596000 nm^3/h. The steady state actual output throughput of the Temperature Regulation plant is also 1596000 nm^3/h because the input to output ratio of the Temperature Regulation plant is one. In this instance the fixed relations of the actual output throughput values of the two possible "bottleneck" plants are easy to determine.

If, at a specific moment in time, two of the modules in the Gas Production plant are being repaired after failure and one module in the Temperature Regulation plant is being serviced, then the maximum possible output throughput of the Gas Production plant is 1516200 nm^3/h (38 of the 40 modules with an output capacity of 39900 nm^3/h each are available) and the maximum possible output throughput of the Temperature Regulation plant is 1470000 nm^3/h (seven of the eight modules with an output capacity of 210000 nm^3/h each are available).

At that specific moment in time the fraction value of the Gas Production plant is 0,950 (1516200 nm^3/h divided by 1596000 nm^3/h) and the fraction value of the Temperature Regulation plant is 0,921 (1470000 nm^3/h divided by 1596000 nm^3/h). The momentary "bottleneck" is identified by the smallest fraction value and that indicates that the Temperature Regulation plant is the momentary "bottleneck". The Benben value is the smallest fraction value and that is 0,921.

At that specific moment in time the actual output throughput of the momentary "bottleneck" (*i.e.* the Temperature Regulation plant) is, of course, the maximum possible output throughput of the Temperature Regulation plant and that is 1470000 nm^3/h or alternatively, the actual output throughput of the Temperature Regulation plant is the Benben value (*i.e.* the smallest fraction value) multiplied by the steady state actual output throughput of the Temperature Regulation plant and that is also 1470000 nm^3/h (0,921 multiplied by 1596000 nm^3/h). The actual output throughput of the Gas Production plant is the Benben value multiplied by the steady state actual output throughput of the Gas Production plant and that is also 1470000 nm^3/h (0,921 multiplied by 1596000 nm^3/h). The actual output throughput values of the Gas Production and Temperature Regulation plants are only equal because the input to output ratio of the Temperature Regulation plant is one.

Section 2.2 indicates that the maximum possible throughput of the imaginary two-plants system at that specific moment in time is defined by a "throughput vector" that comprises the actual

output throughput of the Gas Production and Temperature Regulation plants, as well as the actual input throughput of the imaginary two-plant system. This example uses the FC method to determine two components of the "throughput vector". They are the actual raw gas output throughput of the Gas Production and Temperature Regulation plants. If these components are known, the other four components (*i.e.* the actual steam, oxygen and coarse coal input throughput of the Gas Production plant and the actual gas-water output throughput of the Temperature Regulation plant) of the "throughput vector" can be determined with the input to output ratios of the two smaller plants, as shown in the example in Section 2.2.

To summarise, the example shows that the FC method calculations to identify the momentary "bottleneck" and the maximum possible throughput of the imaginary two-plant system at that specific moment in time, are described by the following:

a)   The steady state number of available modules in each of the smaller plants is (see Column 3 of Table A1):
    i)   Gas Production   : 40 modules
    ii)   Temperature Regulation   : 8 modules

b)   The steady state maximum possible output throughput of each of the smaller plants is (use Equation 2.1):
    i)   Gas Production   : 1596000 nm^3/h
    ii)   Temperature Regulation   : 1680000 nm^3/h

c)   The steady state momentary "bottleneck" of the two-plant system is:
    i)   Gas Production

d)   The steady state actual output throughput of each of the smaller plants is (*i.e.* the steady state output "throughput vector" of the two plants):
    i)   Gas Production   : 1596000 nm^3/h
    ii)   Temperature Regulation   : 1596000 nm^3/h

e)   The number of available modules in each of the smaller plants at that specific moment in time is (use Equation 2.3):
    i)   Gas Production   : 38 modules out of a possible 40 modules
    ii)   Temperature Regulation   : 7 modules out of a possible 8 modules

f)   The maximum possible output throughput of each of the smaller plants at that specific moment in time is (use Equation 2.1):
    i)   Gas Production   : 1516200 nm^3/h
    ii)   Temperature Regulation   : 1470000 nm^3/h

g)   The fraction values of the smaller plants at that specific moment in time are (use Equation 2.7):

i)   Gas Production   : 0,950
ii)   Temperature Regulation   : 0,921

h) The momentary "bottleneck" of the two-plant system at that specific moment in time is:

   i)   Temperature Regulation

i) The Benben value (*i.e.* the smallest fraction value) is (use Equation 2.8):

   i)   Benben   : 0,921

j) The actual output throughput of each of the smaller plants at that specific moment in time is (use Equation 2.9):

   i)   Gas Production   : 1470000 nm^3/h
   ii)   Temperature Regulation   : 1470000 nm^3/h

It is essential to note that the original simulation modelling method does not use the FC method to identify the momentary "bottleneck" at any given moment in time. The original method uses a FORTRAN subroutine to identify the momentary "bottleneck". The *Magister* dissertation (Albertyn, 1995:48-53) provides a description of the technique that the FORTRAN subroutine uses to identify the momentary "bottleneck". A detail description is unnecessary, but the technique that the FORTRAN subroutine uses to identify the momentary "bottleneck" can be described as a "push-product-forward-until-it-reaches-the-bottleneck" technique that operates in a sequential step by step manner. Section 1.4 indicates that the FORTRAN subroutine has a complex structure and that to a large extent it is not generic. Some changes in the system description of the Synthetic Fuel plant can easily be accommodated by the FORTRAN subroutine through the manipulation of the input files of the original simulation model. However, changes in the system description that concern the configuration, process flow or process logic cannot be accommodated easily. The FORTRAN subroutine consists of approximately two thousand lines of FORTRAN programming code and it has an extremely complex structure because of the presence of feedback-loops, the division of the output of the Oxygen and Steam plants and the fact that the number of available modules in each of the 13 possible "bottleneck" points is a function of time. For example, if feedback-loops are changed (*i.e.* moved, removed or added) or if the rules of operation of the plant are changed, it cannot be accommodated without substantial changes in the FORTRAN subroutine. The FORTRAN subroutine uses the gas-feedback-loop-fraction, the steam-division-ratio and the oxygen-division ratio to determine the momentary "bottleneck". The gas-feedback-loop-fraction, the steam-division-ratio and the oxygen-division ratio are referred to as the governing parameters of the original method and they depend on the specific system description of the system that is under scrutiny.

The FC method, by comparison, uses a parameter set that contains the fixed relations of the steady

state actual output throughput values of the possible "bottleneck" points (or smaller plants) to identify the momentary "bottleneck" at any given moment in time. The FC method always operates in exactly the same way, irrespective of any changes in the system description. Changes in the system description are incorporated into the parameter set which is unique for every specific system description. The FC method uses a matrix-based technique for the determination of the momentary "bottleneck" and the actual output throughput values of the possible "bottleneck" points and it is contained in less than one hundred lines of programming code, or the equivalent thereof if basic simulation software package building blocks are used. The FC method parameter set is referred to as the governing parameters of the generic simulation modelling methodology. It depends on the specific system description of the system that is under scrutiny. The FC method does not use the gas-feedback-loop-fraction, the steam-division-ratio and the oxygen-division ratio directly, but their influence on the operation of the Synthetic Fuel plant is incorporated into the parameter set. The determination of the parameter set is detailed in the next section.

The simplicity of the FC method contradicts the complexity of the problem if it is compared to the technique that is used in the original simulation modelling method by the FORTRAN subroutine to determine the momentary "bottleneck". The size of the FC method solution is approximately 5% of the size of the FORTRAN subroutine in the original method. The FC method successfully addresses one of the major problem areas of the generic simulation modelling methodology. It impacts positively on all the design criteria (or simulation model characteristics) of the generic methodology, namely: short development and maintenance times, user-friendliness, short simulation runtimes, compact size, robustness, accuracy and a single software application (see Section 1.5).

Summary

This section describes the FC method. It is an elegant method that identifies the momentary "bottleneck" in a complex system at any given moment in time. The cornerstone of the FC method is that the actual output throughput values of the possible "bottleneck" points (or smaller plants) at any given moment in time are in fixed relations in terms of one another for all possible throughput options of the system that is under scrutiny. The fixed relations are expressed as the steady state actual output throughput values of the possible "bottleneck" points. This is referred to as the governing parameters of the generic simulation modelling methodology or the FC method parameter set and it depends on the specific system description of the system that is under scrutiny. The momentary "bottleneck" is identified by dividing the maximum possible output

throughput of each of the possible "bottleneck" points with the steady state actual output throughput of the possible "bottleneck" point and comparing the resulting fraction values. The possible "bottleneck" point with the smallest fraction value (*i.e.* the Benben value) is the momentary "bottleneck" and that fraction value is used to determine the actual output throughput of each of the possible "bottleneck" points. The original simulation modelling method uses a FORTRAN subroutine with its own governing parameters to identify the momentary "bottleneck" at any given moment in time. The FC method successfully resolves one of the major problem areas of the generic methodology with a solution that is much simpler and smaller than the FORTRAN subroutine of the original method. The solution also has a positive impact on all the design criteria of the generic methodology.

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2.5   DETERMINATION OF THE GOVERNING PARAMETERS

Sections 2.2 and 2.4 indicate that it is necessary to determine the governing parameters of the system that is under scrutiny. The governing parameters are the gas-feedback-loop-fraction, steam-division-ratio, oxygen-division-ratio and the FC method parameter set. The first three are used by the FORTRAN subroutine of the original simulation modelling method and follows from the presence of feedback-loops and the fact that the output of the Steam and Oxygen plants is divided. The governing parameters of the FC method parameter set are necessary for the FC method to function. In the instance of the Synthetic Fuel plant the FC method parameter set consists of the steady state actual output throughput values of the 13 possible "bottleneck" points in the main-gas-cycle. The governing parameters depend on the specific system description of the system that is under scrutiny and are unique for every specific system description.

In essence the problem is to determine the value of the steady state actual output throughput of each of the 13 possible "bottleneck" points in the main-gas-cycle of the Synthetic Fuel plant. As previously explained the term "steady state" implies that the influence of time is removed from the system and therefore the influence of services and failures are ignored. At the steady state the Synthetic Fuel plant operates at the maximum possible throughput of the steady state momentary "bottleneck" or multiple momentary "bottleneck". It is not easy to identify the steady state momentary "bottleneck" because of the presence of feedback-loops and the fact that the output of the Steam and Oxygen plants is divided.

Crowe *et al.* (1971:14) discuss the complexities that follow from the problem of the recycling (*i.e.* the feedback-loops) of either heat or matter in chemical plants and suggest the following technique to handle feedback-loops:

> "*The output from a unit can only be calculated if its input is known, but for a process with recycle its input is only known once its output has been calculated. The classic chemical engineering approach has been to assume values for as many streams as are required to compute a unit and then proceed until the calculated values of stream variables agree with the assumed values. Although steps can be taken to accelerate the solution of a recycle problem, unaided convergence to solution is still widely used.*"

This haphazard technique can be much improved by using an iterative-loop technique that automatically converges to the correct solution. The iterative-loop technique is best explained by an exposition of the steps that are necessary to determine the governing parameters of the Synthetic Fuel plant.

The following steps are necessary to determine the governing parameters of the Synthetic Fuel plant:

a)   Identify all the points of evaluation (*i.e.* the possible "bottleneck" points in the system that influence the maximum possible throughput of the system that is under scrutiny), the relevant process flow (including feedback-loops and the divided output of smaller plants) and the relevant process logic or rules of operation. Characterise all the points of evaluation with their respective number of modules and their input and output capacities. The process flow that influences the maximum possible throughput of the system that is under scrutiny is referred to as the primary process flow and it is divided into the main process flow and the auxiliary process flow. It is extremely important to incorporate the process logic or rules of operation. For example, in this instance the Water Treatment plant can be excluded from the points of evaluation because it never acts as a "bottleneck" in the main-gas-cycle (see Point f) of the rules of operation in Appendix B). The process flow of fine coal from the Coal Processing plant to the Steam plant can also be excluded from the relevant process flow because the "bottleneck" capacity of the Coal Processing plant is determined by its capacity to supply coarse coal (see Point e) of the rules of operation in Appendix B). In this instance the points of evaluation are the 13 possible "bottleneck" points in the main-gas-cycle of the Synthetic Fuel plant. They are the following: Coal Processing, Steam, Gas Production, Temperature Regulation, Oxygen-A,

-B and -C, Plant(I), Plant(II)-A and -B, Plant(III), Division Process and Recycling.

b)   Identify the points of evaluation of the main process flow. The main process flow is the process flow of the coal and its derivatives in the main-gas-cycle. In this instance the points of evaluation of the main process flow are the following: Coal Processing (coarse coal), Gas Production (raw gas), Temperature Regulation (raw gas), Plant(I) (pure gas), Plant(II)-A (residue gas), Plant(II)-B (residue gas), Plant(III) (down gas), Division Process (H_2 and CH_4) and Recycling (recycled gas).

c)   Identify the points of evaluation of the auxiliary process flow. The auxiliary process flow is the process flow that supports the main process flow, namely: the steam and oxygen process flow. In this instance the points of evaluation of the auxiliary process flow are the Steam plant (steam) and the Oxygen plant (oxygen).

d)   Use an iterative loop to determine the actual output throughput values of the points of evaluation of the main process flow with a "push" principle that evaluates the points of evaluation in the sequence of the main process flow. Start with an actual output throughput that is less than the maximum possible output throughput of the first point of evaluation. For example, start off with an actual output throughput of 661,5 ton/h (50% of 14 multiplied by 94,5 ton/h) coarse coal for the actual output throughput of the Coal Processing plant. Move forward through the main process flow and determine all the actual output throughput values of the points of evaluation using their input to output ratios. The actual input throughput of Plant(II)-A is the sum of the actual output throughput of Plant(I), the Division Process plant and the Recycling plant. During the first iteration the actual output throughput of the Division Process and Recycling plants are obviously zero because they follow on Plant(II)-A in the sequence of the main process flow. During the second iteration the actual output throughput of the Division Process and Recycling plants are not zero anymore and they start to influence the actual input throughput of Plant(II)-A. When a number of iterations are completed, the actual output throughput of the Division Process and Recycling plants and hence also the actual input throughput of Plant(II)-A all stabilise on their correct respective actual throughput values. Stop the iterative loop when the actual output throughput values have stabilised. Verify that the actual output throughput values of the points of evaluation of the main process flow do not exceed their respective maximum possible output throughput values. If this happens, reduce the actual output throughput of the first point of evaluation and start the iterative loop again.

e)   Use a straightforward calculation to determine the actual output throughput values of the points of evaluation of the auxiliary process flow with a "pull" principle that evaluates the points of evaluation in the reverse sequence of the auxiliary process flow. If the auxiliary

process flow is linked, once again use the reverse sequence of the linking auxiliary process flow. In this instance the auxiliary process flow of the Steam and Oxygen plants is linked because the Steam plant supplies steam to the Oxygen plant. Using the reverse order of the linked auxiliary process flow, the oxygen will first be "pulled" from the Oxygen plant by the oxygen user plants to determine the actual output throughput of the Oxygen plant (using the input to output ratios of the relevant plants) and then the steam will be "pulled" from the Steam plant by the steam user plants to determine the actual output throughput of the Steam plant (using the input to output ratios of the relevant points of evaluation). Once again, verify that the actual output throughput values of the points of evaluation of the auxiliary process flow do not exceed their respective maximum possible output throughput values. If that happens, reduce the actual output throughput of the first point of evaluation and start the iterative loop again.

f)   Determine the gas-feedback-loop-fraction by determining the ratio of pure gas (the actual output throughput of Plant(I)) to the pure gas plus the H_2 (the actual output throughput of the Division Process plant) and the recycled gas (the actual output throughput of the Recycling plant).

g)   Determine the steam-division-ratio by determining the ratio of the portion of the actual output throughput of the Steam plant that is supplied to the Gas Production plant to the total actual output throughput of the Steam plant. Repeat the calculation for the portion of the actual output throughput of the Steam plant that is supplied to the Oxygen plant.

h)   Determine the oxygen-division-ratio by determining the ratio of the portion of the actual output throughput of the Oxygen plant that is supplied to the Gas Production plant to the total actual output throughput of the Oxygen plant. Repeat the calculation for the portion of the actual output throughput of the Oxygen plant that is supplied to the Recycling plant.

i)   Determine the FC method parameter set. The actual output throughput values of the 13 possible "bottleneck" points and therefore their fixed relations in terms of one another, are already available at this point, because the actual output throughput values of the 13 possible "bottleneck" points are in fixed relations in terms of one another for all possible throughput options of the Synthetic Fuel plant. These actual output throughput values only represent one possible throughput option of the Synthetic Fuel plant and not the steady state maximum possible throughput of the Synthetic Fuel plant. The FC method parameter set is defined by the steady state actual output throughput values of the 13 possible "bottleneck" points. The steady state actual output throughput values are determined by using an inverse variation of the FC method.

The steady state maximum possible output throughput of each of the 13 possible

"bottleneck" points, as a constant, is the steady state number of available modules in the possible "bottleneck" point, as a constant, multiplied by the output capacity of a module in the possible "bottleneck" point, as a constant (see the steady state maximum possible output throughput option of Equation 2.1).

The actual output throughput of each of the 13 possible "bottleneck" points, as a constant, divided by the steady state maximum possible output throughput of the possible "bottleneck" point, as a constant, gives a fraction value of the possible "bottleneck" point, as a constant. The fraction value represents the utilisation fraction value of the possible "bottleneck" point in terms of the steady state maximum possible output throughput of the possible "bottleneck" point.

$$Fraction_{PltUtl} = (Throughput_{PltActOut}) \, / \, (Throughput_{PltSSMaxPosOut}) \quad (number) \quad (Eq.:2.10)$$

Where:

$Fraction_{PltUtl}$: The utilisation fraction value of the smaller plant, as a constant.

$Throughput_{PltActOut}$: The actual output throughput of the smaller plant, as a constant, in ton/h, m^3/h or nm^3/h.

$Throughput_{PltSSMaxPosOut}$: The steady state maximum possible output throughput of the smaller plant, as a constant, in ton/h, m^3/h or nm^3/h.

Even though the discussions in this section use the term "possible "bottleneck" point" to make provision for instances where some of the smaller plants consist of groupings of different types of modules, Equations 2.10 to 2.12 use the term "smaller plant" to maintain commonality with the nomenclature of Equations 2.1 to 2.9.

The possible "bottleneck" point with the largest utilisation fraction value is obviously the momentary "bottleneck" of that particular throughput option of the Synthetic Fuel plant. The reciprocal (*i.e.* the inverse) of the largest utilisation fraction value gives a fraction value that can be used to determine the steady state actual output throughput values of the 13 possible "bottleneck" points. This reciprocal is referred to as the parameter set determination Benben value. The parameter set determination Benben value is a constant and can only assume values that are equal to, or larger than one. (In contrast to the regular Benben value that is a function of time and can only assume values that are equal to, or

smaller than one.)

$$Benben_{PSDet} = (1) / (Largest(Fraction_{PltUtl})) \quad (number) \qquad (Eq.:2.11)$$

Where:

$Benben_{PSDet}$:   The parameter set determination Benben value is the reciprocal of the largest utilisation fraction value, as a constant.

The steady state actual output throughput of each of the 13 possible "bottleneck" points, as a constant, is the parameter set determination Benben value, as a constant, multiplied by the actual output throughput of the possible "bottleneck" point, as a constant.

$$Throughput_{PltSSActOut} = (Benben_{PSDet})(Throughput_{PltActOut}) \quad (ton, m^3, nm^3/h) \quad (Eq.:2.12)$$

Where:

$Throughput_{PltSSActOut}$:   The steady state actual output throughput of the smaller plant, as a constant, in ton/h, m^3/h or nm^3/h.

None of the variables in Equations 2.10, 2.11 and 2.12 is a function of time, because the governing parameters depend on the specific system description of the system that is under scrutiny and they are constants for that specific system description.

The steps that are necessary to determine the governing parameters of the Synthetic Fuel plant are graphically depicted in Figure 2.2: *Governing Parameters Determination*.

The steps of the iterative-loop technique that are described in the previous paragraph (to determine the governing parameters of the Synthetic Fuel plant) can easily be adopted to determine the governing parameters of any system of the class or type of system that is considered in this document.

Governing Parameters Determination

| Identify Points of Evaluation, Process Flow and Process Logic |
| Identify Points of Evaluation in Main Process Flow |
| Identify Points of Evaluation in Auxiliary Process Flow |

Main Process Flow ("Push" Principal)

Choose Start Value for First Point of Evaluation

Use Iterative Loop to Determine Actual Output Throughput

Test for Stabilised Throughput (Yes - Continue, No - Return)

Test for Maximum Throughput (No - Continue, Yes - Return) → Reduce Start Value

Auxiliary Process Flow ("Pull" Principal)

Use Calculation to Determine Actual Output Throughput

Test for Maximum Throughput (No - Continue, Yes - Return) → Reduce Start Value

| Determine Gas-feedback-loop-fraction, Steam-division-ratio and Oxygen-division-ratio |
| Determine FC Method Parameter Set (Use Equations 2.10, 2.11 and 2.12) |

Figure 2.2: Governing Parameters Determination

A software programme that determines the governing parameters of any system of the class or type of system that is considered in this document can also be developed in a general scientific and engineering software package like FORTRAN or Visual Basic for Applications (VBA) quite easily. In this instance the governing parameters are determined with a FORTRAN software programme called PSCALC.FOR. The relevant input values are handled by an input file called PSCALC.IN. The use of an input file enhances the user-friendliness of the determination of the governing parameters and therefore it supports the user-friendliness criterion (see Point c) of the design criteria in Section 1.5) of the generic simulation modelling methodology. An example of PSCALC.IN is provided in Appendix C: *PSCALC.IN (Governing Parameters Determination Input File)*. This example contains the input values of the system description of the Synthetic Fuel plant that is detailed in Section 1.2. A scrutiny of PSCALC.IN reveals that it contains the number of modules in each of the 13 possible "bottleneck" points and the respective relevant input and output capacities of each of their modules. If the number of modules in each of the 13 possible "bottleneck" points changes, or if the input and output capacities of each of their modules change, it can easily be accommodated by the manipulation of the input file alone. However, if the process flow or process logic (*i.e.* the rules of operation) changes, then

PSCALC.FOR has to be revised and changed accordingly.

Visual Basic is a registered trademark and is usually denoted by Visual Basic®. However, for the sake of simplicity it will be written simply as Visual Basic in this document. Visual Basic is a software package from the Microsoft Corporation.

The relevant values for the governing parameters of the Synthetic Fuel plant are determined by PSCALC.FOR and written to an output file named PSCALC.OUT. The use of an output file enhances the user-friendliness of the determination of the governing parameters and therefore it supports the user-friendliness criterion (see Point c) of the design criteria in Section 1.5) of the generic simulation modelling methodology. An example of PSCALC.OUT is provided in Appendix D: *PSCALC.OUT (Governing Parameters Determination Output File)*. This example contains the output values of the system description of the Synthetic Fuel plant that is detailed in Section 1.2. A scrutiny of PSCALC.OUT reveals that the format of lines three to eighteen is identical. Each line represents one iteration of the iterative loop and gives, from left to right, the actual output throughput of Plant(I), the actual input throughput of Plant(II)-A, Plant(III), Division Process and Recycling and the actual output throughput of the Recycling plant. A scrutiny of the second values in lines three to eighteen therefore indicates that the actual input throughput of Plant(II)-A stabilises on a value of 1144532 nm³/h (for a start value of 661,5 ton/h - 50% of 14 multiplied by 94,5 ton/h - coarse coal for the actual output throughput of the Coal Processing plant). In this instance 16 iterations are necessary for the actual throughput values to stabilise. The governing parameters of the Synthetic Fuel plant, for the system description that is detailed in Section 1.2, follow in the rest of PSCALC.OUT.

The governing parameters are summarised in Table 2.1: *Governing Parameters of the Synthetic Fuel Plant*. The values of the gas-feedback-loop-fraction, steam-division-ratio and oxygen-division-ratio are given to six decimal digits which might seem excessive, but it should be remembered that the actual output throughput values of some of the smaller plants are in the order of millions and when a value of that size is multiplied by a parameter set value, it is prudent to provide the parameter set value to a few decimal digits in order to ensure high accuracy. The FC method parameter set values of Coal Processing and Steam are given to three decimal digits because these values are expressed in tons per hour, while the parameter set values of the rest of the 13 possible "bottleneck" points are given to one decimal digit because these values are expressed as normalised cubic metres per hour.

Table 2.1: Governing Parameters of the Synthetic Fuel Plant

Governing Parameter	Value
Gas-feedback-loop-fraction	
Forward (Plant(I) to Plant(II)-A)	1,576576
Backward (Plant(II)-A to Plant(I))	0,634286
Steam-division-ratio	
Gas Production	0,537612
Oxygen	0,462388
Oxygen-division-ratio	
Gas Production	0,741043
Recycling	0,258957
FC Method Parameter Set	
Coal Processing	931,253 ton/h
Steam	1762,830 ton/h
Gas Production	1460000,0 nm^3/h
Temperature Regulation	1460000,0 nm^3/h
Oxygen-A	1569088,9 nm^3/h
Oxygen-B	273062,2 nm^3/h
Oxygen-C	273062,2 nm^3/h
Plant(I)	1022000,0 nm^3/h
Plant(II)-A	515603,6 nm^3/h
Plant(II)-B	515603,6 nm^3/h
Plant(III)	444708,1 nm^3/h
Division Process	180461,2 nm^3/h
Recycling	408800,0 nm^3/h

Section 2.4 indicates that the FC method does not use the gas-feedback-loop-fraction, steam-division-ratio and oxygen-division-ratio directly, but that their influence on the operation of the Synthetic Fuel plant is incorporated into the parameter set. This is illustrated by observing the parameter set values (steady state actual output throughput) of Plant(I) and Plant(II)-A. The parameter set value (steady state actual output throughput) of Plant(I) is 1022000,0 nm^3/h and therefore the parameter set value (steady state actual output throughput) of Plant(II)-A should be 515603,4 nm^3/h (1022000,0 nm^3/h multiplied by the forward gas-feedback-loop-fraction - 1,576576 - multiplied by the output to input ratio of Plant(II)-A - 69440 nm^3/h divided by 217000

nm^3/h). The calculated steady state actual output throughput of Plant(II)-A of 515603,4 nm^3/h is sufficiently close to the parameter set value (steady state actual output throughput) of 515603,6 nm^3/h and the small difference can be attributed to the fact that the forward gas-feedback-loop-fraction is only given to six decimal digits, but the parameter set values are determined by FORTRAN with Double Precision accuracy which is 15 decimal digits.

In this example of PSCALC.OUT the actual output throughput of Plant(II)-A is 366250,2 nm^3/h (1144532 nm^3/h multiplied by the output to input ratio of Plant(II)-A - 69440 nm^3/h divided by 217000 nm^3/h) for the stabilised actual input throughput of 1144532 nm^3/h (see the second value of the 16th and last iteration in PSCALC.OUT - Appendix D). This actual output throughput only represents one possible throughput option (for a chosen start value of the actual output throughput of the Coal Processing plant) of the Synthetic Fuel plant and not the steady state maximum possible throughput of the Synthetic Fuel plant. The actual output throughput values of the FC method parameter set represent the steady state actual output throughput values of the 13 possible "bottleneck" points, which is the steady state maximum possible throughput of the Synthetic Fuel plant. The steady state actual output throughput of Plant(II)-A is 515603,6 nm^3/h.

Summary

A computerised iterative-loop technique that determines the governing parameters of the Synthetic Fuel plant is presented in this section. The governing parameters are the gas-feedback-loop-fraction, steam-division-ratio, oxygen-division-ratio and the FC method parameter set. They are not easy to determine because of the presence of feedback-loops and the fact that the output of the Steam and Oxygen plants is divided. A FORTRAN software programme called PSCALC.FOR determines the governing parameters of the Synthetic Fuel plant. The input file to the programme can easily accommodate changes to the number of modules in the 13 possible "bottleneck" points and their input and output capacities, but changes to the process flow or process logic (*i.e.* the rules of operation) will necessitate changes to the programme itself. The FC method parameter set values that are presented in Table 2.1 represent the parameter set of the Synthetic Fuel plant for the system description that is provided in Section 1.2.

* * * * *

2.6   IDENTIFICATION OF THE "BOTTLENECKS"

Section 1.1 indicates that a simulation model can be used to identify problem areas or "bottlenecks" in a system and Section 1.4 indicates that the identification of the "bottlenecks" in the Synthetic Fuel plant is one of the objectives of the original simulation model that is detailed in the *Magister* dissertation (Albertyn, 1995:3,15). The identification of the "bottleneck" smaller plants should not be confused with the identification of the momentary "bottleneck" (see Section 2.2). The identification of the "bottleneck" smaller plants are necessary to determine which of the smaller plants are "bottlenecks" over a period of time, typically a year or more, while the identification of the momentary "bottleneck" is necessary to determine the maximum possible throughput of the Synthetic Fuel plant at a specific moment in time.

The importance of the throughput as the definitive measurement of plant performance is discussed in Section 2.2. In order to devise an effective strategy to increase the throughput of a plant, it is of vital importance to accurately identify the "bottleneck" smaller plants in the plant. Goldratt and Cox (1992:294) indicate that the principal purpose of the "bottleneck" identification and elimination process is to increase the throughput of the plant.

> "*The entire bottleneck concept is not geared to decrease operating expense, it's focussed* [*sic*] *on increasing throughput.*"

Therefore it seems prudent to incorporate techniques into the generic simulation modelling methodology that accurately identify the "bottleneck" smaller plants. The original simulation modelling method uses the throughput utilisation values of the smaller plants to identify the "bottlenecks" (Albertyn, 1995:29-30). The throughput utilisation value of each of the smaller plants over a chosen period of time, as a percentage, is the mean actual output throughput of the smaller plant over the chosen period of time, as a constant, divided by the mean maximum possible output throughput of the smaller plant over the chosen period of time, as a constant, multiplied by 100.

$$Utilisation_{PltThr} = ((Throughput_{PltMnActOut}) / (Throughput_{PltMnMaxPosOut}))(100) \quad (\%) \quad (Eq.:2.13)$$

Where:

$Utilisation_{PltThr}$: The throughput utilisation value of the smaller plant over the chosen period of time, as a percentage.

$Throughput_{PltMnActOut}$: The mean actual output throughput of the smaller plant

over the chosen period of time, as a constant, in ton/h, m^3/h or nm^3/h.

$Throughput_{PltMnMaxPosOut}$: The mean maximum possible output throughput of the smaller plant over the chosen period of time, as a constant, in ton/h, m^3/h or nm^3/h.

The mean maximum possible output throughput of each of the smaller plants over the chosen period of time, as a constant, is the mean number of available modules in the smaller plant over the chosen period of time, as a constant, multiplied by the output capacity of a module in the smaller plant, as a constant. (It is a logical derivative of Equation 2.1.)

$$Throughput_{PltMnMaxPosOut} = (n_{PltModMnAvl})(Capacity_{PltModOut}) \quad (ton, m3, nm3/h) \qquad (Eq.:2.14)$$

Where:

$n_{PltModMnAvl}$: The mean number of available modules in the smaller plant over the chosen period of time, as a constant.

$Capacity_{PltModOut}$: The output capacity of a module in the smaller plant, as a constant, in ton/h, m^3/h or nm^3/h.

Equation 2.13 determines the throughput utilisation value of each of the smaller plants over the chosen period of time in terms of the mean maximum possible output throughput of the smaller plant and not in terms of the steady state maximum possible output throughput of the smaller plant. The mean maximum possible output throughput of each of the smaller plants incorporates the influence of the services and failures and therefore it is a more useful measurement to use than the steady state maximum possible output throughput of each of the smaller plants that does not take the influence of the services and failures into account.

The throughput utilisation value of each of the smaller plants over a period of time gives an indication of how hard the smaller plant worked over the period of time. A high throughput utilisation value indicates that the smaller plant had very little reserve capacity over the period of time and therefore it was highly utilised over the period of time, while a low throughput utilisation value indicates that the smaller plant had substantial reserve capacity over the period of time and therefore it was not highly utilised over the period of time. Therefore a high throughput utilisation value translates into a high importance as a "bottleneck" and a low throughput utilisation value translates into a low importance as a "bottleneck".

The generic simulation modelling introduces the following two additional "bottleneck" identification techniques:

a)　　　The time that each of the smaller plants is the "bottleneck", as a percentage.

b)　　　The possible production that is lost due to each of the smaller plants, as a percentage.

The time that each of the smaller plants is the "bottleneck" over a chosen period of time, as a percentage, is the period of time that the smaller plant is the "bottleneck" over the chosen period of time, as a constant, divided by the chosen period of time, as a constant, multiplied by 100.

$$\textit{"Bottleneck"}_{PltTim} = ((\textit{Time}_{PltBtt}) / (\textit{Time}_{Tot}))(100) \quad (\%) \qquad (Eq.:2.15)$$

Where:

$\textit{"Bottleneck"}_{PltTim}$	:	The time that the smaller plant is the "bottleneck" over the chosen period of time, as a percentage.
$\textit{Time}_{PltBtt}$	:	The period of time that the smaller plant is the "bottleneck" over the chosen period of time, as a constant, in hours.
$\textit{Time}_{Tot}$	:	The chosen period of time, as a constant, in hours.

The production that is lost due to each of the smaller plants over a chosen period of time, as a percentage, is the production that is lost due to the smaller plant over the chosen period of time, as a percentage of the steady state maximum possible production over the chosen period of time, divided by the total production that is lost over the chosen period of time, as a percentage of the steady state maximum possible production over the chosen period of time, multiplied by 100.

$$\textit{"Bottleneck"}_{PltPrdLst} = ((\textit{Production}_{PltLst}) / (\textit{Production}_{SFPltLst}))(100) \quad (\%) \quad (Eq.:2.16)$$

Where:

$\textit{"Bottleneck"}_{PltPrdLst}$	:	The production that is lost due to the smaller plant over the chosen period of time, as a percentage.
$\textit{Production}_{PltLst}$	:	The production that is lost due to the smaller plant over the chosen period of time, as a percentage of the steady state maximum possible production over the chosen period of time.
$\textit{Production}_{SFPltLst}$	:	The total production that is lost over the chosen period of time, as a percentage of the steady state maximum possible production over the chosen period of time.

Even though Equations 2.13 to 2.16 use the term "smaller plant", they are equally applicable when the term "smaller plant" is replaced with the term "possible "bottleneck" point" to make provision for instances where some of the smaller plants consist of groupings of different types of modules.

The effect of the multiple momentary "bottleneck" occurrences is taken into account when the "bottleneck" smaller plants in the Synthetic Fuel plant are identified. When a multiple momentary "bottleneck" occurs, the time that the multiple momentary "bottleneck" is the "bottleneck", is divided equally among the possible "bottleneck" points that make up the multiple momentary "bottleneck" and the same applies for the production that is lost due to the multiple momentary "bottleneck". This ensures that the two "bottleneck" identification techniques that are included in the generic simulation modelling methodology, give a true reflection of the "bottleneck" status of each of the smaller plants.

The two "bottleneck" identification techniques do not form part of the FC method, but the concepts of the FC method lend themselves to the easy implementation of the two techniques. For example, when the production that is lost due to each of the smaller plants is determined, the difference between the actual output throughput and the steady state actual output throughput (FC method parameter set value) of the momentary "bottleneck" point, is used as the point of departure for the calculation.

The second rule of operation in Appendix B indicates that only the smaller plants that form part of the main-gas-cycle can act as "bottlenecks" that influence the rate of production or throughput of the Synthetic Fuel plant. It is obvious that the two "bottleneck" identification techniques that are detailed in the previous paragraphs are aimed at identifying the "bottlenecks" in the main-gas-cycle of the Synthetic Fuel plant. The two techniques can be used to prioritise the 13 possible "bottleneck" points. The 13 possible "bottleneck" points are referred to as the primary "bottlenecks" and they are the following: Coal Processing, Steam, Gas Production, Temperature Regulation, Oxygen-A, -B and -C, Plant(I), Plant(II)-A and -B, Plant(III), Division Process and Recycling. They are referred to as primary "bottlenecks" because the throughput of the Synthetic Fuel plant at any given moment in time is adjusted to coincide with the maximum possible throughput of the momentary "bottleneck" at that specific moment in time.

The fourth rule of operation in Appendix B indicates that if Plant(IV), Plant(V) and Sub(I) to Sub(VI) do not have the capacity to process the throughput at their respective positions in the Synthetic Fuel plant, then the portions of the throughput that cannot be processed are flared. It

is obvious that these smaller plants act as "bottlenecks" if it is necessary to flare portions of their throughput at any of their respective positions in the Synthetic Fuel plant. These smaller plants are referred to as secondary "bottlenecks" because they do not influence the main-gas-cycle but flare the portions of the throughput that cannot be accommodated at their respective positions. The portions of the throughput that are flared at their respective positions are determined by the generic simulation modelling methodology to ensure that the secondary "bottlenecks"can be identified, prioritised and managed accordingly.

Both the primary and secondary "bottlenecks" are undesirable from the perspectives of increased efficiency and the realisation of profit (see Section 1.3). Therefore they need to be managed with circumspection. Furthermore, the secondary "bottlenecks" are also undesirable as seen from the environmental perspective.

Summary

This section indicates that a simulation model can be used to identify the problem areas or "bottlenecks" in a system. The original simulation modelling method uses the throughput utilisation values of the 13 possible "bottleneck" points to identify the "bottlenecks" in the main-gas-cycle of the Synthetic Fuel plant. They are referred to as the primary "bottlenecks". The generic simulation modelling methodology introduces two additional techniques to identify the primary "bottlenecks". The first technique determines the time that each of the 13 possible "bottleneck" points is the "bottleneck" and the second technique determines the production that is lost due to each of the possible "bottleneck" points. If portions of the throughput are flared at Plant(IV), Plant(V) and Sub(I) to Sub(VI) it is indicative of the existence of a secondary "bottleneck" and they also have to be identified and managed.

* * * * *

2.7   STRUCTURE OF THE GENERIC METHODOLOGY

From the discussions in the previous sections of this chapter, the structure of the generic simulation modelling methodology can now be conceptualised. This section indicates how the different methods and techniques that are developed in the previous sections of this chapter are integrated to render the structure of the generic methodology. A simulation model mimics the behaviour of a system and in this instance the behaviour of a stochastic continuous system is mimicked. It is of cardinal importance for any simulation modelling methodology to be based on the characteristics of the class or type of system that is under scrutiny.

In Section 2.1 the characteristics of the Synthetic Fuel plant are identified and in the following sections methods and techniques are identified and developed to effectively accommodate the characteristics in a simulation model. Table 2.2: *System Characteristics and Appropriate Methods and Techniques* gives an overview of the characteristics of the Synthetic Fuel plant and the corresponding "toolbox" of appropriate methods and techniques that are detailed in this chapter to solve the problems that are posed by the characteristics.

The two "bottleneck" identification techniques are shown in Table 2.2 as in relation to the complex interrelationship characteristic because even though the two techniques do not form part of the FC method, they both use the FC method concepts as the point of departure for their respective calculations.

The key objective of the generic simulation modelling methodology is to provide a simulation modelling methodology that can be used to construct simulation models of stochastic continuous systems (*i.e.* systems that are similar to the Synthetic Fuel plant) effectively. The first rule of operation in Appendix B states that the Synthetic Fuel plant always strives to maintain the maximum possible rate of production or throughput and Section 2.2 indicates that the throughput of a plant is considered to be the definitive measurement of plant performance. The two statements in the previous sentence clearly highlight the pivotal role that the determination of the maximum possible throughput, as a function of time, plays in a simulation model of the Synthetic Fuel plant. Equation 2.4 (repeated here for the sake of the continuity of the argument) indicates that the maximum possible throughput of the Synthetic Fuel plant is a function of the maximum possible throughput of each of the smaller plants.

Table 2.2: System Characteristics and Appropriate Methods and Techniques

System Characteristic	Method or Technique	Purpose
Continuous Process	Variables Technique (Section 2.2)	Uses variables to represent process flow, like the output throughput values of the smaller plants, as real numbers.
	Fixed Time Interval Technique (Section 2.2)	Uses a fixed time interval to advance the simulation model in time.
Discrete Events (Services and Failures)	ERM Method (Section 2.3)	Determines the state of the modules in the system that is under scrutiny at any given moment in time.
Complex Interrelationships	FC Method (Section 2.4)	Identifies the momentary "bottleneck" in a complex system at any given moment in time.
	Iterative-loop Technique (Section 2.5)	Determines the governing parameters (gas-feedback-loop-fraction, steam-division-ratio, oxygen-division-ratio and FC method parameter set).
	Time "Bottleneck" Identification Technique (Section 2.6)	Identifies primary "bottleneck" smaller plants based on the time that the smaller plant is the "bottleneck".
	Production Lost "Bottleneck" Identification Technique (Section 2.6)	Identifies primary "bottleneck" smaller plants based on the production that is lost due to the smaller plant.

$$Throughput_{SFPltMaxPos}(t) = f(Throughput_{PltMaxPos}(t) \text{ for No.1 ... } n_{Plt}) \quad (ton, m^3, nm^3/h) \ (Eq.:2.4rep)$$

Where:

$Throughput_{SFPltMaxPos}(t)$	:	The maximum possible throughput of the Synthetic Fuel plant, as a function of time, in ton/h, m^3/h or nm^3/h.
$Throughput_{PltMaxPos}(t)$	:	The maximum possible throughput of the smaller plant, as a function of time, in ton/h, m^3/h or nm^3/h.
n_{Plt}	:	The number of smaller plants, as a constant.

It is difficult to determine the maximum possible throughput of the Synthetic Fuel plant, as a function of time, because of the presence of feedback-loops, the division of the output of the Steam and Oxygen plants and the fact that the number of available modules in each of the smaller plants is a function of time.

A scrutiny of Table 2.2 indicates that the "toolbox" of methods and techniques provides solutions to all the problems that are posed in the previous paragraph. The ERM method determines the

number of available modules in each of the smaller plants at any given moment in time and then the FC method identifies the momentary "bottleneck" and determines the maximum possible throughput of the Synthetic Fuel plant at that specific moment in time. The FC method uses a parameter set that is determined with the iterative-loop technique. The FC method parameter set is unique for every specific system description and incorporates the influence of the gas-feedback-loop-fraction, steam-division-ratio and oxygen-division-ratio on the operation of the Synthetic Fuel plant.

The maximum possible throughput of the Synthetic Fuel plant at any given moment in time is only influenced by the 13 possible "bottleneck" points in the main-gas-cycle and therefore only the 13 possible "bottleneck" points are included in the FC method. This implies that the actual output throughput values of only the 13 possible "bottleneck" points at that specific moment in time are provided by the FC method. The 13 possible "bottleneck" points belong to the 10 smaller plants in the main-gas-cycle and these plants are referred to as the "heart" of the Synthetic Fuel plant. The smaller plants that do not form part of the main-gas-cycle are referred to as the peripheral plants.

The maximum possible throughput of the Synthetic Fuel plant at any given moment in time is defined by a "throughput vector" that consists of the actual input throughput of the Synthetic Fuel plant and the actual output throughput of each of the smaller plants (see the convention that is detailed in Section 2.2). The FC method only renders the actual output throughput values of the 13 possible "bottleneck" points at that specific moment in time and therefore the other outstanding throughput values need to be determined. The outstanding throughput values (*i.e.* the actual input throughput of the Synthetic Fuel plant and the actual output throughput of all the peripheral plants) of the "throughput vector" at that specific moment in time are easy to determine because there are no feedback-loops or the division of output to complicate the calculations. There is one complication though, the modules of some of the peripheral plants are subject to services and failures. Fortunately the ERM method also provides the number of available modules at any given moment in time in each of the peripheral plants that are subject to services and failures.

The operation of the Synthetic Fuel plant can be likened to a huge transfer function that turns coal and water into chemical products. If the main-gas-cycle is viewed as the primary transfer function, then the ERM method determines the status of the time-dependent elements (*i.e.* the modules) of the transfer function and the FC method identifies the momentary "bottleneck" in the primary transfer function and hence determines the maximum possible throughput of the primary

transfer function. The FC method actually optimises the primary transfer function in terms of possible throughput. The FC method parameter set values represent the governing parameters of the elements of the primary transfer function that determine the maximum possible throughput of the primary transfer function. If the configuration of the transfer function changes, it means that the governing parameters must change to reflect these changes. The peripheral plants can be viewed as constituting the secondary transfer functions of the Synthetic Fuel plant that turn the throughput from the main-gas-loop into the final products of the Synthetic Fuel plant. The secondary transfer functions are straightforward, because there are no feedback-loops or the division of output in the secondary transfer functions and the ERM method determines the status of the time-dependent elements.

To summarise, Equation 2.4 represents the 13 possible "bottleneck"points in the "heart"of the Synthetic Fuel plant and it is solved over time for the maximum possible throughput of the Synthetic Fuel plant with the help of the ERM method (which determines the state of the time-dependent elements) and the FC method (which identifies the momentary "bottleneck" and determines the maximum possible throughput). The actual input throughput of the Synthetic Fuel plant and the actual output throughput of the peripheral plants are determined over time with straightforward calculations and the help of the ERM method.

If the maximum possible throughput at any given moment in time is known, the corresponding number of modules that is switched on or off in each of the smaller plants at that specific moment in time, can easily be determined with Equations 2.5 and 2.6. The input that is needed to identify the "bottleneck" smaller plants can also be determined at that specific moment in time and after the completion of the simulation run it is used to identify the "bottleneck" smaller plants with Equations 2.15 and 2.16.

The generic simulation modelling methodology, as presented in this instance, assumes that the system that is under scrutiny strives to maintain the maximum possible rate of production or throughput, but the generic methodology can easily be adapted to represent a system that strives to maintain a given constant rate of production or throughput. An example of such a system is a power plant that supplies electricity into a national network or grid. In such an instance the demand for electricity from the power plant is relatively constant (depending on seasonal variation) and the maximum possible rate of production is reserved for emergencies only.

A scrutiny of the "toolbox " of seven methods and techniques that is presented in Table 2.2 indicates that they are applicable at different stages during the completion of a simulation run.

The majority of the methods and techniques are used continuously by the simulation model during the simulation run. The notable exception to this rule is the iterative-loop technique that determines the governing parameters of the system that is under scrutiny before the start of the simulation run. This implies that the iterative-loop technique does not need to be an integral part of the simulation model. Therefore the generic simulation modelling methodology consists of two separate parts, namely: an iterative-loop technique part and a simulation model part. The iterative-loop technique part accommodates the specific system description of the system that is under scrutiny and the simulation model part contains the six methods and techniques that accommodate the time dependent behaviour of the system that is under scrutiny. This concept is graphically depicted in Figure 2.3: *Generic Simulation Modelling Methodology Parts, Methods and Techniques*.
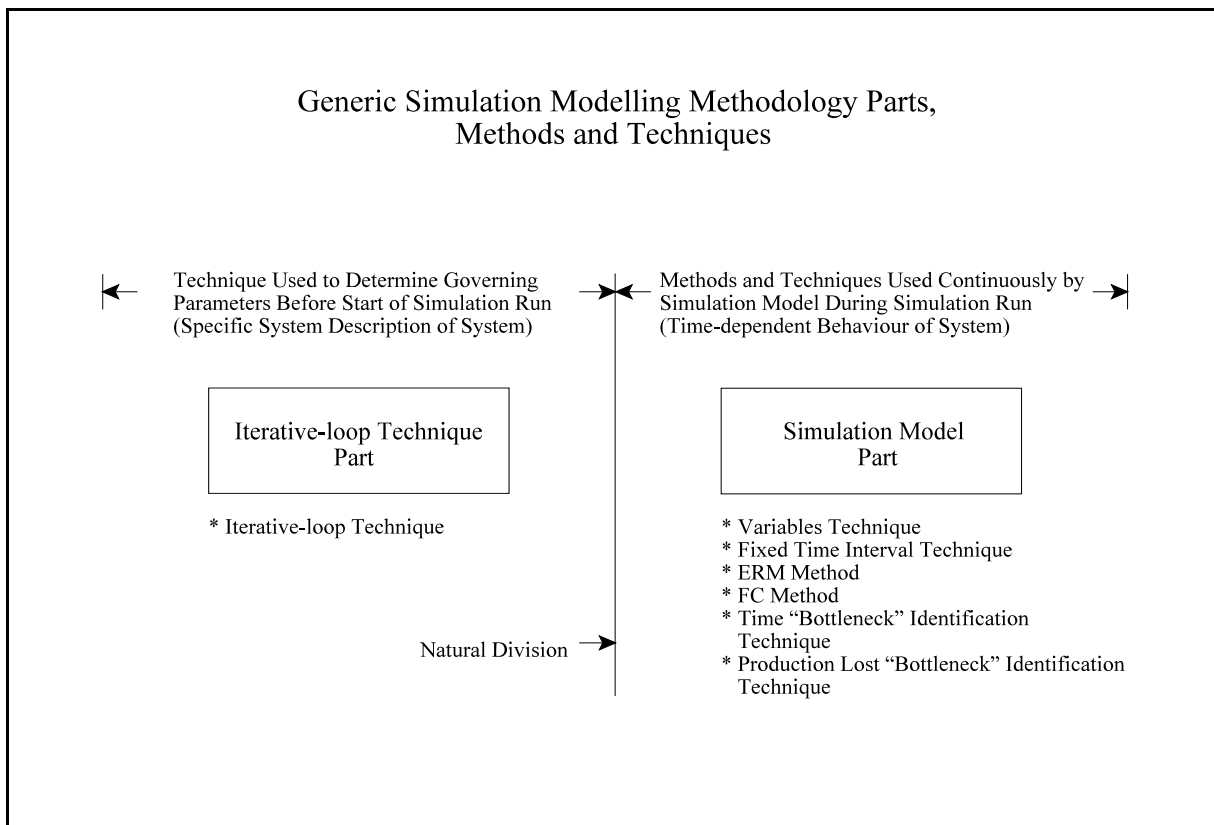
**Figure 2.3: Generic Simulation Modelling Methodology Parts,
Methods and Techniques**

The advantages of this natural division of the generic simulation modelling methodology are the following:

a)   It supports the compact simulation model size design criterion of the generic simulation

modelling methodology (see Point e) of the design criteria in Section 1.5), because a general scientific and engineering software package like FORTRAN can be used for the cumbersome but straightforward calculations that are necessary for the iterative-loop technique to determine the governing parameters (see Section 2.5). If a general scientific and engineering software package like FORTRAN is used, the resulting programme that consists of lines of programming code is appreciably smaller than if basic simulation software package building blocks are used to achieve the same outcome in a simulation software package.

b)   It supports the short simulation runtime criterion of the generic simulation modelling methodology (see Point d) of the design criteria in Section 1.5), because a general scientific and engineering software package like FORTRAN is ideally suited to the "number crunching" that is required when the iterative-loop technique determines the governing parameters.   Simulation software packages are not partial to "number crunching" and a time penalty is incurred when "number crunching" is performed by a simulation software package.

Section 2.2 indicates that the continuous processes of the Synthetic Fuel plant can be presented by variables in a simulation model and Section 2.3 indicates that the behaviour of the modules can be represented by the ERM method in a simulation model. The substantial differences between the representation of the continuous processes and the representation of the behaviour of the modules lead to a natural division of the simulation model into two parts. One part deals with the continuous processes while the other deals with the behaviour of the modules. The part of the simulation model that deals with the continuous processes is referred to as the "virtual" part of the simulation model because the actual processes are represented by variables and logical equations (*i.e.* the process flow and process logic or rules of operation are represented by variables and logical equations). The "virtual" part of the simulation model also accommodates all the other concepts that are necessary for the simulation model to function. The part that deals with the behaviour of the modules is referred to as the "real" part of the simulation model because the actual modules are represented by standard simulation software package building blocks. This concept is already introduced in Section 2.3 but it is repeated here for the sake of the continuity of the argument.

The concepts that are accommodated by the "virtual" part of the simulation model are the following:
a)   The variables technique that uses variables to represent process flow.
b)   The fixed time interval technique that uses a fixed time interval to advance the simulation

model in time.

c)   The control of the ERM method that determines the number of available modules in each of the smaller plants at any given moment in time.

d)   The FC method that identifies the momentary "bottleneck" in a complex system at any given moment in time.

e)   The determination of the maximum possible throughput (*i.e.* the "throughput vector") at any given moment in time.

f)   The determination of the number of modules that is switched on or off at any given moment in time.

g)   The determination of the input that is needed to identify the primary and secondary "bottleneck" smaller plants at any given moment in time.

h)   The determination of the variables that keep record of the functioning of the simulation model at any given moment in time (*i.e.* the number of evaluations completed, the number of services completed, the number of failures repaired, *etc.*).

i)   The determination of all the mean values of the relevant variables at the end of the simulation run (*i.e.* the mean values of the "throughput vector", the mean values of the number of available modules, the mean values of the number of modules that is switched on or off, *etc.*).

j)   The identification of the primary and secondary "bottleneck" smaller plants at the end of the simulation run. (The primary "bottleneck" smaller plants are identified with the time and production lost "bottleneck" identification techniques.)

Section 2.3 indicates that four of the different types of smaller plants can be represented in the "real" part of the simulation model by four different high-level building blocks. The four different high-level building blocks are the following: a smaller plant with a multiple service cycle and failures of the modules, a smaller plant with a service cycle and failures of the modules, a smaller plant with a service cycle of the modules and a smaller plant with failures of the modules. The concepts of the "virtual" part of the simulation model that are discussed in the previous paragraph can be grouped together in one high-level building block that represents the "virtual" part of the simulation model. This high-level building block is referred to as the logic engine.

To summarise, the simulation model consists of a "virtual" part that deals with the continuous processes and all the other concepts that are necessary for the simulation model to function and a "real" part that deals with the behaviour of the modules. The "virtual" part of the simulation model is represented by the logic engine high-level building block and the "real" part is

represented by the four different high-level building blocks of the ERM method.

From the discussions in the previous paragraphs it is clear that a simulation model of the Synthetic Fuel plant, or any other stochastic continuous system, can easily be constructed with the five high-level building blocks. The basic structure of the simulation model is graphically depicted in Figure 2.4: *Simulation Model Parts and Building Blocks*.
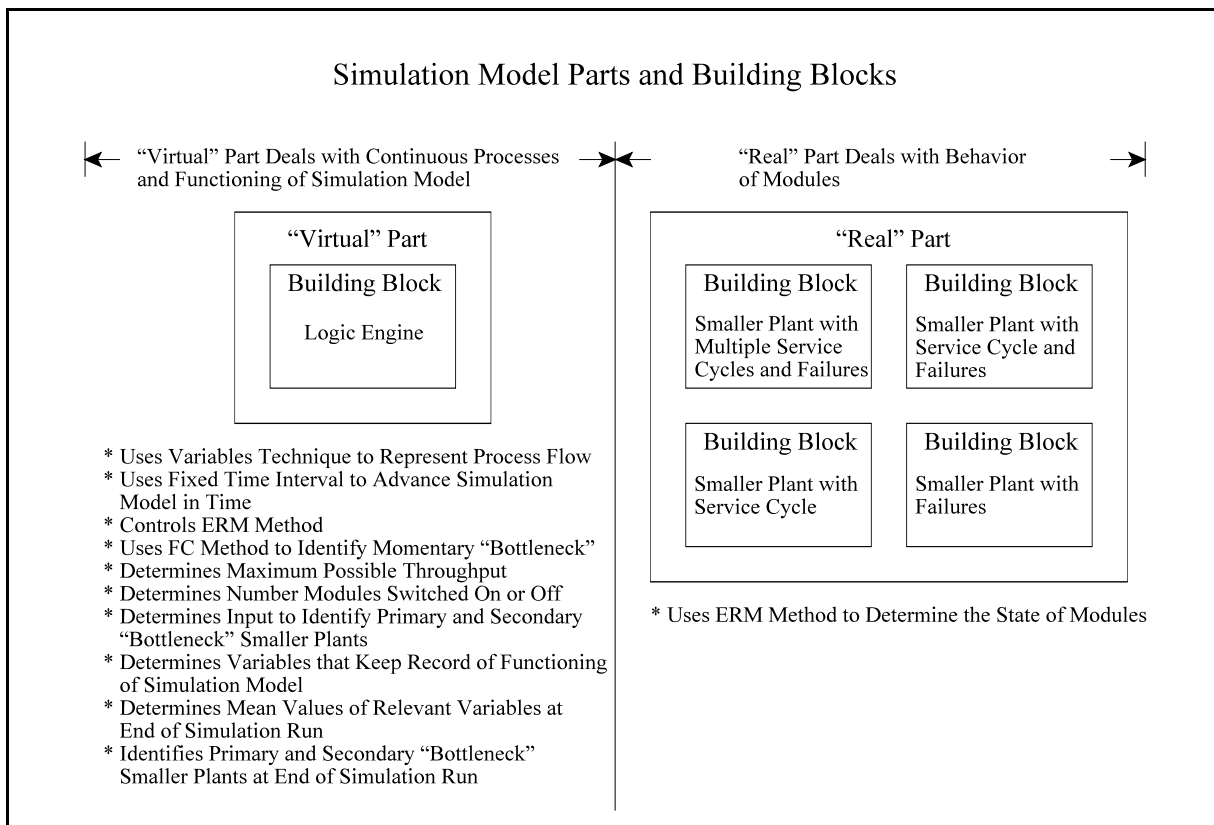
Figure 2.4: Simulation Model Parts and Building Blocks

Section 2.3 indicates that the building blocks that represent the smaller plants in the "real" part of the simulation model are populated with the corresponding correct number of entities that represent the modules and appropriate values are also assigned to the attributes of each of the entities (*i.e.* the modules) before the start of the simulation run. This process can either be handled centrally by the logic engine or every one of the building blocks that represent the smaller plants can populate itself, depending on the simulation software package that is used and the personal preference of the modeller. For example, in the Arena simulation model that is developed in Chapter 3 the smaller plants are populated with entities by the logic engine (*i.e.* centralised populating), but in the Simul8 simulation model that is developed in Chapter 3 each

of the building blocks that represents the smaller plants is populated by itself (*i.e.* decentralised populating).

During the simulation run the logic engine controls the functioning of the simulation model and uses the fixed time interval technique to advance the simulation model in time. Every time interval an evaluation takes place and the logic engine completes the necessary tasks of the concepts of the "virtual" part of the simulation model that are discussed above in Points c) to h). After the completion of the simulation run the logic engine completes the necessary tasks of the concepts of the "virtual" part of the simulation model that are discussed above in Points i) and j).

One of the major benefits of using the variables technique to represent the process flow is that the simulation run can start immediately after the building blocks of the smaller plants have been populated with modules, no warm-up period is necessary to wait for the simulation model to "fill up" with entities before the actual simulation run can start. A simulation model of a simulation modelling method that uses entities to represent the "commodities" that move or flow through the system, is usually empty when a simulation run starts and therefore a warm-up period is necessary for the simulation model to "fill up" with entities. The exceptions, of course, are when the actual start-up of a system is modelled (*i.e.* the commissioning of a new plant), or if the system starts every cycle empty (*i.e.* the post office opens at nine o'clock in the morning). Usually only the actual part of the simulation run is of importance and Taha (1987:714) indicates that the observations gathered during the warm-up period of the simulation run have to be discarded in such an instance.

> "*We have seen ... that early output of the simulation experiment is **unstable** (transient state) and that **stability** (steady state) is usually reached after the simulation run becomes "sufficiently" long. As a result, care must be taken that observations are not gathered during the early stages of the simulation run, because the information obtained is subject to large variation and hence may not be representative of the true behaviour of the system.*" [Bold typeface added for emphasis]

Taha uses the terms "transient" and "steady state" in a slightly different context than the way that the two terms are used in this document. Taha uses the two terms on the "macro" level (*i.e.* the level of the behaviour of the simulation model) to distinguish between the "fill up" period of the simulation model and the actual simulation run. In this document the term "transient" is used on

the "micro" level (*i.e.* the level of the behaviour of the system that is modelled) to indicate the behaviour of the system if it changes form one state to another during the simulation run and the term "steady state" is also used on the "micro" level to indicate that the influence of time has been removed from the system that is modelled. In this document the terms "unstable" and "stable" are preferred to distinguish between the warm-up period and the actual simulation run.

Pegden *et al.* (1995:180) indicate that, while there are some "rules" to determine the length of the warm-up period, they are subject to constraints and therefore restricted in their application.

> "*..., but experience suggests that a rule's performance depends largely on the nature of the simulation response. Consequently, these rules are generally **not used** in simulation applications.*" [Bold typeface added for emphasis]

Pegden *et al.* (1995:180) also propose a practical method to identify the truncation point (*i.e.* to determine the length of the warm-up period).

> "*The simplest, most practical, and probably best method for selecting the truncation point is visual determination, i.e., selecting the point from a plot of the simulation response over time.*"

The *Simul8®: Manual and Simulation Guide* (1999:35-38) suggest a short simulation run, visual inspection of the results (*i.e.* the data and the graphs) and a judgement call to determine the warm-up period. Harrell and Tumay (1999:129-130) and Kelton *et al.* (1998:219-223) also advocate the use of this technique. Two of the three aforementioned references also suggest adding a 20% to 30% safety factor to the observed warm-up period. It seems time-consuming and also risky from an accuracy perspective to use this technique.

The advantages of the fact that the variables technique needs no warm-up period are the following:
a)   It supports the short simulation runtime criterion of the generic simulation modelling methodology (see Point d) of the design criteria in Section 1.5) because no computer time is wasted on a warm-up period.
b)   It supports the accurate modelling ability criterion of the generic simulation modelling methodology (see Point g) of the design criteria in Section 1.5) because the risk of including data from the "unstable" warm-up period into the results is negated.

Another small improvement of the generic simulation modelling methodology over the original simulation modelling method is that the generic methodology immediately starts the simulation run, whereas the original method uses the first time interval to set up the simulation model and only then starts the simulation run. This does not have a major impact because the part of the behaviour of the system that is lost over the first time interval by the original method constitutes only a very small fraction of the total behaviour of the system over the period of time that is usually modelled in a simulation run. However, it is still important to work as accurately as possible and therefore the generic methodology eliminates this small aberration that exists in the original method. This small change obviously also supports the accurate modelling ability criterion of the generic methodology (see Point g) of the design criteria in Section 1.5).

Summary

This section conceptualises the structure of the generic simulation modelling methodology. The seven methods and techniques that are developed in the previous sections to solve the problems that are posed by the characteristics of stochastic continuous systems are integrated to form the generic methodology. There is a natural division of the generic methodology into two parts, namely: an iterative-loop technique part that determines the governing parameters before the start of a simulation run and a simulation model part that uses the other six methods and techniques continuously during the simulation run. The simulation model itself consists of a "virtual" part that deals with the continuous processes and the functioning of the simulation model (*i.e.* the logic engine high-level building block) and a "real" part that deals with the behaviour of the modules (*i.e.* the four different high-level building blocks of the ERM method). The five high-level building blocks can facilitate the construction of simulation models of stochastic continuous systems. The use of the variables technique ensures that simulation models that are developed with the generic methodology do not need a warm-up period and therefore it supports the short simulation runtimes and accurate modelling ability criteria.

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CHAPTER 3

MODEL DEVELOPMENT

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INTRODUCTION

This chapter demonstrates and validates the generic simulation modelling methodology that is conceptualised in Chapter 2 by applying the generic methodology to develop two simulation models of the Synthetic Fuel plant in two different simulation software packages.

The first section investigates three simulation software packages that were considered during this research as candidates for the development of a simulation model of the Synthetic Fuel plant. The three candidates are Arena, Simul8 and Extend. Unfortunately, Extend was excluded from the list of candidates because it was impossible to determine its compatibility with the specific requirements. In the end it was decided to develop simulation models of the Synthetic Fuel plant in Arena and Simul8.

In the second section a simulation model breakdown is derived from the system description of the Synthetic Fuel plant. The simulation model breakdown provides guidelines for the development of the Arena and Simul8 simulation models. The 28 points of evaluation of the Synthetic Fuel plant are identified and they are divided into three types, namely: primary, secondary and tertiary points of evaluation. The 21 primary and secondary points of evaluation are represented in the "real" part of the simulation model by 21 instances of the four different high-level building blocks of the ERM method, while the seven tertiary points of evaluation are accommodated in the "virtual" part of the simulation model by the logic engine high-level building block. The points of evaluation are also classified as either primary or secondary "bottlenecks".

The third section describes the development of two identical simulation models of the Synthetic Fuel plant in Arena and Simul8. The structure of the simulation models is based on the simulation model breakdown of the Synthetic Fuel plant that is discussed in the previous paragraph. In each of the simulation software packages the five high-level building blocks of the generic simulation modelling methodology are developed and then used to construct the simulation models. The primary and secondary points of evaluation are accommodated by the four different high-level building blocks of the ERM method. The tertiary points of evaluation

and all the concepts that are necessary for the simulation model to function are accommodated by the logic engine high-level building block. The simulation models use input and output files and spreadsheet variables as input and output mechanisms. They also use two hierarchical levels to represent the Synthetic Fuel plant.

In the fourth section an appropriate iteration time interval for the simulation models of the Synthetic Fuel plant is determined. The results from a series of simulation runs (conducted with the Simul8 simulation model) are interpreted and the assumption that a one hour iteration time interval should be appropriate is substantiated. It is also indicated that the simulation runtime of the Simul8 simulation model with an iteration time interval of one hour represents a twentyfold improvement over the simulation runtime of the original simulation model with an iteration time interval of one hour.

Two possible techniques to determine minimum sufficient sample size are discussed in the fifth section and one of the techniques is identified as the appropriate one to use in this instance. A FORTRAN software programme that determines the minimum sufficient sample size is detailed. The name of the programme is N.FOR and an example of its use is provided.

The sixth section discusses and demonstrates some of the verification and validation concepts of the Arena and Simul8 simulation models with examples. The first example demonstrates the verification of the simulation models and indicates that the simulation models operate as intended, insofar as the number of failures created is concerned. In the second example the simulation models are validated by comparing the mean output throughput values of the Gas Production plant of the simulation models with the mean output throughput value of the Gas Production plant during the 1993 production year. The results indicate deviations of less than 1% from the 1993 production year and therefore the simulation models can be accepted as valid representations of the Synthetic Fuel plant. A sensitivity analysis confirms that the simulation models are not overly sensitive to variation in the start times of the service cycles. Confidence intervals for the results are also determined.

The Arena and Simul8 simulation models are enhanced by the inclusion of an additional evaluation method option in the seventh section. With this enhancement the simulation models now make provision for two different evaluation method options, namely: an iteration time interval (ITI) evaluation method option and an event-driven (ED) evaluation method option. The ED evaluation method option evaluates the simulation models only when an event takes place and not every time interval like the ITI evaluation method option. The concept of event density is

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introduced and it is indicated that the event density value of a simulation model can be used to determine which of the evaluation method options is appropriate for that specific application. Simulation runs are completed with the ED evaluation method option simulation models and the simulation models are validated by comparing the mean output throughput values of the Gas Production plant of the simulation models with the mean output throughput value of the Gas Production plant during the 1993 production year. The results indicate deviations of less than 1% from the 1993 production year and therefore the ED evaluation method option simulation models can be accepted as valid representations of the Synthetic Fuel plant. The evaluation methods are also compared and their strengths and weaknesses are discussed.

In the last section the ED evaluation method option Arena and Simul8 simulation models and the Arena and Simul8 simulation software packages are compared. An important result that follows from the simulation model comparison is that the simulation runtimes of the ED evaluation method option simulation models represent an approximate fortyfold improvement over the simulation runtime of the original simulation model. The strengths and weaknesses of the two simulation software packages are also discussed.

* * * * *

3.1   INVESTIGATION OF THE SIMULATION SOFTWARE PACKAGES

The generic simulation modelling methodology is conceptualised in Chapter 2 and in the last section the structure of the generic methodology is developed. It is indicated that the generic methodology is divided into two separate parts. The first is the iterative-loop technique part that determines the governing parameters before the start of a simulation run and the second is the simulation model part that uses six methods and techniques continuously during the simulation run. The six methods and techniques are encapsulated in five high-level building blocks that can be used to construct simulation models of stochastic continuous systems.

In Section 2.5 the iterative-loop technique is detailed and a FORTRAN software programme called PSCALC.FOR is used to determine the governing parameters of the Synthetic Fuel plant for the system description that is provided in Section 1.2. This chapter is primarily concerned with the simulation model part of the generic simulation modelling methodology.

The first obvious step is to identify candidates from the available simulation software packages that could be used to develop a simulation model of the Synthetic Fuel plant. A superficial perusal of the possible candidates revealed three simulation software packages worthy of in-depth scrutiny.

The three candidates are the following:
a)   Arena
b)   Simul8
c)   Extend

Extend is a trademark and is usually denoted by Extend™. However, for the sake of simplicity it will be written simply as Extend in this document. Extend is a simulation software package from Imagine That, Inc.

The inclusion of Arena in the shortlist follows logically from the fact that the final 1996 simulation model (that included the whole Sasol Synfuels complex) was upgraded to one of the first versions of Arena (see Section 1.4). Therefore it seems a logical point of departure to use Arena for the development of a simulation model that demonstrates the use of the generic simulation modelling methodology. An important factor is also that the Arena Standard Edition simulation software package was available for this research. Arena is an accomplished and widely accepted simulation software package.

Simul8 was introduced as a contender when the Simul8 Standard simulation software package was made available for the research. Simul8 is a relative "newcomer" to the simulation software package fraternity and it was concluded that it would be a worthwhile exercise to determine its prowess with this challenging application.

Extend was perceived to be a possible contender because of its claims in terms of continuous modelling ability. A demonstrator version of Extend was procured and evaluated. Unfortunately it was very difficult to adequately fathom the capabilities of Extend because the demonstrator version is severely restricted. For example, a modeller is only allowed to build simulation models that contain up to 25 blocks and the save function has been disabled. These restrictions made it virtually impossible to determine without doubt whether the simulation model part of the generic simulation modelling methodology could be developed in Extend and consequently Extend was disqualified as a contender after the in-depth scrutiny of the simulation software packages. It is worthwhile to note that Imagine That, Inc. responded very quickly (less than one month for the package to arrive by post) to the request for the demonstrator version of Extend and that the Extend user's guide is exemplary among its peers.

It was therefore decided to use the high-level building blocks of the simulation model part of the generic simulation modelling methodology to develop two identical simulation models of the Synthetic Fuel plant in two different simulation software packages, namely: Arena and Simul8.

Two simulation models were built to illustrate clearly that the generic simulation modelling methodology is not based on, or restricted to, a specific simulation software package.

Summary

This section discusses three different simulation software packages that were considered to develop a simulation model of the Synthetic Fuel plant. The three candidates are the following: Arena, Simul8 and Extend. Extend was disqualified from the list of candidates because it was impossible to determine its compatibility with the requirements from the demonstrator version. It was finally decided to develop simulation models of the Synthetic Fuel plant in Arena and Simul8.

* * * * *

3.2   SIMULATION MODEL BREAKDOWN

Before a simulation model can be constructed, it is necessary to develop a simulation model breakdown of the system that is being modelled. From the system description of the Synthetic Fuel plant that is provided in Section 1.2 and Table A1 it is apparent that the total plant consists of 20 smaller plants, or alternatively, 21 smaller plants if the extra oxygen "train" is considered as a separate smaller plant. Some of the smaller plants consist of groupings of different types of modules, namely: the Oxygen plant (three types of modules), the Oxygen Extra plant (three types of modules), Plant(II) (two types of modules) and Plant(IV) (three types of modules). That implies that there are actually 28 points of evaluation in the Synthetic Fuel plant. The points of evaluation can be ranked into three levels of evaluation in terms of their importance.

The three levels of importance (or types of evaluation points) are the following:
a)   Primary points of evaluation.
b)   Secondary points of evaluation.
c)   Tertiary points of evaluation.

The primary points of evaluation are the points of evaluation in the smaller plants that influence the throughput of the Synthetic Fuel plant directly and that are also subject to services and failures of their modules. The second rule of operation in Appendix B states that the smaller plants that form part of the main-gas-cycle influence the throughput of the Synthetic Fuel plant. There are 10 smaller plants and 13 points of evaluation in the main-gas-cycle. These smaller plants are sometimes referred to as the "heart" of the Synthetic Fuel plant. The 13 primary points of evaluation are Coal Processing, Steam, Gas Production, Temperature Regulation, Oxygen-A, -B and -C, Plant(I), Plant(II)-A and -B, Plant(III), Division Process and Recycling. These 13 primary points of evaluation can act as primary "bottlenecks" and the two "bottleneck" identification techniques that are developed in Section 2.6 are used to prioritise them. If the extra oxygen "train" is also considered, it ads another three points of evaluation, namely: Oxygen Extra-A, -B and -C. Oxygen Extra-A, -B and -C cannot act as primary "bottlenecks" because their output throughput is added to that of Oxygen-A, -B and -C respectively, if the extra oxygen "train" is included in the simulation run. In total there are thus 16 primary points of evaluation.

The secondary points of evaluation are the points of evaluation in the smaller plants that do not influence the throughput of the Synthetic Fuel plant directly but that are subject to services and failures of their modules. The third rule of operation in Appendix B states that the Electricity Generation plant, Plant(IV), Plant(V) and Sub(I) to Sub(VI) do not form part of the main-gas-

cycle and therefore they do not influence the throughput of the Synthetic Fuel plant directly. These smaller plants are referred to as the peripheral plants. However, a scrutiny of Table A2 reveals that Sub(I) to Sub(VI) are not subject to services and failures of their modules and therefore they are excluded from the secondary points of evaluation. That leaves five secondary points of evaluation, namely: the Electricity Generation plant, Plant(IV)-A, -B and -C and Plant(V). The fourth rule of operation in Appendix B states that if Plant(IV), Plant(V) and Sub(I) to Sub(VI) do not have the capacity to process the throughput at their respective positions, then the portions of the throughput that cannot be processed are flared. Once again Sub(I) to Sub(VI) are excluded because they are not subject to services and failure of their modules. The five secondary points of evaluations can act as secondary "bottlenecks" and therefore the portions of the throughput that are flared at Plant(IV) and Plant(V) are determined to ensure that these secondary "bottlenecks" can be identified and prioritised.

The tertiary points of evaluation are the points of evaluation in the smaller plants that do not influence the throughput of the Synthetic Fuel plant directly and that are also not subject to services and failure of their modules. From the previous paragraph it follows that Sub(I) to Sub(VI) qualify. The Water Treatment plant also qualifies because its modules are not subject to services and failures and even though it actually forms part of the main-gas-cycle it never influences the throughput of the Synthetic Fuel plant (see Points b) and f) of the rules of operation in Appendix B). That gives a total of seven tertiary points of evaluation, namely: the Water Treatment plant and Sub(I) to Sub(VI). Sub(I) to Sub(VI) can act as secondary "bottlenecks". Therefore the portions of the throughput that are flared at Sub(I) to Sub(VI) are determined to ensure that these secondary "bottlenecks" can be identified and prioritised.

It is obvious that the primary and secondary points of evaluation have to be represented in the "real" part of the simulation model by the four different high-level building blocks of the ERM method because they are subject to services and failures of their modules. That gives a total of 21 ERM method high-level building blocks (16 for the primary points of evaluation if the extra oxygen "train" is included and five for the secondary points of evaluation). The seven tertiary points of evaluation are accommodated in the "virtual" part of the simulation model by the logic engine high-level building block.

The 13 primary points of evaluation that are left after Oxygen Extra-A, -B and C have been excluded are included in the FC method and they also make up the primary "bottlenecks". The secondary and tertiary points of evaluation that flare excess throughput make up the secondary "bottlenecks".

The previous paragraphs are summarised in tabular format in Table 3.1: *Simulation Model Breakdown*.

Table 3.1: Simulation Model Breakdown

No.	Name	POE No.	POE Type	ERM Method Block No.	"Bottleneck" Type
1	Coal Processing	1	Primary	1	Primary
2	Water Treatment	2	Tertiary	(Logic Engine)	-
3	Steam	3	Primary	2	Primary
4	Gas Production	4	Primary	4	Primary
5	Temperature Regulation	5	Primary	2	Primary
6-A	Oxygen-A	6	Primary	2	Primary
6-B	Oxygen-B	7	Primary	2	Primary
6-C	Oxygen-C	8	Primary	2	Primary
6E-A	Oxygen Extra-A	9	Primary	3	-
6E-B	Oxygen Extra-B	10	Primary	3	-
6E-C	Oxygen Extra-C	11	Primary	2	-
7	Electricity Generation	12	Secondary	2	-
8	Plant(I)	13	Primary	2	Primary
9-A	Plant(II)-A	14	Primary	1	Primary
9-B	Plant(II)-B	15	Primary	2	Primary
10	Plant(III)	16	Primary	4	Primary
11	Division Process	17	Primary	4	Primary
12	Recycling	18	Primary	3	Primary
	Tank	-	-	-	-
13-A	Plant(IV)-A	19	Secondary	4	Secondary (Flare-A)
13-B	Plant(IV)-B	20	Secondary	4	Secondary (Flare-A)
13-C	Plant(IV)-C	21	Secondary	4	Secondary (Flare-A)
14	Sub(I)	22	Tertiary	(Logic Engine)	Secondary (Flare-C1)
15	Sub(II)	23	Tertiary	(Logic Engine)	Secondary (Flare-C2)
16	Sub(III)	24	Tertiary	(Logic Engine)	Secondary (Flare-C3)
17	Sub(IV)	25	Tertiary	(Logic Engine)	Secondary (Flare-C4)
18	Sub(V)	26	Tertiary	(Logic Engine)	Secondary (Flare-C5)
19	Sub(VI)	27	Tertiary	(Logic Engine)	Secondary (Flare-C6)
20	Plant(V)	28	Secondary	4	Secondary (Flare-B)

Where:

No.   :   The plant identification number.

POE No.   :   The point of evaluation number.

POE Type   :   The point of evaluation type.

The numbers in Column 5 of Table 3.1 indicate which one of the four different high-level building blocks of the ERM method is needed at each of the primary and secondary points of evaluation.

The numbers that identify the four different high-level building blocks of the ERM method are the following:

a)   No.1 - A smaller plant with a multiple service cycle and failures of the modules.

b)   No.2 - A smaller plant with a service cycle and failures of the modules.

c)   No.3 - A smaller plant with a service cycle of the modules.

d)   No.4 - A smaller plant with failures of the modules.

Summary

This section provides a simulation model breakdown of the Synthetic Fuel plant. The breakdown is derived from the system description. The 28 points of evaluation of the Synthetic Fuel plant are divided into three types, namely: primary, secondary and tertiary points of evaluation. The 21 primary and secondary points of evaluation are represented in the "real" part of the simulation model by 21 instances of the four different high-level building blocks of the ERM method and the seven tertiary points of evaluation are accommodated in the "virtual" part of the simulation model by the logic engine high-level building block. The points of evaluation that form part of the FC method and that are primary "bottlenecks", as well as the secondary "bottlenecks" that flare excess throughput, are identified.

* * * * *

3.3   SIMULATION MODEL CONSTRUCTION

Section 3.1 indicates that it was decided to develop two identical simulation models of the Synthetic Fuel plant in two different simulation software packages, namely: Arena and Simul8. Section 3.2 provides a simulation model breakdown of the Synthetic Fuel plant and this section details the Arena and Simul8 simulation models.

In both the Arena and Simul8 simulation modelling environments the first step was to develop the five high-level building blocks of the generic simulation modelling methodology. (The four different high-level building blocks of the ERM method are detailed in Section 2.3 and the logic engine high-level building block is detailed in Section 2.7.) Each high-level building block is constructed from several basic simulation software package building blocks in the respective simulation software packages. The way that the high-level building blocks manifest themselves in the two different simulation software packages differs because each software package has its own unique philosophy, conventions, logic, nomenclature, *etc.* This is especially true for the logic engine high-level building block that is constructed mainly from basic simulation software package building blocks in the Arena environment, but in the Simul8 environment it consists primarily of a block of Visual Logic (VL) code. The following quotation from the *Simul8®: Manual and Simulation Guide* (1999:29) explains what VL is and how it is used in a simulation model:

> "*Visual Logic (VL) is Simul8's logic building environment. In a simulation of significant complexity you will want to add your own rules for deciding how to process work. VL lets you add very detailed logic to control the operation of your simulation.*"

The four different high-level building blocks of the ERM method accommodate the primary and secondary points of evaluation and are all based on the basic structure of the three separate parts of each of the smaller plants that is shown in Figure 2.1. The basic structure is simply adapted to suit the needs of each of the four different high-level building blocks of the ERM method. The logic engine high-level building block accommodates the tertiary points of evaluation and all the concepts that are necessary for the simulation model to function (see Figure 2.4). The five high-level building blocks represent the "virtual" part (*i.e.* the logic engine high-level building block) and the "real" part (*i.e.* the four different high-level building blocks of the ERM method) of the simulation model (see Figure 2.4).

The five high-level building blocks of the Arena environment were used to develop a simulation model of the Synthetic Fuel plant in the Arena environment and the five high-level building blocks of the Simul8 environment were used to develop a simulation model of the Synthetic Fuel plant in the Simul8 environment. The simulation model of the Synthetic Fuel plant in the Arena environment is referred to as the Arena simulation model and the one in the Simul8 environment is referred to as the Simul8 simulation model in the rest of this document. Both the Arena and Simul8 simulation models consist of two No.1 ERM method high-level building blocks, nine No.2 ERM method high-level building blocks, three No.3 ERM method high-level building blocks, seven No.4 ERM method high-level building blocks and one logic engine high-level building block (see Table 3.1). That is a total of 21 ERM method high-level building blocks and one logic engine high-level building block in each of the simulation models. The Arena and Simul8 simulation models are identical in the sense of conforming to exactly the same system description (see Section 1.2) but they differ in terms of the construction of the high-level building blocks (as explained previously in this section).

The high-level building blocks of each of the four different types of high-level building blocks of the ERM method are truly generic because all the high-level building blocks of a specific type are absolutely identical except for the modules that populate them. Each high-level building block of the ERM method is populated with the correct number of entities that represents the modules of the Synthetic Fuel plant. The relevant information about each module is stored in the attributes of the entity that represents the module.

To a large extent, the logic engine high-level building block is generic because most of the concepts that are necessary for the simulation model to function are basically the same for every simulation model that is developed with the generic simulation modelling methodology. However, the unique concepts of a specific simulation model that are usually described by the process logic or rules of operation of that specific simulation model cannot be accommodated generically and therefore a part of the logic engine high-level building block of that specific simulation model will contain certain concepts that are unique to that specific simulation model. For instance, Point g) of the rules of operation of the Synthetic Fuel plant in Appendix B states that steam is only supplied to the Electricity Generation plant once the Gas Production and Oxygen plants have been supplied. It is virtually impossible to make provision to accommodate all possible combinations and permutations of such rules of operation generically in the logic engine high-level building block. Other concepts, like the inclusion of a tank to buffer flow, are more universal and therefore lend themselves more readily to generic use.

The logic engine high-level building block controls the functioning of the simulation model. Before the start of the simulation run the ERM method high-level building blocks are populated with the corresponding correct number of entities that represent the modules and appropriate values are assigned to the attributes of the entities (*i.e.* the modules). In the Arena simulation model this process is handled by the logic engine (*i.e.* centralised populating) but in the Simul8 simulation model this process is handled by the ERM method building blocks themselves (*i.e.* decentralised populating).

The three main tasks (already touched upon in Section 2.7) of the logic engine high-level building block are the following:

a)   Before the start of the simulation run the logic engine sets up the simulation model and populates the ERM method high-level building blocks with entities (in the case of the Arena simulation model). The simulation model is set up with input values that reflect the system description of the scenario that is under scrutiny. The input values are accessed with the appropriate input mechanisms of the Arena and Simul8 simulation models.

b)   During the simulation run the logic engine uses the fixed time interval technique to advance the simulation model in time. Every time interval an evaluation of the state of the simulation model takes place and the logic engine completes all the tasks that are necessary for the simulation model to function. The tasks that are completed by the logic engine during every evaluation are indicated in Figure 3.1: *Tasks of the Logic Engine (Every Evaluation)*.

c)   After the completion of the simulation run the logic engine prepares the results and writes it to the appropriate output mechanisms of the Arena and Simul8 simulation models. (The results that follow from a simulation run are detailed in Section 4.1.)

Figure 3.1 indicates the detail and the sequence of the tasks that are completed by the logic engine during every evaluation and which are described in a more generic and less detailed format in Section 2.7.

Both the Arena and Simul8 simulation models use the theoretical probability distributions that are provided in the respective simulation software packages to model the failure rates and repair times of the modules (see Section 1.2). The failure rates are modelled with the exponential distribution and the repair times with the triangular distribution (see Section 1.2 and Table A2).

Tasks of the Logic Engine (Every Evaluation)

Determines Evaluation Start Variables that Keep Record of Functioning of Simulation Model

↓

Determines Accumulated Values (With System Behaviour of Previous Time Interval):
a) Primary POE: Throughput, "Bottleneck" Time and Production Lost (Primary
    "Bottlenecks"), Number Available, Switched On, Switched Off
b) Secondary POE: Throughput, Tank Volume, Flares (Secondary "Bottlenecks"),
    Number Available, Switched On, Switched Off
c) Tertiary POE: Throughput, Flares (Secondary "Bottlenecks")

↓

Controls ERM Method (For Each ERM Method Building Block):
a) Evaluates Next Service Attribute of Each Module in Availability Part of ERM Method
    Building block
b) Moves Due for Service Modules from Availability Part to Service Part of ERM Method
    Building Block
c) Evaluates Next Failure Attribute of Each Module in Availability Part of ERM Method
    Building Blocks
d) Moves Failed Modules from Availability Part to Service Part of ERM Method Building
    Block

↓

Determines Values (For System Behaviour of Next Time Interval):
a) Determines Number of Available Modules in Each Primary and Secondary POE
b) Uses FC Method to Determine Momentary "Bottleneck" and Actual Output Throughput of
    Primary POE
c) Determines Actual Output Throughput of Secondary POE

↓

Determines Evaluation End Variables that Keep Record of Functioning of Simulation Model

Figure 3.1: Tasks of the Logic Engine (Every Evaluation)

The Arena simulation model uses input files to provide access to, and manipulation of, the most important aspects of the system description of the Synthetic Fuel plant that is provided in Section 1.2. For instance, the service schedules are addressed in an input file called SERVIC.DAT. An example of SERVIC.DAT is provided in Appendix E: *SERVIC.DAT (Arena Simulation Model Service Schedules Input File)*. This example contains the input values for the service schedules of the smaller plants of the Synthetic Fuel plant that are detailed in Section 1.2 and Table A2. A scrutiny of SERVIC.DAT reveals that it bears a close resemblance to the part of Table A2 that addresses the service schedules of the smaller plants. Each of the smaller plants that is subjected to services is represented by a header line that identifies the smaller plant and one (for a regular service cycle) or more (for a multiple service cycle) lines of three values each. The first value of each line represents the start time of the first service of the first service cycle, the second value represents the cycle time and the third value represents the service time. The way that the service schedule values are used to control the services is detailed in Section 2.3. The determination of the start times is detailed in Section 3.6. The input files are manipulated with a text editor.

The Arena simulation model uses WKS files as the output mechanism for the results that are generated by a simulation run. The following excerpt from the Arena help function explains what a WKS file is:

> "*The worksheet format, specified by the WKS File keyword, refers to a binary, sequential access data structure used by LOTUS™ spreadsheets. Numeric values can be read from or written to these files to facilitate data collection or analysis using LOTUS™ products. Worksheet files are sequential access only.*"

An example of a WKS output file is shown in Appendix F: *PRIORI.WKS (Arena Simulation Model "Bottleneck" Identification Output File*. Each line of values represents the results of one of the replications that was completed during the simulation run. Kelton *et al.* (1998:36) defines replications as identical, independent simulation runs.

> "*Each run starts and stops the same way and uses the same input-parameter settings (that's the "identical" part), but uses separate input random numbers (that's the "independent" part) to generate the interarrival and service times.*"

Kelton *et al.* use the term "simulation run" to define replications as identical, independent simulation runs, but in this document the term "simulation run" is used exclusively to indicate a complete simulation experiment that usually consists of more than one replication of a simulated scenario.

The first value in each line identifies the replication and the following 13 values in each line represent the possible throughput that was lost (as a percentage of the steady state maximum possible throughput) due to each of the 13 possible "bottleneck" points in the main-gas-cycle. This example shows the results of a simulation run that comprises 20 replications. The WKS output files can easily be imported into Microsoft Excel or Quattro Pro for further manipulation and output analysis (see Section 4.1).

Microsoft Excel and Quattro Pro are registered trademarks and are usually denoted by Microsoft® Excel and Quattro® Pro respectively. However, for the sake of simplicity they will be written simply as Microsoft Excel and Quattro Pro in this document. Microsoft Excel is a spreadsheet software package from the Microsoft Corporation and Quattro Pro is a spreadsheet software package from Corel®.

The Simul8 simulation model uses spreadsheet variables as the input and output mechanisms of the simulation model. In Simul8 every variable that is used by the simulation model is defined in the *Information Store*. A variable is called a *Global Data Item* and may be defined as a spreadsheet. This is a very useful feature because it allows easy manipulation of variables and simplifies the import and export of values into and out of the simulation model. For example, the values that define the service schedules of the Synthetic Fuel plant can be arranged in either a Microsoft Excel or a Quattro Pro spreadsheet and are then simply copied into the Simul8 simulation model after manipulation to reflect the system description of the scenario that is under scrutiny. This process can be simplified even more by instructing the Simul8 simulation model to automatically read the service schedules from a Microsoft Excel spreadsheet when the simulation run starts. The problem with this technique is that the appropriate Microsoft Excel file has to be open and therefore it restricts the amount of Random Access Memory (RAM) that is available to the Simul8 simulation software package during the execution of the simulation run and adversely affects the simulation runtime.

The input files and WKS output files of the Arena simulation model and the spreadsheet variables of the Simul8 simulation model greatly simplify the manipulation of input and output variables and therefore they enhance the user-friendliness of the simulation models. These concepts also support the user-friendliness design criterion (see Point c) of the design criteria in Section 1.5) of the generic simulation modelling methodology.

Both the Arena and Simul8 simulation models use two hierarchical levels to represent the Synthetic Fuel plant. The use of hierarchical levels in simulation models ensures that the simulation models are logical, structured and orderly. The higher hierarchical level of both the Arena and Simul8 simulation models consists of 21 ERM method high-level building blocks and one logic engine high-level building block. On the higher hierarchical level each instance of the five high-level building blocks of the generic simulation modelling methodology is represented as a singular entity. Such an entity is referred to as a *submodel* in the Arena environment and as a *sub-window* in the Simul8 environment. The content of the *submodels* and *sub-windows* represents the next or lower hierarchical level. The lower hierarchical level of both the Arena and Simul8 simulation models consists of the basic simulation software package building blocks of the Arena and Simul8 simulation software packages respectively.

The higher hierarchical level *submodels* and *sub-windows* are arranged in the simulation windows of the Arena and Simul8 simulation software packages in such a way that the layout of the *submodels* and *sub-windows* conforms closely to the configuration of the Synthetic Fuel plant that

is represented in Figure 1.2. (The simulation windows are the main representations of the simulation models within the simulation software packages.) The realistic representation of a simulation model in a layout or configuration that is immediately recognisable is fundamental to the successful familiarisation with, orientation to, and acceptance of, the simulation model by clients and users (Elder, 1992:150-153).

Appendix G: *Simulation Window of the Higher Hierarchical Level (Simul8 Simulation Model)* shows the higher hierarchical level simulation window of the Simul8 simulation model. In the top left of the simulation window the 21 ERM method high-level building blocks are arranged in a layout that conforms to the configuration of the Synthetic Fuel plant that is depicted in Figure 1.2. In the bottom left of the simulation window are the logic engine and animation engine high-level building blocks. The animation engine controls the animation of the Simul8 simulation model.

The animation concepts that are controlled by the animation engine are the following:
a)   The graphical representation of the output throughput of the Gas Production plant of the Synthetic Fuel plant over time as a graph in the bottom centre of the simulation window.
b)   The animation of the momentary "bottleneck" status of the 13 possible "bottleneck" points in the main-gas-cycle over time with a grey or a red dot above the icon of the appropriate possible "bottleneck" point (a red dot signifying that the possible "bottleneck" point is the momentary "bottleneck" at that specific moment in time).
c)   The animation of the flares at Plant(IV) and Plant(V) over time with a grey or a red flare at the top of the appropriate stack (a red flare signifying that the flare is active at that specific moment in time).

The animation engine is unique to the Simul8 simulation model. The animation features are mostly for demonstration purposes and can be switched off to speed up simulation runtimes when simulation runs are conducted.

The four different high-level building blocks of the ERM method are represented by different icons in the simulation window to facilitate immediate recognition and differentiation. The different icons of the high-level building blocks of the ERM method are identified in the symbol key in the bottom right of the simulation window. The icons of the logic and animation engines are self-explanatory and they are not included in the symbol key.

Appendix H: *Simulation Window of the Lower Hierarchical Level (Arena Simulation Model -*

Example No.1) shows the lower hierarchical level simulation window of one of the 21 ERM method high-level building blocks of the Arena simulation model. This example shows the lower hierarchical level simulation window of the No.1 ERM method high-level building block that represents the Coal Processing plant (*i.e.* a smaller plant with a multiple service cycle and failures of modules). The basic simulation software package building blocks of the Arena simulation software package and the connections between them can clearly be distinguished in the simulation window. The lower hierarchical level simulation windows of the other ERM method high-level building blocks are similar but less complex. The lower hierarchical level simulation window of the logic engine high-level building block of the Arena simulation model contains considerably more basic simulation software package building blocks and is much more complex. This lower hierarchical level simulation window is shown in Appendix I: *Simulation Window of the Lower Hierarchical Level (Arena Simulation Model - Example No.2)*.

Summary

In this section two identical simulation models of the Synthetic Fuel plant are developed in Arena and Simul8. The structure of the simulation models is based on the simulation model breakdown of the Synthetic Fuel plant that is provided in Section 3.2. The five high-level building blocks of the generic simulation modelling methodology were developed in each of the simulation software packages and then used to construct the simulation models. The four different high-level building blocks of the ERM method accommodate the primary and secondary points of evaluation and the logic engine high-level building block accommodates the tertiary points of evaluation and all the concepts that are necessary for the simulation model to function. The Arena simulation model uses input and output files and the Simul8 simulation model uses spreadsheet variables as input and output mechanisms. Both the simulation models use two hierarchical levels to represent the Synthetic Fuel plant. The higher hierarchical level consists of the instances of the high-level building blocks while the lower hierarchical level consists of the basic simulation software package building blocks.

* * * * *

3.4   DETERMINATION OF THE ITERATION TIME INTERVAL

Section 2.2 indicates that a fixed time interval can be used to advance a simulation model in time. Such a fixed time interval to advance a simulation model in time is usually referred to as an iteration time interval. The size of the iteration time interval depends on the required accuracy and is usually chosen in accordance with the dynamic response characteristics of the system that is modelled. If the iteration time interval is chosen correctly, the results that are obtained can be a very close approximation of the real-world situation that is modelled.

In general terms it can be stated that the iteration time interval of a simulation model should be chosen in such a way that it makes provision to accurately register or capture the effect of the shortest event that may occur in the simulation model during a simulation run. The *Magister* dissertation (Albertyn, 1995:64-69) provides a more detailed discussion of this principle.

A scrutiny of the processes of the Synthetic Fuel plant suggests that an iteration time interval of one hour should be appropriate. Table A2 indicates that the shortest service time of the modules in the smaller plants of the Synthetic Fuel plant is one hour for the services of the first service cycle of the Coal Processing plant. Table A2 also indicates that the shortest repair times of the modules in the smaller plants of the Synthetic Fuel plant are those of the Oxygen Extra-C plant, the Electricity Generation plant and Plant(IV)-A. The three values of the triangular distribution that are used to represent the repair times of the Oxygen Extra-C module are 0,5 (minimum), 12 (mode) and 24 (maximum) hours while those of the Electricity Generation plant and Plant(IV)-A modules are 0,25 (minimum), 1 (mode) and 3 (maximum) hours and 0,5 (minimum), 0,5 (mode) and 3 (maximum) hours respectively. Even though smaller values than one are present in these triangular distributions, the modes of the distributions are 12, 1 and 0,5 hours and therefore the assumption that a one hour iteration time interval should be appropriate seems reasonable.

The validity of the assumption that a one hour iteration time interval should be appropriate for simulation models of the Synthetic Fuel plant is tested by conducting a series of simulation runs (*i.e.* simulation experiments) that starts with a very short iteration time interval and gradually increases it, until the answers of the simulation runs start to deviate from the perceived correct one.   In this instance, the perceived correct answer will be the one that is generated by the simulation run with the shortest iteration time interval.

Table 3.2: *Effect of the Iteration Time Interval* shows the results if the iteration time interval of the Simul8 simulation model is increased in steps from 0,125 to 24 hours in a series of 10

simulation runs. The Simul8 simulation model was used for this series of simulation runs because the simulation runtimes of the Simul8 simulation model are slightly shorter than those of the Arena simulation model. The input values for the services and failures that were used are those that are represented in Table A2 (service schedules and failure characteristics) and Appendix E (start times of service cycles).

Table 3.2: Effect of the Iteration Time Interval

No.	ITI (hour)	n_{Rep}	Runtime (min)	GasPro (nm³/h)	StdDev (nm³/h)	n_{Sam}	Deviation (%)
1	0,125	20	133,9	1331972,2	7185,9	12	0,000
2	0,25	20	67,0	1331894,1	7185,6	12	-0,006
3	0,5	20	33,6	1331780,6	7159,0	12	-0,014
4	1	20	17,0	1331462,8	7154,9	12	-0,038
5	2	20	8,7	1330787,6	7131,7	12	-0,089
6	3	20	5,9	1330159,2	7112,1	12	-0,136
7	4	20	4,5	1329644,9	7153,3	12	-0,175
8	6	20	3,1	1328126,0	7204,7	12	-0,289
9	12	20	1,7	1323017,8	7087,1	12	-0,672
10	24	20	1,0	1309800,0	7781,5	13	-1,665

Where:

No. : The simulation run identification number.

ITI : The iteration time interval (hour).

n_{Rep} : The number of replications completed.

Runtime : The simulation runtime for n_{Rep} replications (minute).

GasPro : The mean output throughput value of the Gas Production plant, calculated from n_{Rep} replications (nm³/h).

StdDev : The standard deviation from the mean output throughput value (nm³/h).

n_{Sam} : The minimum sufficient sample size.

Deviation : The deviation of the specific mean output throughput value from the 0,125 hour iteration time interval mean output throughput value (%).

A simulation run consisting of 20 replications of a simulated time period of one year (see Appendix L) was completed for every iteration time interval. The mean and the standard deviation from the mean of the output throughput values of the Gas Production plant are

calculated from the results of the 20 replications. The standard deviation is used to calculate the corresponding minimum sufficient sample size with an allowance for a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant (see Appendix M: *Synthetic Fuel Plant Raw Gas Production - 1993*) and a 99% confidence interval. Section 3.5 provides a detailed explanation of the determination of minimum sufficient sample size. The number of replications completed in all instances should be more than, or equal to, the calculated minimum sufficient sample sizes for the answers to be taken as representative of the simulated scenario. A scrutiny of Columns 3 and 7 of Table 3.2 indicates that this constraint is adhered to.

The mean output throughput value of the Gas Production plant is used as the variable of comparison in this series of simulation runs because it is the point in the Synthetic Fuel plant where the coarse coal is transformed into raw gas and the volume of raw gas that is generated determines the final output of the Synthetic Fuel plant.

It is essential to note that one of the benefits of short simulation runtimes immediately becomes apparent when these results are compared to the results of the comparable series of simulation runs that were conducted in the *Magister* dissertation (Albertyn, 1995:64-69). Even though Table 3.4 in the *Magister* dissertation (Albertyn, 1995:66) does not provide the simulation runtimes, it can be deducted from the results presented in Appendix D and E of the *Magister* dissertation (Albertyn, 1995:118-127) that one replication of a simulated time period of one year with an iteration time interval of one hour with the original simulation model, took 17,1 minutes to complete. It can therefore be concluded that a simulation run consisting of 20 replications would have taken approximately 5,7 hours to complete with the original simulation model. If the value of 5,7 hours for a simulation run consisting of 20 replications of a simulated time period of one year with an iteration time interval of one hour for the original simulation model is compared to the value of 17,0 minutes for a simulation run consisting of 20 replications of a simulated time period of one year with an iteration time interval of one hour for the Simul8 simulation model, it is found that the Simul8 simulation model represents a twentyfold improvement in simulation runtime over the original simulation model. This phenomenal improvement in simulation runtime allows the minimum sufficient sample size of the Simul8 simulation model to be determined with an allowance of a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant and a 99% confidence interval, as compared with the 1% deviation from the real-world mean output throughput value of the Gas Production plant and a 99% confidence interval that are used to determine the minimum sufficient sample size of the original simulation model in the *Magister* dissertation (Albertyn, 1995:66). The minimum sufficient sample size in this instance is 12 (see Table 3.2) for the Simul8

simulation model (*i.e.* for an allowance of a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant) and it is five (Albertyn, 1995:76) for the original simulation model (*i.e.* for an allowance of a 1% deviation from the real-world mean output throughput value of the Gas Production plant). Simulation runs of the original simulation model were usually restricted to 10 replications due to the long simulation runtimes and therefore it was impossible to achieve an allowance of only a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant.

The results of Table 3.2 are graphically depicted in Figure 3.2: *Effect of the Iteration Time Interval*.
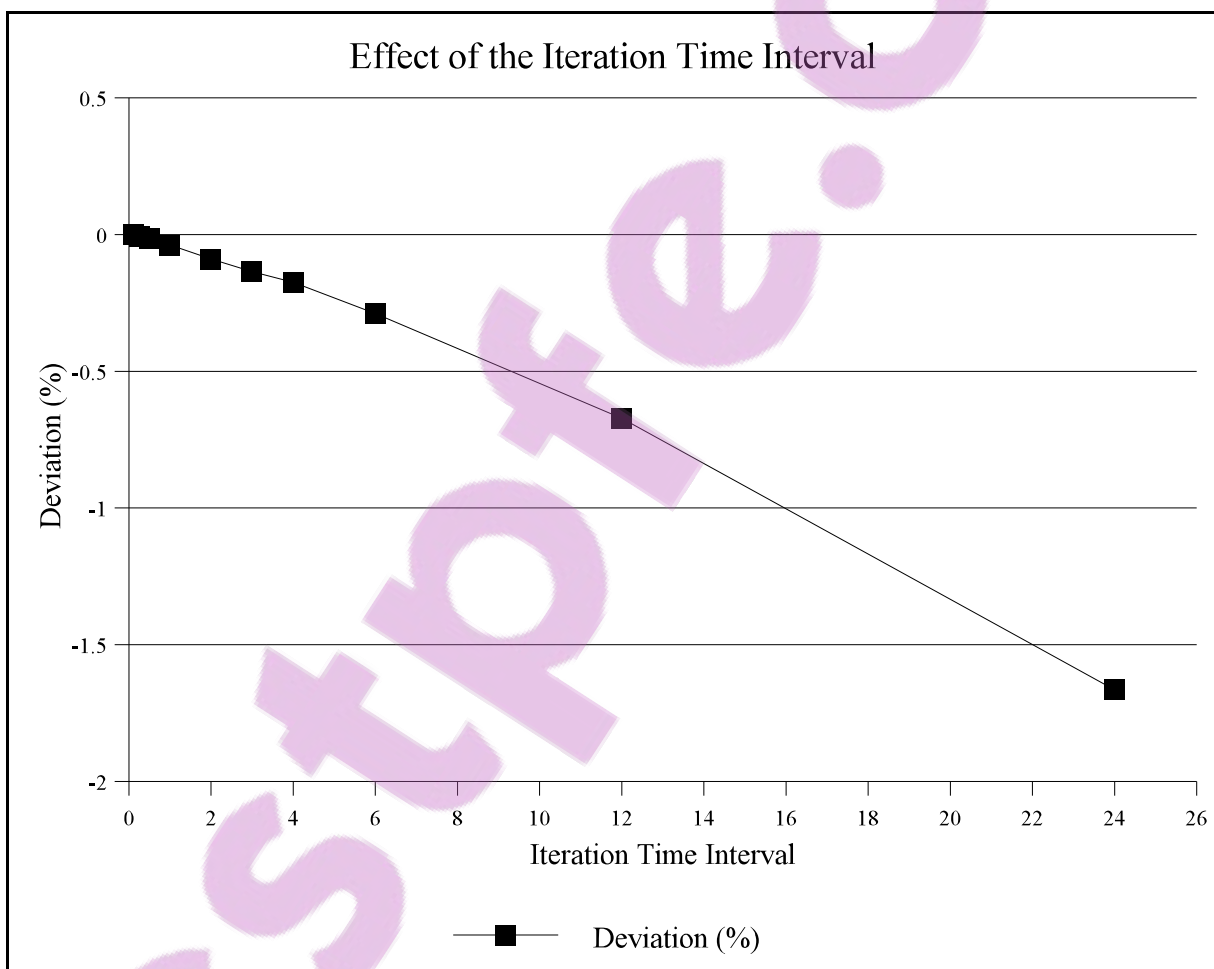
Figure 3.2: Effect of the Iteration Time Interval

A scrutiny of Table 3.2 and Figure 3.2 indicates that the deviation from the perceived correct answer (*i.e.* the one that is generated by the simulation run with the shortest iteration time

interval) increases with an increase in the iteration time interval. If a deviation of 0,5% is taken as an acceptable deviation, all iteration time intervals up to and including six hours seem acceptable. The assumption that a one hour iteration time interval should be appropriate for simulation models of the Synthetic Fuel plant is therefore validated by this exercise.

The downward trend in deviation is caused by a fall in the output throughput value of the Gas Production plant if the iteration time interval is increased. This happens because the Synthetic Fuel plant always strives to maintain the maximum possible throughput and would have resumed the maximum possible throughput as soon as possible after the return of a module from service or failure. This return is delayed if the iteration time interval is long. The Synthetic Fuel plant is thus modelled as operating at a lower throughput than that which is actually possible for the remainder of the iteration time interval.

Summary

This section determines an appropriate iteration time interval for the simulation models of the Synthetic Fuel plant. The results from a series of simulation runs are presented and the assumption that a one hour iteration time interval should be appropriate is shown to be realistic. It is furthermore indicated that the simulation runtime of the Simul8 simulation model with an iteration time interval of one hour represents a twentyfold improvement over the simulation runtime of the original simulation model with an iteration time interval of one hour. This huge improvement in simulation runtime allows the minimum sufficient sample size of the Simul8 simulation model to be determined with an allowance of a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant and a 99% confidence interval, as compared with the 1% deviation and a 99% confidence interval that are used to determine the minimum sufficient sample size of the original simulation model.

* * * * *

3.5   DETERMINATION OF THE SAMPLE SIZE

The results of the different replications of a simulation run of a stochastic simulation model are usually not identical because of the random (*i.e.* the stochastic) behaviour of the random phenomena like failures. This implies that a simulation run consisting of more than one replication has to be completed in order to obtain a mean result that is representative of the simulated scenario.

The determination of the minimum number of replications that would yield a mean result that is representative of the simulated scenario is a determination of minimum sufficient sample size problem. Section 2.1 indicates that Leedy (1993:71) perceives a determination of minimum sufficient sample size problem as a pseudo-subproblem. Leedy maintains that the problem to determine the correct sample size (*i.e.* the minimum sufficient sample size) is merely a pseudo-subproblem or procedural indecision, because there are techniques available to determine sample sizes and it is only necessary to identify the correct one to use in every instance.

In the *Magister* dissertation (Albertyn, 1995:70-72) two different techniques to determine the minimum number of replications (*i.e.* the minimum sufficient sample size) of a simulation run of a stochastic simulation model of the Synthetic Fuel plant are scrutinised. The first is a technique proposed by Crow *et al.* (1960:48) and the second is a technique proposed by Miller *et al.* (1990:209).

Crow *et al.* (1960:48) state that if an estimate of the standard deviation is available, Equation 3.1 can be used to give the sample size necessary to obtain a confidence interval with an expected length of 2*h*.

$$n_{Sam} = ((\sigma t_{(\alpha / 2, n-1)}) / h)^2 \quad (number) \qquad (Eq.:3.1)$$

Where:

n_{Sam}	:	The sample size.
σ	:	The standard deviation, in the appropriate unit of measurement.
t	:	The upper percentage point of the *t* distribution value.
100(1-α)	:	The confidence interval, as a percentage.
n-1	:	The sample size minus one.
h	:	Half (50%) of the expected length of the confidence interval, in the appropriate unit of measurement.

Crow *et al.* refer to the "length" of a confidence interval, while many other references on statistics refer to the "width" of a confidence interval.

Miller *et al.* (1990:209) propose that Equation 3.2 can be used to determine the sample size.

$$n_{Sam} = ((Z_{(\alpha/2)}\sigma) / E)^2 \quad (number) \tag{Eq.:3.2}$$

Where:

n_{Sam}	:	The sample size.
Z	:	The Fisher *Z* transformation value.
100(1-α)	:	The confidence interval, as a percentage.
σ	:	The standard deviation, in the appropriate unit of measurement.
E	:	The maximum error of the estimate, in the appropriate unit of measurement.

In the *Magister* dissertation (Albertyn, 1995:70-72) examples are presented where Equations 3.1 and 3.2 are used to determine minimum sufficient sample sizes. It is also indicated that Equation 3.2 can only be used for instances where the minimum sufficient sample size is larger than or equal to 30 (Miller *et al.*, 1990:198,208). A scrutiny of Column 7 of Table 3.2 indicates that the minimum sufficient sample size of a simulation run of a stochastic simulation model of the Synthetic Fuel plant is usually in the order of 12 to 13 (with an allowance for a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant and a 99% confidence interval). These minimum sufficient sample sizes are substantially smaller than the "larger than or equal to 30" requirement of Equation 3.2 and therefore it stands to reason that Equation 3.1 is used throughout this document for the determination of minimum sufficient sample sizes.

The technique that is proposed by Crow *et al.* (1960:48) uses a table that gives the upper percentage point of the *t* distribution values for different sample sizes in the rows of the table and for the most frequently used different confidence intervals in the columns of the table. The technique then uses Equation 3.1 to move with increasing sample size downward through the column of a specific confidence interval until a certain condition is met, thus identifying the required sample size. The condition that must be met is that Equation 3.1 must return a real value that is less than or equal to the integer value of the sample size in the table that corresponds to the upper percentage point of the *t* distribution value in the table that was used to resolve Equation 3.1 in that instance.

This technique lends itself to computerisation and a FORTRAN software programme was developed to speed up the repetitive and rather cumbersome process that the technique uses to determine the sample size. The FORTRAN software programme is called N.FOR and it automatically converges to the correct minimum sufficient sample size with an iterative-loop technique. The relevant input values are handled by an input file called N.IN. An example of N.IN is provided in Appendix J: *N.IN (Sample Size Determination Input File)*. A scrutiny of N.IN reveals that line three contains the value of the confidence interval and that line five contains the value of half (50%) of the expected length of the confidence interval. Lines seven to sixteen contain two values each. The first value in each line is an identifier that identifies a specific simulation run in a series of simulation runs (*i.e.* simulation experiments) and the second value is the standard deviation of that specific simulation run. This example contains the input values of the series of simulation runs that is detailed in Section 3.4. A scrutiny of Table 3.2 reveals that Column 2 of the table contains the identifiers (in this instance it is the iteration time interval of each simulation run) and Column 6 contains the standard deviations of the series of 10 simulation runs that is the topic of discussion in Section 3.4.

N.FOR determines the minimum sufficient sample sizes with the input values that are provided in N.IN and writes the output values to an output file named N.OUT. An example of N.OUT is provided in Appendix K: *N.OUT (Sample Size Determination Output File)*. This example contains the output values that are generated with the input values that are shown in Appendix J (*i.e.* the minimum sufficient sample sizes of the series of simulation runs that is detailed in Section 3.4). A scrutiny of N.OUT reveals that line three contains the value of the confidence interval and that line five contains the value of half (50%) of the expected length of the confidence interval. Lines seven to sixteen contain four values each. The first value in each line is the identifier that identifies the specific simulation run, the second value is the standard deviation of that specific simulation run, the third value is the integer value of the minimum sufficient sample size of that specific simulation run and the fourth value is the real value of the minimum sufficient sample size of that specific simulation run that is returned when Equation 3.1 is resolved. The integer values of the minimum sufficient sample sizes of the series of 10 simulation runs are reflected in Column 7 of Table 3.2.

Summary

The determination of minimum sufficient sample size is addressed in this section. It is indicated that this is merely a pseudo-subproblem or procedural indecision. Two possible techniques are discussed and the technique that is proposed by Crow *et al.* is identified as the appropriate one

to use in this instance. A FORTRAN software programme that determines the minimum sufficient sample size is detailed and an example of its use is provided.

* * * * *

3.6   SIMULATION MODEL VERIFICATION AND VALIDATION

Various authors and manuals stress the importance of comprehensive simulation model verification and validation before the results that are generated by a simulation run can be accepted as representative of the simulated scenario (Harrell and Tumay, 1999:87-88; Kelton *et al.*, 1998:444-446; Pegden *et al.*, 1995:129-153; *Simul8®: Manual and Simulation Guide*, 1999:34).

The following quotation from Pegden *et al.* (1995:129) provides definitions for, and distinguishes between, verification and validation:

> "***Verification*** *is the process of determining that a model operates as intended. Throughout the verification process, we try to find and remove unintentional errors in the logic of the model. This activity is commonly referred to as* ***debugging*** *the model. In contrast,* ***validation*** *is the process of reaching an acceptable level of confidence that the inferences drawn from the model are correct and applicable to the real-world system being represented. Through validation , we try to determine whether the simplifications and omissions of detail, which we have knowingly and deliberately made in our model, have introduced unacceptably large errors in the results*"

Harrell and Tumay (1999:87) discuss some of the difficulties that are encountered during simulation model verification and validation.

> "*Eliminating bugs* [verification] *in a program model can take a considerable amount of time especially if a general purpose language is used in which frequent coding errors occur.*"

> "*Proving validity* [validation] *is an elusive undertaking.*"

It is obvious that it is no arbitrary task to verify and validate simulation models of the size and complexity of the Arena and Simul8 simulation models of the Synthetic Fuel plant. A detailed discussion of the verification and validation of the Arena and Simul8 simulation models does not fall within the scope of this document. However, some of the verification and validation concepts are demonstrated with examples in the rest of this section.

One of the most basic tests to verify the Arena and Simul8 simulation models of the Synthetic Fuel plant is to count the number of services and failures that are created by the Arena and Simul8 simulation models during a simulation run and to compare it with the real-world number of services and failures that occur.

In Table 3.3: *Verification of the Simulation Models* a comparison is provided between the real-world number of failures of the modules in the smaller plants that are subject to failures and the number of failures of the modules created by the Arena and Simul8 simulation models during a simulation run.

Simulation runs consisting of 20 replications of a simulated time period of one year (see Appendix L) and with an iteration time interval of one hour were completed with the Arena and Simul8 simulation models. The input values for the services and failures that were used are those that are represented in Table A2 (service schedules and failure characteristics) and Appendix E (start times of service cycles). The mean number of failures of the modules in the smaller plants over the simulated time period of one year created by the Arena and Simul8 simulation models are calculated from the results of the 20 replications and are shown in Columns 6 and 8 of Table 3.3 for the Arena and Simul8 simulation models respectively.

It is important to note that the MTBF and real-world number of failures that occur are calculated for a 360-day year (*i.e.* an 8640-hour year). This is done to conform to the 360-day simulation model year that is used by the Arena and Simul8 simulation models. The primary reason why the 360-day simulation model year is used by the Arena and Simul8 simulation models, is to accommodate the service schedules of the modules of the Synthetic Fuel plant. The concept of the simulation model year is discussed in detail in Appendix L.

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Table 3.3: Verification of the Simulation Models

No.	Name	Mod.	MTBF (hour)	No. Fail Real	No. Fail Ar	Dev-Ar (%)	No. Fail S8	Dev-S8 (%)
1	Coal Processing	14	336	360,00	334,50	-7,08	335,20	-6,89
3	Steam	9	2880	27,00	22,70	-15,93	25,00	-7,41
4	Gas Production	40	960	360,00	347,20	-3,56	352,10	-2,19
5	Temperature Regulation	8	5760	12,00	12,45	3,75	11,35	-5,42
6-A	Oxygen-A	6	1080	48,00	46,85	-2,40	46,20	-3,75
6-B	Oxygen-B	6	8640	6,00	6,20	3,33	5,80	-3,33
6-C	Oxygen-C	7	840	72,00	71,95	-0,07	72,05	0,07
6E-C	Oxygen Extra-C	1	1234	7,00	6,75	-3,59	7,40	5,69
7	Electricity Generation	4	1440	24,00	24,95	3,96	22,80	-5,00
8	Plant(I)	4	8640	4,00	4,45	11,25	3,95	-1,25
9-A	Plant(II)-A	8	11520	6,00	6,45	7,50	4,90	-18,33
9-B	Plant(II)-B	2	17280	1,00	1,05	5,00	1,25	25,00
10	Plant(III)	2	8640	2,00	2,50	25,00	1,95	-2,50
11	Division Process	2	8640	2,00	1,80	-10,00	1,80	-10,00
13-A	Plant(IV)-A	4	34560	1,00	0,95	-5,00	0,90	-10,00
13-B	Plant(IV)-B	2	17280	1,00	0,65	-35,00	1,15	15,00
13-C	Plant(IV)-C	1	34560	0,25	0,15	-40,00	0,30	20,00
20	Plant(V)	8	5317	13,00	10,90	-16,15	11,05	-15,00

Where:

No.	:	The plant identification number.
Mod.	:	The number of modules in the plant.
MTBF	:	The Mean Time Between Failure of the modules (hour).
No. Fail Real	:	The real-world number of failures that occur during a one year period (calculated with the real-world MTBF).
No. Fail Ar	:	The mean number of failures created by the Arena simulation model during a simulated time period of one year.
Dev-Ar	:	The deviation of the mean number of failures created by the Arena simulation model from the real-world number of failures that occur (%).
No. Fail S8	:	The mean number of failures created by the Simul8 simulation model during a simulated time period of one year.

Dev-S8　　　:　　　The deviation of the mean number of failures created by the Simul8 simulation model from the real-world number of failures that occur (%).

A scrutiny of Column 7 of Table 3.3 reveals that the deviations of the number of failures created by the Arena simulation model, from the real-world number of failures that occur, vary in a range from a deviation as small as -0,07% (Oxygen-C) to a deviation as large as -40,00% (Plant(IV)-C). A deviation of -40,00% seems excessive but it could still be acceptable if the large MTBF value (or conversely the low failure rate) of Plant(IV)-C is taken into account. The MTBF of Plant(IV)-C is 34560 hours and that translates into approximately one failure every four years. Such a low failure rate could easily lead to a large deviation from the real-world number of failures that occur because the simulated time period of one year is considerably shorter than the MTBF of four years. This implies that the number of failures created by the Arena simulation model is small and therefore the randomness of the failures is accentuated. However, it is still good simulation modelling practice to thoroughly investigate any large deviations. Even though some of the deviations in Column 7 of Table 3.3 assume large values, the overall impression is that the Arena simulation model operates as intended, insofar as the number of failures created is concerned.

A scrutiny of Column 9 of Table 3.3 reveals that the deviations of the number of failures created by the Simul8 simulation model, from the real-world number of failures that occur, vary in a range from a deviation as small as 0,07% (Oxygen-C) to a deviation as large as 25,00% (Plant(II)-B). The same arguments as those stated in the previous paragraph about the Arena simulation model deviations is applicable to the Simul8 simulation model deviations. Even though some of the deviations in Column 9 of Table 3.3 assume large values, the overall impression is that the Simul8 simulation model operates as intended, insofar as the number of failures created is concerned.

A simulation model is usually validated by comparing the behaviour of the simulation model in a known scenario with the behaviour of the real-world system in the known scenario. In this instance the mean output throughput values of the Arena and Simul8 simulation models in a known scenario are compared to the real-world mean output throughput value of the Synthetic Fuel plant in the known scenario. The known scenario is the 1993 production year of the Synthetic Fuel plant and the mean raw gas output throughput value of the Gas Production plant is used as the variable of comparison. The monthly mean output throughput values of the Gas Production plant during the 1993 production year are indicated in Table M1: *Gas Production Plant Output Throughput -1993* (see Appendix M). From Table M1 it follows that the mean

output throughput value of the Gas Production plant during the 1993 production year was 1332234,2 nm^3/h.

In Table 3.4: *Validation of the Simulation Models* the Arena and Simul8 simulation models are validated by comparing the mean output throughput values of the Gas Production plant that are generated by their respective simulation runs with the mean output throughput value of the Gas Production plant during the 1993 production year.

Table 3.4: Validation of the Simulation Models

Simulation Model	ITI (hour)	n_{Rep}	Runtime (min)	GasPro (nm^3/h)	StdDev (nm^3/h)	n_{Sam}	Deviation (%)
Arena	1	20	24,0	1326773,7	8066,6	14	-0,410
Simul8	1	20	17,0	1331462,8	7154,9	12	-0,058

Where:

ITI	:	The iteration time interval (hour).
n_{Rep}	:	The number of replications completed.
Runtime	:	The simulation runtime for n_{Rep} replications (minute).
GasPro	:	The mean output throughput value of the Gas Production plant, calculated from n_{Rep} replications (nm^3/h).
StdDev	:	The standard deviation from the mean output throughput value (nm^3/h).
n_{Sam}	:	The minimum sufficient sample size.
Deviation	:	The deviation of the specific mean output throughput value from the mean output throughput value of the Gas Production plant during the 1993 production year (%).

Simulation runs consisting of 20 replications of a simulated time period of one year (see Appendix L) and with an iteration time interval of one hour were completed with the Arena and Simul8 simulation models. The input values for the services and failures that were used are those that are represented in Table A2 (service schedules and failure characteristics) and Appendix E (start times of service cycles).

The means and the standard deviations from the means of the output throughput values of the Gas Production plant are calculated from the results of the 20 replications. The standard deviations are used to calculate the corresponding minimum sufficient sample sizes with an allowance for

a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant (see Appendix M) and a 99% confidence interval. Section 3.5 provides a detailed explanation of the determination of minimum sufficient sample size. The number of replications completed in both instances should be more than, or equal to, the calculated minimum sufficient sample sizes for the answers to be taken as representative of the simulated scenario. A scrutiny of Columns 3 and 7 of Table 3.4 indicates that this constraint is adhered to.

From Table 3.4 it follows that the mean output throughput values of the Gas Production plant of the Arena and Simu8 simulation models deviate only -0,410% and -0,058% respectively from the mean output throughput value of the Gas Production plant during the 1993 production year.

These results (deviations of less than 1% for the Arena and Simul8 simulation models) indicate that it can be accepted that the Arena and Simul8 simulation models with an iteration time interval of one hour are valid representations of the Synthetic Fuel plant.

These results correlate closely with the *Magister* dissertation (Albertyn, 1995:76) which indicates that the original simulation model with an iteration time interval of one hour also deviates less than 1% (0,59%) from the real-world situation for the same known scenario.

The sensitivity of the Arena and Simul8 simulation models, with regard to the input values for the services and failures that are used, is also worthy of consideration. The only input values that are "variable" in the strict sense of the word are the start times of the service cycles (see Appendix E). The input values for the cycle times, services times, failure rates and repair times are "fixed" in terms of the system description of the Synthetic Fuel plant that is provided in Section 1.2 (see Table A2).

Table 3.5: *Sensitivity of the Simulation Models* provides an indication of the sensitivity of the Arena and Simul8 simulation models in terms of variation in the start times of the service cycles. Three different scenarios for the start times of the service cycles are considered for both simulation models.

The three different scenarios are the following:

a)   Scenario 1 - at the start of the simulation run, every service cycle (excluding the "phase" services) is considered to start just after the completion of the last service of a sequence of services.

b)   Scenario 2 - at the start of the simulation run, every service cycle (excluding the "phase"

services) is considered to start exactly halfway through the service cycle (see Appendix E).

c)   Scenario 3 - at the start of the simulation run, every service cycle (excluding the "phase" services) is considered to start with the first service of a sequence of services.

Table 3.5: Sensitivity of the Simulation Models

Simulation Model	ITI (hour)	n_{Rep}	Runtime (min)	GasPro (nm³/h)	StdDev (nm³/h)	n_{Sam}	Deviation (%)
Arena (Scenario 1)	1	20	24,0	1340731,2	7220,3	12	0,638
Arena (Scenario 2)	1	20	24,0	1326773,7	8066,6	14	-0,410
Arena (Scenario 3)	1	20	24,0	1320225,4	7863,5	14	-0,901
Simul8 (Scenario 1)	1	20	17,0	1343426,6	6887,4	11	0,840
Simul8 (Scenario 2)	1	20	17,0	1331462,8	7154,9	12	-0,058
Simul8 (Scenario 3)	1	20	17,0	1322135,6	7015,2	12	-0,758

Where:

ITI   :   The iteration time interval (hour).

n_{Rep} :   The number of replications completed.

Runtime   :   The simulation runtime for n_{Rep} replications (minute).

GasPro   :   The mean output throughput value of the Gas Production plant, calculated from n_{Rep} replications (nm³/h).

StdDev   :   The standard deviation from the mean output throughput value (nm³/h).

n_{Sam} :   The minimum sufficient sample size.

Deviation :   The deviation of the specific mean output throughput value from the mean output throughput value of the Gas Production plant during the 1993 production year (%).

Scenario 2 represents the input values for the start times of the service cycles (see Appendix E) that are used for all the other simulation runs in this document because they represent a good middle-of-the-road option.

Simulation runs consisting of 20 replications of a simulated time period of one year (see Appendix L) and with an iteration time interval of one hour were completed for the previously mentioned three different scenarios with the Arena and Simul8 simulation models (*i.e.* a total of six simulation runs was completed). The input values for the services and failures that were used

are those that are represented in Table A2 (service schedules and failure characteristics). The input values for the start times of the service cycles are those that are described above for the three different scenarios.

The means and the standard deviations from the means of the output throughput values of the Gas Production plant are calculated from the results of the 20 replications. The standard deviations are used to calculate the corresponding minimum sufficient sample sizes with an allowance for a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant (see Appendix M) and a 99% confidence interval. Section 3.5 provides a detailed explanation of the determination of minimum sufficient sample size. The number of replications completed in all instances should be more than, or equal to, the calculated minimum sufficient sample sizes for the answers to be taken as representative of the simulated scenario. A scrutiny of Columns 3 and 7 of Table 3.5 indicates that this constraint is adhered to.

From Table 3.5 it follows that none of the mean output throughput values of the Gas Production plant of the Arena and Simu8 simulation models deviate more than 1% from the mean output throughput value of the Gas Production plant during the 1993 production year. The maximum delta between the deviations of the Arena simulation model is between Scenario 1 and 3 and it is 1,539% (0,638% minus -0,901%). The maximum delta between the deviations of the Simul8 simulation model is between Scenario 1 and 3 and it is 1,598% (0,840% minus -0,758%).

These results indicate that the maximum bandwidth of variation of the mean output throughput values of the Gas Production plant of the Arena and Simu8 simulation models is less than 2% of the mean output throughput value of the Gas Production plant during the 1993 production year. It can therefore be deducted that the Arena and Simul8 simulation models are not overly sensitive to variation if the input values for the start times of the service cycles are varied between the extremes of Scenario 1 and 3.

Another concept that has to be introduced is the confidence interval for a population mean. Various sources (Miller *et al.*, 1990:210-214; Pegden *et al.*, 1995:36-38; *Simul8*[®]*: Manual and Simulation Guide*, 1999:39-48) detail the theoretical background for the determination of a confidence interval for a population mean (see Appendix N: *Determination of the Confidence Interval*).

Table 3.6: *99% Confidence Intervals for the Output Throughput* provides the 99% confidence intervals for the mean output throughput values of the six scenarios that are under scrutiny. The

mean output throughput values of the Gas Production plant are used.

Table 3.6: 99% Confidence Intervals for the Output Throughput

Simulation Model	GasPro (nm³/h)	StdDev (nm³/h)	ConInt (nm³/h)	Lower ConLmt (nm³/h)	Upper ConLmt (nm³/h)
Arena (Scenario 1)	1340731,2	7220,3	9238,2	1336112,1	1345350,3
Arena (Scenario 2)	1326773,7	8066,6	10321,0	1321613,2	1331934,2
Arena (Scenario 3)	1320225,4	7863,5	10061,2	1315194,8	1325256,0
Simul8 (Scenario 1)	1343426,6	6887,4	8812,3	1339020,5	1347832,7
Simul8 (Scenario 2)	1331462,8	7154,9	9154,5	1326885,5	1336040,1
Simul8 (Scenario 3)	1322135,6	7015,2	8975,8	1317647,7	1326623,5

Where:

GasPro   :   The mean output throughput value of the Gas Production plant, calculated from n_{Rep} replications (nm³/h).

StdDev   :   The standard deviation from the mean output throughput value (nm³/h).

ConInt   :   The confidence interval (nm³/h).

ConLmt   :   The confidence limit (nm³/h).

Pegden *et al.* (1995:36-38) and the *Simul8®: Manual and Simulation Guide* (1999:39-48) indicate that the confidence intervals should be taken into consideration when alternatives are compared. If the confidence intervals for the mean output throughput values of two scenarios overlap, the two scenarios cannot be differentiated in terms of representing two different outcomes.

A scrutiny of Columns 5 and 6 of Table 3.6 reveals that the 99% confidence intervals for the mean output throughput values of the Scenario 1 and 3 Arena simulation models do not overlap and therefore the two scenarios can be assumed to represent two different outcomes. This implies that it is valid to determine and use the delta between the deviations of Scenario 1 and 3 of the Arena simulation model during the sensitivity analysis (see Table 3.5). Furthermore, the 99% confidence intervals for the mean output throughput values of the Scenario 1 and 3 Simul8 simulation models also do not overlap and therefore the two scenarios can be assumed to represent two different outcomes. This implies that it is valid to determine and use the delta between the deviations of Scenario 1 and 3 of the Simul8 simulation model during the sensitivity analysis (see Table 3.5).

Summary

Some of the verification and validation concepts of the Arena and Simul8 simulation models are discussed and demonstrated with examples in this section. The example that demonstrates the verification of the simulation models indicates that the simulation models operate as intended, insofar as the number of failures created is concerned. The validation example compares the mean output throughput values of the Gas Production plant of the simulation models with the mean output throughput value of the Gas Production plant during the 1993 production year. The results (deviations of less than 1% from the 1993 production year) indicate that the simulation models can be accepted as valid representations of the Synthetic Fuel plant. The sensitivity of the simulation models in terms of variation in the start times of the service cycles is investigated and the conclusion is reached that the simulation models are not overly sensitive for variation in the start times of the service cycles. Confidence intervals for the mean output throughput values of the simulation models are also determined.

* * * * *

3.7   SIMULATION MODEL ENHANCEMENT

The original, Arena and Simul8 simulation models use a fixed time interval (*i.e.* an iteration time interval) to advance the simulation models in time. This concept is explained, developed and detailed in Sections 1.4, 1.6, 1.7, 2.2 and 3.4. If an iteration time interval concept is used to advance a simulation model in time, it will be referred to as an iteration time interval (ITI) evaluation method in the rest of this document.

However, another possibility to advance the original, Arena and Simul8 simulation models in time, does exist. The event-driven evaluation concept advances a simulation model in time by evaluating the simulation model only when an event takes place. If an event-driven evaluation concept is used to advance a simulation model in time, it will be referred to as an event-driven (ED) evaluation method in the rest of this document.

A summary of the most salient points of the ITI evaluation method is provided here for the sake of continuity and to provide an introduction to the arguments that support the development of the ED evaluation method.

The basic principles of the ITI evaluation method are based on the methods of classical mathematics. In classical mathematics the behaviour of a continuous system over a period of time is usually modelled with the help of differential equations. Unfortunately, analytical solutions are only available for rather simplistic differential equations. As soon as more complex differential equations are encountered, numerical methods seem to be the only viable solution. One such method involves the discretisation (division into discrete elements) of the continuous behaviour of the system over the time period into behaviour during specific time intervals. The behaviour of the system is evaluated at the start of every time interval and is assumed to remain constant for the duration of the time interval. The total behaviour of the system over the time period is then found by the summation of the behaviour during the specific time intervals. If the time interval between evaluations is chosen correctly in accordance with the dynamic response characteristics of the system that is modelled the results that are obtained can be a very close approximation of the real-world situation that is modelled. It is common practice to use a fixed time interval (*i.e.* an iteration time interval) between evaluations.

The ED evaluation method works on the principle that the behaviour of a system over a period of time can only change when an event takes place and assumes that the behaviour is constant between events. Therefore the behaviour of the system will remain constant until an event takes place that necessitates the re-evaluation of the system to determine the new behaviour. The total behaviour of the system over the time period is then found by the summation of the behaviour between the different points in time that the events took place.

The basic difference between the two evaluation methods is that the ITI evaluation method evaluates a simulation model with a time interval that is of constant (*i.e.* fixed) length, while the ED evaluation method evaluates a simulation model with a time interval that is of variable length, depending on the events that take place.

The flexibility of the generic simulation modelling methodology and therefore also the flexibility of the Arena and Simul8 simulation models, can be greatly enhanced by the inclusion of an ED evaluation method option. The reason why an ED evaluation method option can be incorporated into the generic methodology, is because the generic methodology does not make provision for the inclusion of transient behaviour. It is assumed that the changes in the state of the system occur at isolated (specific) points in time. The reasons for this assumption are provided in Section 1.7 and its validity is provided in Section 3.6.

The following six different types of events that take place in simulation models that are developed

with the generic simulation modelling methodology can be identified:

a)   The beginning and end of each replication of the simulation run.

b)   The beginning and end of each service of the modules.

c)   The beginning and end of each failure of the modules.

In order to explain one of the possible benefits of using an ED evaluation method in simulation models that are developed with the generic simulation modelling methodology, it is necessary to introduce the concept of event density. In this context event density may be defined as the number of events per time unit (see Equation 3.3).

$$Density_{Evt} = n_{Evt} \, / \, Time \quad (event/hour) \hspace{2cm} (Eq.:3.3)$$

Where:

$Density_{Evt}$:   The event density, in events per hour.

n_{Evt} :   The number of events.

The event density value of a simulation model can be used to determine which of the two evaluation methods (*i.e.* the ITI or ED evaluation method) is appropriate for that specific application. Of course, the event density value of a simulation model cannot be calculated before a simulation run consisting of a number of replications has been completed. During a simulation run the number of events that take place during each replication can be counted and consequently the mean number of events and the event density value of the simulation model can be calculated. Paradoxically, this implies that the simulation model should already exist before it can be determined which of the two evaluation methods is appropriate for a specific application. This problem is circumvented by making a first-order estimate of the number of events that should take place per replication.

Table O1: *Number of Services and Failures (8640-hour year)* of Appendix O: *First-order Estimate of the Number of Services and Failures* provides a first-order estimate of the number of services and failures that should take place in the Arena and Simul8 simulation models over a simulated time period of one year. From Table O1 it follows that the estimated number of events in the simulation models over a simulated time period of one year is 4024 events. That is two events for the beginning and end of each replication, 2132 events that are related to the beginning and end of each service (1066 services multiplied by 2) and 1890 events that are related to the beginning and end of each failure (945 failures multiplied by 2). That gives an estimated event density value of 0,47 events per hour (4024 events divided by 8640 hours) for the

simulation models.

An ED evaluation method option was incorporated into the Arena and Simul8 simulation models and a simulation run was completed with the ED evaluation method option for both the simulation models. In Table 3.7: *Validation of the ED Evaluation Method Option Simulation Models* the ED evaluation method option Arena and Simul8 simulation models are validated and a comparison with the validation of their ITI evaluation method option counterparts with an iteration time interval of one hour (see Table 3.4) is provided.

It is imperative to note that both the Arena and Simul8 simulation models incorporate an ITI evaluation method option and an ED evaluation method option in the same simulation model. The original simulation model, on the other hand, only incorporates an ITI evaluation method option. All the results that are shown up to this point were generated with the ITI evaluation method option of the Arena and Simul8 simulation models. Even though both evaluation method options are available in the Arena simulation model and it is essentially exactly the same simulation model that is used, the simulation model will be referred to as the ITI evaluation method option Arena simulation model when the ITI evaluation method option is used and as the ED evaluation method option Arena simulation model when the ED evaluation method option is used. The same logic applies to the Simul8 simulation model.

Table 3.7: Validation of the ED Evaluation Method Option Simulation Models

Simulation Model	ITI (hour)	n_{Evt}	D_{Evt} (e/h)	n_{Rep}	Runtime (min)	GasPro (nm³/h)	StdDev (nm³/h)	n_{Sam}	Deviation (%)
Arena (ITI)	1	-	-	20	24,0	1326773,7	8066,6	14	-0,410
Arena (ED)	-	3242,3	0,38	20	8,6	1332471,8	6620,5	11	0,018
Simul8 (ITI)	1	-	-	20	17,0	1331462,8	7154,9	12	-0,058
Simul8 (ED)	-	3259,6	0,38	20	6,8	1332253,3	7462,5	13	0,001

Where:

ITI	:	The iteration time interval (hour).
n_{Evt}	:	The mean number of events (simulation model evaluations), calculated from n_{Rep} replications.
D_{Evt} (e/h)	:	The event density value (event/hour).
n_{Rep}	:	The number of replications completed.
Runtime	:	The simulation runtime for n_{Rep} replications (minute).

GasPro	:	The mean output throughput value of the Gas Production plant, calculated from n_{Rep} replications (nm^3/h).
StdDev	:	The standard deviation from the mean output throughput value (nm^3/h).
n_{Sam}	:	The minimum sufficient sample size.
Deviation	:	The deviation of the specific mean output throughput value from the mean output throughput value of the Gas Production plant during the 1993 production year (%).

Simulation runs consisting of 20 replications of a simulated time period of one year (see Appendix L) were completed with the ED evaluation method option Arena and Simul8 simulation models. The input values for the services and failures that were used are those that are represented in Table A2 (service schedules and failure characteristics) and Appendix E (start times of service cycles).

The mean number of events and the event density values, as well as the means and the standard deviations from the means of the output throughput values of the Gas Production plant, are calculated from the results of the 20 replications. The standard deviations are used to calculate the corresponding minimum sufficient sample sizes with an allowance for a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant (see Appendix M) and a 99% confidence interval. Section 3.5 provides a detailed explanation of the determination of minimum sufficient sample size. The number of replications completed in both instances should be more than, or equal to, the calculated minimum sufficient sample sizes for the answers to be taken as representative of the simulated scenario. A scrutiny of Columns 5 and 9 of Table 3.7 indicates that this constraint is adhered to.

From Table 3.7 it follows that the mean output throughput values of the Gas Production plant of the ED evaluation method option Arena and Simu8 simulation models deviate only 0,018% and 0,001% respectively from the mean output throughput value of the Gas Production plant during the 1993 production year.

These results (deviations of less than 1% for the ED evaluation method option Arena and Simul8 simulation models) indicate that it can be accepted that the ED evaluation method option Arena and Simul8 simulation models are valid representations of the Synthetic Fuel plant.

Section 3.6 indicates that the ITI evaluation method option Arena and Simul8 simulation models

with an iteration time interval of one hour are also valid representations of the Synthetic Fuel plant and therefore it is clear that the ITI (with an iteration time interval of one hour) and ED evaluation method option Arena and Simul8 simulation models (*i.e.* two instances of the Arena simulation model and two instances of the Simul8 simulation model) are all valid representations of the Synthetic Fuel plant.

From Table 3.7 it follows that the calculated event density value of the ED evaluation method option Arena and Simul8 simulation models is 0,38. This differs significantly from the estimated event density value of 0,47. This deviation can be attributed to the fact that the n_{Evt} values in Table 3.7 represent the mean number of simulation model evaluations and not, in the strict sense of the word, the exact mean number of events. The mean number of simulation model evaluations differs from the mean number of events because some of the events are concurrent. For instance, more than one module can start a service at exactly the same time. This implies that one evaluation can capture more than one event and therefore the mean number of simulation model evaluations is generally less than the mean number of events in an ED evaluation method simulation model.

The difference in the simulation runtimes of the ITI and ED evaluation method option Arena and Simul8 simulation models are of special significance. The simulation runtime of the ITI evaluation method option Arena simulation model with an iteration time interval of one hour is 24,0 minutes and that of the ED evaluation method option Arena simulation model is 8,6 minutes. That is an improvement of more than 50% in terms of simulation runtime for the Arena simulation model, if the ED evaluation method option is used. The simulation runtime of the ITI evaluation method option Simul8 simulation model with an iteration time interval of one hour is 17,0 minutes and that of the ED evaluation method option Simul8 simulation model is 6,8 minutes. That is an improvement of more than 50% in terms of simulation runtime for the Simul8 simulation model, if the ED evaluation method option is used.

These results could be expected because the event density value of the ITI evaluation method option Arena and Simul8 simulation models with an iteration time interval of one hour is 1,00 (8641 events or evaluations divided by 8640 hours - the extra event or evaluation is the beginning of each replication). In the instance of the ITI evaluation method option Arena and Simul8 simulation models the events are, of course, the simulation model evaluations that take place every iteration time interval. It can therefore be concluded that a low event density value leads to a shorter simulation runtime.

In Section 3.4 the effect of the iteration time interval on the accuracy of the ITI evaluation method option Simul8 simulation model is investigated. The results indicate that if a deviation of 0,5% from the perceived correct answer (*i.e.* the one that is generated by the simulation run with the shortest iteration time interval) is taken as an acceptable deviation, all iteration time intervals up to and including six hours seem acceptable. From Table 3.2 it follows that the simulation runtime for the ITI evaluation method option Simul8 simulation model with an iteration time interval of six hours is only 3,1 minutes. That is considerably shorter than the simulation runtime of 6,8 minutes for the ED evaluation method option Simul8 simulation model. It therefore seems tempting to use the ITI evaluation method option Simul8 simulation model with an iteration time interval of six hours if a short simulation runtime is a prerequisite. Even though the cold figures suggest that it is a valid option, intuitively it seems a better option to avoid the possible risk of deviation from the correct answer, by rather using the ED evaluation method option Simul8 simulation model with the still very acceptable simulation runtime of 6,8 minutes.

The ITI and ED evaluation methods are compared and their strengths and weaknesses are discussed in a conference paper by Albertyn (2000 Summer Computer Simulation Conference, 2000:129-134). Only the most pertinent points of discussion in the paper will be touched upon here to provide some insight into the characteristics of the two evaluation methods. The ITI and ED evaluation methods can be compared in terms of accuracy, complexity of simulation model construction, ease of use and simulation runtimes.

In terms of accuracy there is no discernible distinction between the two evaluation methods, provided that an appropriate iteration time interval is used by the ITI evaluation method (see Section 3.4 and Table 3.7). Both evaluation methods can render extremely accurate results.

As far as complexity of simulation model construction is concerned, an ITI evaluation method simulation model is more straightforward and less complex than an ED evaluation method simulation model. An ED evaluation method simulation model needs additional logic to identify when the next event will take place and consequently the complexity of simulation model construction increases. In the instance of the Arena and Simul8 simulation models it proved to be extremely difficult to incorporate an ITI and ED evaluation method option into the same simulation model. The basic concepts of the ITI and ED evaluation methods differ substantially and therefore they do not lend themselves to easy integration and synergism.

There is no difference in the ease of use of the two evaluation methods. The ITI and ED evaluation method option Arena simulation models use exactly the same input and output files

and the ITI and ED evaluation method option Simul8 simulation models use exactly the same spreadsheet variables as input and output mechanisms (see Section 3.3). The input and output files of the Arena simulation models and the spreadsheet variables of the Simul8 simulation models enhance user-friendliness.

The simulation runtimes of ITI and ED evaluation method simulation models depend on the computer hardware configuration and simulation software package that are used as well as the size and complexity of the simulation model. In addition, the simulation runtime of an ITI evaluation method simulation model also depends on the iteration time interval that is used (see Section 3.4). The simulation runtimes of the ITI and ED evaluation method option Arena and Simul8 simulation models have already been discussed in this section. It will suffice to summarise by stating that, for the computer hardware configuration and simulation software packages that were used for the simulation experiments that are discussed in this document, the simulation runtimes of the ED evaluation method option Arena and Simul8 simulation models are about 50% of those of the ITI evaluation method option Arena and Simul8 simulation models with an iteration time interval of one hour.

The principal features of the hardware configuration of the computer that was used for all the simulation experiments that are discussed in this document are an 800-megahertz processor and 128 megabytes of RAM.

The **strengths** of the ITI evaluation method are accuracy (if an appropriate iteration time interval is used), straightforward and less complex simulation model construction and ease of use (if input and output files or spreadsheet variables are used). Short simulation runtimes can also be achieved by increasing the iteration time interval up to the acceptable limit.

The **weakness** of the ITI evaluation method is that a bandwidth of iteration time intervals that render valid results has to be determined before the simulation model can be used. This is a somewhat cumbersome exercise (see Section 3.4).

The **strengths** of the ED evaluation method are accuracy and ease of use (if input and output files or spreadsheet variables are used). There is also no need to determine a bandwidth of iteration time intervals that render valid results.

The **weaknesses** of the ED evaluation method are a more complex simulation model construction and the fact that the simulation runtime for a specific simulation model in a specific simulation

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software package is a given that depends on the computer hardware configuration.

Summary

In this section the Arena and Simul8 simulation models are enhanced by the inclusion of an additional evaluation method option. The ED evaluation method option evaluates the simulation models only when an event takes place. The concept of event density is introduced and it is indicated that the event density value of a simulation model can be used to determine which of the ITI or ED evaluation method options is appropriate for that specific application. Simulation runs are completed with the ED evaluation method option simulation models and the results are validated. The results (deviations of less than 1% from the 1993 production year) indicate that the ED evaluation method option simulation models can be accepted as valid representations of the Synthetic Fuel plant. The ITI and ED evaluation methods are also compared and their strengths and weaknesses are discussed.

* * * * *

3.8 COMPARISON OF THE SIMULATION MODELS AND THE SIMULATION SOFTWARE PACKAGES

In Section 3.6 the ITI evaluation method option Arena and Simul8 simulation models with an iteration time interval of one hour are validated and in Section 3.7 the ED evaluation method option Arena and Simul8 simulation models are validated. Table 3.7 indicates that the simulation runtimes of the ED evaluation method option Arena and Simul8 simulation models are approximately 50% of those of their ITI evaluation method option counterparts with an iteration time interval of one hour. These results follow from the fact that the event density value of the ED evaluation method option Arena and Simul8 simulation models is only 0,38 (see Table 3.7) while the event density value of the ITI evaluation method option Arena and Simul8 simulation models is 1,00. It therefore stands to reason that the ED evaluation method option Arena and Simul8 simulation models are the preferred options when scenario analysis is conducted because of their shorter simulation runtimes. From this point onward, only the ED evaluation method option Arena and Simul8 simulation models are used and discussed.

An introductory comparison of the ED evaluation method option Arena and Simul8 simulation models and the Arena and Simul8 simulation software packages are provided in a conference

paper by Albertyn and Kruger (16th European Simulation Multiconference, 2002:29-36) and a more detailed version thereof is provided in a published article by Albertyn and Kruger (2003:57-60). The comparisons provided in the conference paper and the published article are repeated here and expanded upon for the sake of continuity and completeness.

Table 3.8: *Comparison of the Simulation Models* provides a comparison between the ED evaluation method option Arena and Simul8 simulation models. The values that are presented in Table 3.8 are mostly taken from Table 3.7 (*i.e.* for a simulated time period of one year) but a few other values are also added. This might seem like an unnecessary repetition but the discussion in Section 3.7 compares the ITI and ED evaluation methods and the way that they manifest themselves in the Arena and Simul8 simulation model environments, while the discussion here compares the ED evaluation method option Arena and Simul8 simulation models.

Table 3.8: Comparison of the Simulation Models

Attribute	ED Evaluation Method Option Arena Simulation Model	ED Evaluation Method Option Simul8 Simulation Model
n_{Evt}	3242,3	3259,6
$Density_{Evt}$ (event/h)	0,38	0,38
n_{Rep}	20	20
Runtime (min)	8,6	6,8
GasPro (nm^3/h)	1332471,8	1332253,3
StdDev (nm^3/h)	6620,5	7462,5
n_{Sam}	11	13
Deviation (%)	0,018	0,001
Size (KB)	2438	937

Where:

n_{Evt}	:	The mean number of events (simulation model evaluations), calculated from n_{Rep} replications.
$Density_{Evt}$	:	The event density value (event/hour).
n_{Rep}	:	The number of replications completed.
Runtime	:	The simulation runtime for n_{Rep} replications (minute).
GasPro	:	The mean output throughput value of the Gas Production plant, calculated from n_{Rep} replications (nm^3/h).
StdDev	:	The standard deviation from the mean output throughput value (nm^3/h).

n_{Sam}	:	The minimum sufficient sample size.
Deviation	:	The deviation of the specific mean output throughput value from the mean output throughput value of the Gas Production plant during the 1993 production year (%).
Size	:	The simulation model size (kilobyte).

The mean number of events (*i.e.* the mean number of simulation model evaluations) of the ED evaluation method option Arena and Simul8 simulation models correlates closely and are 3242,3 and 3259,6 respectively. That gives an identical event density value of 0,38 for both simulation models. The simulation runtime of the Arena simulation model is 8,6 minutes and that of the Simul8 simulation model is slightly less at 6,8 minutes. The minimum sufficient sample size of the Arena simulation model is 11 and that of the Simul8 simulation model is 13 because of the slightly larger standard deviation value of the Simul8 simulation model. Both simulation models render extremely accurate results with deviations of only 0,018% (Arena simulation model) and 0,001% (Simul8 simulation model) from the mean output throughput value of the Gas Production plant during the 1993 production year. The size of the Arena simulation model is 2438 kilobytes while the Simul8 simulation model is considerably smaller at only 937 kilobytes.

The simulation runtimes of 8,6 and 6,8 minutes for the ED evaluation method option Arena and Simul8 simulation models respectively, represent an approximate fortyfold improvement in simulation runtime over the 5,7 hour simulation runtime of the original simulation model (see Section 3.4).

Table 3.9: *Comparison of the Simulation Software Packages* provides a comparison between the *Arena Standard Edition* and *Simul8 Standard* simulation software packages. It should be noted that some of the statements in Table 3.9 are subjective perceptions and not scientifically deduced conclusions. These perceptions follow from the use of the two simulation software packages during the development of the Arena and Simul8 simulation models.

The Arena acquisition cost and annual licencing fees are given as values normalised to the acquisition cost of Simul8. The acquisition cost and annual licencing fees of the simulation software packages change over time because the developers adjust prices to accommodate software upgrades and inflation. Therefore the values for acquisition cost and annual licencing fees that are presented in Table 3.9 are only representative and not absolute.

Table 3.9: Comparison of the Simulation Software Packages

Attribute	Arena	Simul8
Acquisition cost	13,6	1
Annual licencing fees	2,0	None
Graphics capability	More advanced	More basic
Modelling environment complexity (familiarisation, use, *etc.*)	More complex	More simplistic
Simulation modelling capability	More capable	Adequate
Simulation model ease of use (variable manipulation, input and output mechanisms, *etc.*)	More difficult	More easy
Numerical accuracy	15 decimal digits	10 decimal digits
Logic programming language accessibility	Less accessible (VBA is accessible but not integral part of software)	More accessible (Visual Logic is integral part of software)
Simulation model size	Larger	Smaller
Simulation runtime	Longer	Shorter
Random number generation test	Pass	Pass

Where:

VBA   :   Visual Basic for Applications

It should be noted that a less expensive version of Arena, called *Arena Basic Edition*, is also available. The acquisition cost of *Arena Basic Edition* is about a third of that of Simul8 and it has no annual licencing fee. It does, however, only allow modelling with the *Basic Process* template. The *Basic Process* template contains only the most basic simulation software package building blocks and a vital omission is the ability to read data from, or write data to, an external file. The *ReadWrite* building block of Arena is contained in the *Advanced Process* template that is not available in *Arena Basic Edition*. A basic design philosophy of the generic simulation modelling methodology is to use the most basic of the standard simulation software package building blocks (in the respective simulation software packages) whenever possible. This approach supports the design criteria of compact simulation model size and short simulation runtimes (see Section 1.5). The ability to read input variables from, or to write output variables to, an external file is seen as one of the basic capabilities that is needed to support the user-friendliness design criterion of the generic methodology. Apparently the capability to read input variables from, or to write output variables to, an external file can be achieved in *Arena Basic*

Edition through the use of VBA code. This possibility, however, violates the single software application design criterion of the generic methodology and it was thus not considered a viable option.

A variable in Arena is accurate to 15 decimal digits (that is comparable with a Double Precision or Real*8 variable defined in FORTRAN) and in Simul8 a variable is accurate to 10 decimal digits. This difference should not be of concern to a modeller in the normal applications of this type of simulation software package. Operations where floating-point errors tend to accumulate, however, will need extra consideration (see Section 2.3 for a discussion about the effect of floating-point errors on the service schedules).

Section 1.5 shows that the generic simulation modelling methodology presents a structured approach that renders simulation models with the following characteristics: short development time, short maintenance time, user-friendliness, short simulation runtimes, compact size, robustness, accuracy and preferably a single software application. Both the Arena and Simul8 simulation software packages conform to all these characteristics. In both packages short development and maintenance times are achieved through the use of the high-level building blocks. Both packages allow hierarchical modelling (through the use of *submodels* in the Arena environment and *sub-windows* in the Simul8 environment) and support user-friendliness with their input and output mechanisms (through the use of input and output files in the Arena environment and spreadsheet variables in the Simul8 environment). These input mechanisms allow fast and easy access to input and output variables. Acceptable simulation runtimes and compact simulation model sizes are achievable with both packages. The robustness of the generic methodology and both packages are proved by the ease of simulation model construction in both instances. Both packages produce accurate simulation models (proved through verification and validation) and allow the whole simulation model to be accommodated in a single software application.

The **strengths** of the Arena simulation software package are a more advanced graphics capability and additional modelling capabilities, like transporters, conveyors, *etc.* These additional capabilities do not feature in the generic simulation modelling methodology, but could be important for users when seen in the broader perspective of general simulation modelling applications. Arena is also more widely accepted as an "industry standard" among simulation software packages. According to marketing material of Arena more than 75% of the top 30 companies in Fortune's Global 500 use Arena. The use of input and output files as input and output mechanisms enhance user-friendliness and therefore the ease of use of Arena simulation

models is also perceived as a strength of Arena, even though the ease of use is described as "more difficult" in Table 3.9.

The **weaknesses** of the Arena simulation software package are higher acquisition cost, annual licencing fees, more complex modelling environment (and thus more difficult to learn and use), no internal logic programming language, larger simulation model size and longer simulation runtime.

The **strengths** of the Simul8 simulation software package are lower acquisition cost, no annual licencing fees, more simplistic modelling environment (and thus easier to learn and use), inclusion of an internal logic programming language, smaller simulation model size and shorter simulation runtime. The use of spreadsheet variables as input and output mechanisms enhance user-friendliness and therefore the ease of use of Simul8 simulation models is also a strength of Simul8.

The **weaknesses** of the Simul8 simulation software package are a more basic graphics capability and less modelling capabilities. The *Simul8 Standard* package only provides five building blocks but the inclusion of Visual Logic allows great modelling freedom and creativity.

The random number generation functionality of the Arena and Simul8 simulation software packages was also investigated. A string of random numbers was generated with both packages and then subjected to a statistical random number test. The random number generation test and the results are detailed in Appendix P: *Random Number Generation Test*. Both packages passed the test of randomness with a significance level of 95%.

Summary

In this section the ED evaluation method option Arena and Simul8 simulation models and the Arena and Simul8 simulation software packages are compared. It is indicated that the simulation runtimes of the ED evaluation method option simulation models represent an approximate fortyfold improvement over the simulation runtime of the original simulation model. The strengths and weaknesses of the simulation software packages are also discussed.

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CHAPTER 4

MODEL APPLICATION

INTRODUCTION

In this chapter the ED evaluation method option Arena and Simul8 simulation models are used to evaluate two alternative scenarios.

The first section defines the two alternative scenarios. Scenario I is representative of the Synthetic Fuel plant without the inclusion of the Oxygen Extra plant (*i.e.* the inclusion of an extra oxygen "train") and is used to identify the problem areas or "bottlenecks" in the plant. Scenario II is representative of the Synthetic Fuel plant with the Oxygen Extra plant incorporated and is used to determine how this addition impacts on the throughput of the plant. Preformatted spreadsheets are used to manipulate and present the results of the simulation runs.

In the second section the Scenario I results of the ED evaluation method option Arena and Simul8 simulation models are used to identify the primary and secondary "bottlenecks" in the Synthetic Fuel plant. In order of importance, the three most important primary "bottlenecks" are the following: Plant(II)-A, Plant(I) and Oxygen-A. The Scenario I results indicate that Oxygen-A is responsible for a large proportion of the production that is lost and that Plant(IV) and Plant(V) are the only two secondary "bottlenecks".

The Scenario I and II results of the ED evaluation method option Arena and Simul8 simulation models are used in the third section to verify the Scenario II simulation models, to compare the Scenario I and II simulation models and to establish the 99% confidence intervals for the mean output throughput values of the Scenario I and II simulation models. The two scenarios can be assumed to represent two different outcomes because the confidence intervals do not overlap. The Scenario II results are used to identify the primary and secondary "bottlenecks". The two most important primary "bottlenecks" are Plant(II)-A and Plant(I), while Oxygen-A is only responsible for a small portion of the production that is lost in Scenario II. Once again, Plant(IV) and Plant(V) are the only two secondary "bottlenecks" in Scenario II.

In the fourth section the Scenario I results of the three most important primary "bottlenecks" (*i.e.* Plant(II)-A, Plant(I) and Oxygen-A) are compared with those of Scenario II. The comparison

clearly shows that Oxygen-A does not qualify as an important primary "bottleneck" in Scenario II anymore. The Scenario I and II results also indicate that the total volume and mean rate of flare values at the two secondary "bottlenecks" (*i.e.* Plant(IV) and Plant(V)) are larger in Scenario II than in Scenario I. This is caused by the larger mean output throughput value of the Gas Production plant in Scenario II. The gain in the output throughput value in Scenario II, expressed in terms of production days of the Gas Production plant, is approximately five production days. The impact, when an additional oxygen "train" (the Oxygen Extra plant) is incorporated into the Synthetic Fuel plant, is that the "bottleneck" effect of Oxygen-A is removed and that the output throughput of the Synthetic Fuel plant is increased.

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4.1   BACKGROUND INFORMATION

Section 1.1 indicates that the original simulation model of the Sasol East plant was used to investigate two alternative scenarios in the *Magister* dissertation (Albertyn, 1995:81-96). The two scenarios were used to identify the problem areas in the plant and to study the effect of a proposed change on the plant. The first scenario identified the "bottlenecks" in the plant and the second scenario determined the effect of an extra oxygen "train" on the plant. The addition of an extra oxygen "train" was chosen as a scenario, because it was one of the real-world decision options that confronted the management of the plant when the original simulation model was developed. The first scenario will be referred to as Scenario I and the second scenario as Scenario II in the rest of this document.

In this chapter the ED evaluation method option Arena and Simul8 simulation models are used to replicate the two scenarios that were investigated with the original simulation model in the *Magister* dissertation. The purpose of this replication is to further validate the generic simulation modelling methodology and to provide a basis for a comparison of the original simulation modelling method and the generic methodology.

The three most obvious differences (apart from all the other differences) between the original simulation model and the ED evaluation method option Arena and Simul8 simulation models are the following:
a)   The original simulation model uses the ITI evaluation method, while the ED evaluation method option Arena and Simul8 simulation models use the ED evaluation method (see Section 3.7).
b)   The original simulation model uses the throughput utilisation values to identify the primary "bottlenecks", while the ED evaluation method option Arena and Simul8 simulation models use the time and production lost "bottleneck" identification techniques to identify the primary "bottlenecks" (see Section 2.6).
c)   The original simulation model does not make provision for the identification of the secondary "bottlenecks" (flares), while the ED evaluation method option Arena and Simul8 simulation models do identify the secondary "bottlenecks" (see Section 2.6).

Section 3.3 indicates that the Arena and Simul8 simulation models use input and output files and spreadsheet variables as input and output mechanisms. The input and output variables (data) in the input and output files and spreadsheet variables, however, still need further manipulation to provide coherent and comprehensible results (see the process of moving from data to information

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that is described in Section1.3). To this end preformatted spreadsheets were developed for the manipulation of the output files and spreadsheet variables (the input files are manipulated with a text editor). The most obvious benefits that follow from this development are standardisation in the presentation of results and ease of use. These concepts obviously also support the user-friendliness design criterion (see Section 1.5) of the generic simulation modelling methodology.

A detail discussion of all the results that are presented in the preformatted spreadsheets does not fall within the scope of this document. The following summary, however, provides an insight into the most important aspects of the results that are presented in the preformatted spreadsheets.

The most important aspects of the results that are presented in the preformatted spreadsheets are the following:

a)   The mean output throughput values of the 16 primary points of evaluation (see Table 3.1). (Some of the points of evaluation have more than one mean output throughput value and in such an instance only the most important mean output throughput value is considered.) Only 13 values are presented because the three mean output throughput values of the Oxygen Plant incorporate the three mean output throughput values of the Oxygen Extra plant, when the Oxygen Extra plant is incorporated into the simulation model in Scenario II.

b)   The mean output throughput values of the five secondary and seven tertiary points of evaluation (see Table 3.1). The three mean output throughput values of the Oxygen Extra plant are also incorporated into this group because they are used to verify that the simulation models operate correctly, when the Oxygen Extra plant is incorporated into the simulation model in Scenario II.

c)   The mean time that each of the 16 primary points of evaluation is the primary "bottleneck", as a percentage (see the time "bottleneck" identification technique in Section 2.6). Only 13 values are presented because the three mean time values of the Oxygen plant incorporate the three mean time values of the Oxygen Extra plant, when the Oxygen Extra plant is incorporated into the simulation model in Scenario II. The three mean time values of the Oxygen Extra plant are also incorporated into this group because they are used to verify that the simulation models operate correctly, when the Oxygen Extra plant is incorporated into the simulation model in Scenario II.

d)   The mean production that is lost when each of the 16 primary points of evaluation is the primary "bottleneck", as a percentage (see the production lost "bottleneck" identification technique in Section 2.6). Only 13 values are presented because the three mean production lost values of the Oxygen plant incorporate the three mean production lost

values of the Oxygen Extra plant, when the Oxygen Extra plant is incorporated into the simulation model in Scenario II.

e) The mean volume in the tank and the total volumes and mean rates of flare at the secondary "bottlenecks".

f) The mean number of available modules in each of the smaller plants and the mean number of modules that is switched on or off in each of the smaller plants.

g) The mean number of services completed and missed in each of the smaller plants and the mean number of failures repaired in each of the smaller plants.

h) The mean values of various variables that monitor the functioning of the simulation models. It includes a histogram that indicates how many modules were removed for service or repair every simulation model evaluation.

i) The mean number of times that each of the 16 primary points of evaluation is the primary "bottleneck". Only 13 values are presented because the three values of the Oxygen plant incorporate the three values of the Oxygen Extra plant, when the Oxygen Extra plant is incorporated into the simulation model in Scenario II. This histogram values are used to verify the time primary "bottleneck" identification technique values if the ITI evaluation method is used.

j) The "throughput vector" that consists of the mean input throughput values of the Synthetic Fuel plant and the mean output throughput values of each of the smaller plants (see the convention that is detailed in Section 2.2).

k) The mean utilisation values of the Service and Repair Teams of all the smaller plants that are subject to services and failures, as percentages.

l) A comparison test that compares the mean utilisation values of the Service and Repair Teams of all the smaller plants that are subject to services and failures with the theoretical utilisation values to validate the mean utilisation values. Other variables that monitor the functioning of the simulation models are also subjected to logical tests.

The previous discussion on the aspects that are addressed in the preformatted spreadsheets is based on the preformatted spreadsheet of the Arena simulation model. The preformatted spreadsheet of the Simul8 simulation model contains exactly the same data and information, but not necessarily in exactly the same order.

In Section 3.7 the means of the output throughput values of the Gas Production plant are calculated from the results of the 20 replications of the simulation runs that were completed with the ED evaluation method option Arena and Simul8 simulation models. The mean output throughput values of the Gas Production plant are used to validate the simulation models and it

is indicated that it can be accepted with a high level of confidence that the simulation models are valid representations of the Synthetic Fuel plant. The full results of the simulation run that was completed with the ED evaluation method option Arena simulation model represent the Scenario I results of the Arena simulation model and is shown in Appendix Q: *ED Evaluation Method Option Arena Simulation Model Results (Scenario I)*. The full results of the simulation run that was completed with the ED evaluation method option Simul8 simulation model represent the Scenario I results of the Simul8 simulation model and is shown in Appendix R: *ED Evaluation Method Option Simul8 Simulation Model Results (Scenario I)*.

Summary

This section identifies the two alternative scenarios that are investigated in this chapter. Scenario I represents the Synthetic Fuel plant without the inclusion of the Oxygen Extra plant (*i.e.* the inclusion of an extra oxygen "train") and is used to identify the problem areas or "bottlenecks" in the plant. Scenario II represents the Synthetic Fuel plant with the Oxygen Extra plant incorporated and is used to determine how this addition impacts on the throughput of the plant. An overview of the most important aspects of the results that are presented in the preformatted spreadsheets, is also provided.

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4.2   SCENARIO I RESULTS

In this section the problem areas or "bottlenecks" in the Synthetic Fuel plant are identified by analysing the results of the Scenario I simulation runs that were completed with the ED evaluation method option Arena and Simul8 simulation models.

Table 4.1: *Scenario I Primary "Bottlenecks"* provides the Scenario I results of the ED evaluation method option Arena and Simul8 simulation models for the primary "bottlenecks" in terms of the time (see Equation 2.15) and production lost (see Equation 2.16) criteria. The throughput utilisation values (see Equations 2.13 and 2.14) for the primary "bottlenecks" are also shown.

It is important to note that each of the throughput utilisation values is given as a percentage for the specific point of evaluation while the time and production lost values are given as percentages of the total time and total production lost values.

Table 4.1: Scenario I Primary "Bottlenecks"

No.	Name	Arena Simulation Model			Simul8 Simulation Model		
		ThrUtl (%)	Time (%)	PrdLst (%)	ThrUtl (%)	Time (%)	PrdLst (%)
1	Coal Processing	68,58	0,02	0,02	68,59	0,08	0,09
3	Steam	50,47	0,00	0,00	50,38	0,00	0,00
4	Gas Production	85,58	0,77	0,31	85,65	1,09	0,51
5	Temperature Regulation	80,33	0,00	0,00	80,31	0,00	0,00
6-A	Oxygen-A	90,41	10,96	18,11	90,41	11,17	18,45
6-B	Oxygen-B	88,77	1,14	1,86	88,78	1,32	2,14
6-C	Oxygen-C	77,51	0,18	0,30	77,50	0,19	0,31
8	Plant(I)	93,58	28,63	28,30	93,57	27,91	28,20
9-A	Plant(II)-A	93,82	57,53	47,16	93,90	57,53	46,70
9-B	Plant(II)-B	59,45	0,03	0,08	59,44	0,04	0,10
10	Plant(III)	84,14	0,25	1,32	84,13	0,26	1,34
11	Division Process	84,25	0,49	2,54	84,20	0,41	2,16
12	Recycling	75,82	0,00	0,00	75,80	0,00	0,00

Where:

No.	:	The plant identification number.
ThrUtl	:	The throughput utilisation value of the primary "bottleneck" (%).
Time	:	The time that the primary "bottleneck" is the "bottleneck" (%).
PrdLst	:	The production lost due to each of the primary "bottlenecks" (%).

From Table 4.1 it follows that the three most important primary "bottlenecks", in order of importance, are Plant(II)-A, Plant(I) and Oxygen-A. All three the primary "bottleneck" identification criteria support this finding. According to the throughput utilisation value criterion the three most important primary "bottlenecks" are Plant(II)-A (93,82% - Arena and 93,90% - Simul8), Plant(I) (93,58% - Arena and 93,57% - Simul8) and Oxygen-A (90,41% - Arena and Simul8). According to the time criterion the three most important primary "bottlenecks" are Plant(II)-A (57,53% - Arena and Simul8), Plant(I) (28,63% - Arena and 27,91% - Simul8) and Oxygen-A (10,96% - Arena and 11,17% - Simul8). According to the production lost criterion the three most important primary "bottlenecks" are Plant(II)-A (47,16% - Arena and 46,70% - Simul8), Plant(I) (28,30% - Arena and 28,20% - Simul8) and Oxygen-A (18,11% - Arena and 18,45% - Simul8).

These results are presented in Table 4.2: *Scenario I Primary "Bottlenecks" Prioritised*.

Table 4.2: Scenario I Primary "Bottlenecks" Prioritised

No.	Name	Arena Simulation Model			Simul8 Simulation Model		
		ThrUtl (%)	Time (%)	PrdLst (%)	ThrUtl (%)	Time (%)	PrdLst (%)
9-A	Plant(II)-A	93,82	57,53	47,16	93,90	57,53	46,70
8	Plant(I)	93,58	28,63	28,30	93,57	27,91	28,20
6-A	Oxygen-A	90,41	10,96	18,11	90,41	11,17	18,45

Where:

No.	:	The plant identification number.
ThrUtl	:	The throughput utilisation value of the primary "bottleneck" (%).
Time	:	The time that the primary "bottleneck" is the "bottleneck" (%).
PrdLst	:	The production lost due to each of the primary "bottlenecks" (%).

A discussion on the interpretation of the throughput utilisation values of Scenario I is provided in the *Magister* dissertation (Albertyn, 1995:84-89). The throughput utilisation values of the Scenario I ED evaluation method option Arena and Simul8 simulation models correlates extremely closely with those of the original simulation model (Albertyn, 1995:88). In this document, however, the time and production lost criteria are the focus of the discussion.

From Table 4.2 it follows that Plant(II)-A is the primary "bottleneck" for approximately 58% of the time and is responsible for approximately 47% of the production that is lost. Plant(I) is the primary "bottleneck" for approximately 28% of the time and is responsible for approximately 28% of the production that is lost. These results thoroughly substantiate the perception of the engineering division of the Synthetic Fuel plant that Plant(II)-A and Plant(I) are the "troublemakers". Oxygen-A is the primary "bottleneck" for approximately 11% of the time but is responsible for approximately 18% of the production that is lost. This indicates that when Oxygen-A is the primary "bottleneck", it has a pronounced effect on the throughput of the Synthetic Fuel plant and therefore Oxygen-A is a valid candidate for increased capacity, even though more production is lost at Plant(II)-A and Plant(I). In this document the addition of an extra oxygen "train" is the proposed change scenario that is under scrutiny, but it should be noted that both Plant(II)-A and Plant(I) are also subjected to continuous improvement drives.

Table 4.3: *Scenario I Secondary "Bottlenecks"* provides the Scenario I results of the ED evaluation method option Arena and Simul8 simulation models for the secondary "bottlenecks" in terms of the total volumes and mean rates of flare at the secondary "bottlenecks".

Table 4.3: Scenario I Secondary "Bottlenecks"

No.	Name	Flare	Arena Simulation Model		Simul8 Simulation Model	
			Volume (m³, nm³)	Rate (m³/h, nm³/h)	Volume (m³, nm³)	Rate (m³/h, nm³/h)
13	Plant(IV)	Flare-A	3362,1	0,389	7264,6	0,841
14	Sub(I)	Flare-C1	0,0	0,000	0,0	0,000
15	Sub(II)	Flare-C2	0,0	0,000	0,0	0,000
16	Sub(III)	Flare-C3	0,0	0,000	0,0	0,000
17	Sub(IV)	Flare-C4	0,0	0,000	0,0	0,000
18	Sub(V)	Flare-C5	0,0	0,000	0,0	0,000
19	Sub(VI)	Flare-C6	0,0	0,000	0,0	0,000
20	Plant(V)	Flare-B	17036,7	1,972	17191,2	1,990

Where:

No.   : The plant identification number.

From Table 4.3 it is evident that there are only two secondary "bottlenecks", namely: Plant(IV) and Plant(V). The difference in the total volume and mean rate of flare values at Plant(IV), between the results of the Arena and Simul8 simulation models, is immediately noticeable. The total volume and mean rate of flare values of the Arena simulation model are approximately half that of the Simul8 simulation model. This discrepancy warrants further investigation. Closer examination of the rest of the results of the two simulation runs, however, reveals that the mean number of failures created at Plant(IV)-C is 0,15 for the Arena simulation model and 0,30 for the Simul8 simulation model. The higher number of failures created by the Simul8 simulation model implies that Plant(IV)-C was less available in the Simul8 simulation run and therefore a bigger portion of the throughput was flared. There is no discernible difference in the total volume and mean rate of flare values at Plant(V) between the results of the Arena and Simul8 simulation models. A scrutiny of the rest of the results of the two simulation runs reveals that the mean number of failures created at Plant(V) is 11,20 for the Arena simulation model and 11,05 for the Simul8 simulation model.

Summary

In this section the Scenario I results of the ED evaluation method option Arena and Simul8 simulation models are used to identify the primary and secondary "bottlenecks" in the Synthetic Fuel plant. The three most important primary "bottlenecks" are Plant(II)-A, Plant(I) and Oxygen-A (arranged in order of declining importance). Oxygen-A is responsible for approximately 18% of the production that is lost. Plant(IV) and Plant(V) are the only two secondary "bottlenecks" that have to flare portions of their throughput.

* * * * *

4.3   SCENARIO II RESULTS

In this section the effect of a proposed change (the addition of an extra oxygen "train") on the Synthetic Fuel plant is determined by analysing the results of the Scenario II simulation runs that were completed with the ED evaluation method option Arena and Simul8 simulation models. Simulation runs consisting of 20 replications of a simulated time period of one year (see Appendix L) were completed with the Scenario II simulation models. The input of the Scenario II simulation runs was exactly the same as those of the Scenario I simulation runs that are described in Section 3.7, with the exception that the Oxygen Extra plant was incorporated into the Synthetic Fuel plant.

In Table 4.4: *Verification of the Scenario II Simulation Models* the Scenario II ED evaluation method option Arena and Simul8 simulation models are verified by comparing the time that each of Oxygen-A, -B and -C is the primary "bottleneck" (including the time that they are multiple "bottlenecks") in Scenario I, with the number of modules that is switched on values of each of Oxygen Extra-A, -B and -C in Scenario II. It logically follows that there should be a close correlation between the time that a point of evaluation is the "bottleneck" in Scenario I and the number of additional modules that is switched on in Scenario II. Oxygen Extra-A, -B and -C has only one module each and therefore the number of modules that is switched on values in the Scenario II results also represent the time that the modules were switched on because the modules are only switched on when needed.

Table 4.4: Verification of the Scenario II Simulation Models

No.	Name	Arena Simulation Model		Simul8 Simulation Model	
		Scenario I Time "Btt" (%)	Scenario II No. Swt On	Scenario I Time "Btt" (%)	Scenario II No. Swt On
6-A	Oxygen-A	11,15	-	11,37	-
6-B	Oxygen-B	1,22	-	1,38	-
6-C	Oxygen-C	0,30	-	0,32	-
6E-A	Oxygen Extra-A	-	0,112	-	0,114
6E-B	Oxygen Extra-B	-	0,012	-	0,014
6E-C	Oxygen Extra-C	-	0,003	-	0,003

Where:

No.   :   The plant identification number.

Time "Btt"   :   The time that each point of evaluation is the primary "bottleneck" (including the time that they are multiple "bottlenecks").

No. Swt On :   The number of modules that is switched on.

A scrutiny of Table 4.4 reveals that there is a 100% correlation between the time that each of Oxygen-A, -B and -C is the primary "bottleneck" (including the time that they are multiple "bottlenecks") in Scenario I and the number of modules that is switched on values of each of Oxygen Extra-A, -B and -C in Scenario II for both the Arena and Simul8 simulation models. It can therefore be concluded that the Scenario II simulation models operate as intended, insofar as Oxygen Extra-A, -B and -C are concerned.

It is interesting to note that the inclusion of an extra oxygen "train" (*i.e.* the Oxygen Extra plant) into the simulation models of the Synthetic Fuel plant is not a straightforward matter. A scrutiny of Table A1 reveals that Oxygen Extra-A and -C are electricity-driven while Oxygen-A and -C are steam-driven. This implies that the ratio of steam that is supplied to the Gas Production plant to steam that is supplied to the Oxygen plant (*i.e.* the steam-division-ratio) changes when Oxygen Extra-A or -C is switched on. Iterative loops are used in the logic engine high-level building block to accommodate this very complex concept. A detail discussion of these iterative loops does not fall within the scope of this document.

Table 4.5: *Comparison of the Scenario I and II Simulation Models* provides a comparison between the Scenario I (see Table 3.7) and II ED evaluation method option Arena and Simul8

simulation models.

Table 4.5: Comparison of the Scenario I and II Simulation Models

Simulation Model	Scn	n_{Rep}	Runtime (min)	GasPro (nm³/h)	StdDev (nm³/h)	n_{Sam}	Deviation (%)
Arena (ED)	I	20	8,6	1332471,8	6620,5	11	0,018
Arena (ED)	II	20	8,7	1351034,1	7443,5	13	-
Simul8 (ED)	I	20	6,8	1332253,3	7462,5	13	0,001
Simul8 (ED)	II	20	7,0	1351484,8	8149,1	14	-

Where:

Scn	:	The scenario number.
n_{Rep}	:	The number of replications completed.
Runtime	:	The simulation runtime for n_{Rep} replications (minute).
GasPro	:	The mean output throughput value of the Gas Production plant, calculated from n_{Rep} replications (nm³/h).
StdDev	:	The standard deviation from the mean output throughput value (nm³/h).
n_{Sam}	:	The minimum sufficient sample size.
Deviation	:	The deviation of the specific mean output throughput value from the mean output throughput value of the Gas Production plant during the 1993 production year (%).

The means and the standard deviations from the means of the output throughput values of the Gas Production plant, are calculated from the results of the 20 replications of the simulation runs that were completed with the ED evaluation method option Arena and Simul8 Scenario II simulation models. The standard deviations are used to calculate the corresponding minimum sufficient sample sizes with an allowance for a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant (see Appendix M) and a 99% confidence interval. Section 3.5 provides a detailed explanation of the determination of minimum sufficient sample size. The number of replications completed in both instances should be more than, or equal to, the calculated minimum sufficient sample sizes for the answers to be taken as representative of the simulated scenario. A scrutiny of Columns 3 and 7 of Table 4.5 indicates that this constraint is adhered to.

From Table 4.5 it follows that the simulation runtimes of the Scenario II simulation models are

slightly longer than those of the Scenario I simulation models for both the Arena and Simul8 simulation models. This can be attributed to the fact that the Scenario II simulation models complete additional tasks when the Oxygen Extra plant is incorporated. The mean output throughput values of the Gas Production plant of the Scenario II simulation models are also larger than those of the Scenario I simulation models for both the Arena and Simul8 simulation models. This indicates that the addition of the extra oxygen "train" leads to a higher throughput.

Table 4.6: *99% Confidence Intervals for the Output Throughput (Scenario I and II Simulation Models)* provides the 99% confidence intervals for the mean output throughput values of the Scenario I and II ED evaluation method option Arena and Simul8 simulation models. The mean output throughput values of the Gas Production plant are used.

Table 4.6: 99% Confidence Intervals for the Output Throughput
(Scenario I and II Simulation Models)

Simulation Model	Scn	GasPro (nm^3/h)	StdDev (nm^3/h)	ConInt (nm^3/h)	Lower ConLmt (nm^3/h)	Upper ConLmt (nm^3/h)
Arena (ED)	I	1332471,8	6620,5	8470,8	1328236,4	1336707,2
Arena (ED)	II	1351034,1	7443,5	9523,8	1346272,2	1355796,0
Simul8 (ED)	I	1332253,3	7462,5	9548,1	1327479,2	1337027,4
Simul8 (ED)	II	1351484,8	8149,1	10426,6	1346271,5	1356698,1

Where:

Scn	:	The scenario number.
GasPro	:	The mean output throughput value of the Gas Production plant, calculated from n_{Rep} replications (nm^3/h).
StdDev	:	The standard deviation from the mean output throughput value (nm^3/h).
ConInt	:	The confidence interval (nm^3/h).
ConLmt	:	The confidence limit (nm^3/h).

Section 3.6 indicates that the confidence intervals should be taken into consideration when alternatives are compared. If the confidence intervals for the mean output throughput values of two scenarios overlap, the two scenarios cannot be differentiated in terms of representing two different outcomes.

A scrutiny of Columns 6 and 7 of Table 4.6 reveals that the 99% confidence intervals for the

mean output throughput values of the Scenario I and II Arena simulation models do not overlap and therefore the two scenarios can be assumed to represent two different outcomes. This implies that it is valid to use the delta between the mean output throughput values of the Scenario I and II Arena simulation models to determine the effect of the additional oxygen "train" on the throughput of the Synthetic Fuel plant. Furthermore, the 99% confidence intervals for the mean output throughput values of the Scenario I and II Simul8 simulation models also do not overlap and therefore the two scenarios can be assumed to represent two different outcomes. This implies that it is valid to use the delta between the mean output throughput values of the Scenario I and II Simul8 simulation models to determine the effect of the additional oxygen "train" on the throughput of the Synthetic Fuel plant.

Table 4.7: *Scenario II Primary "Bottlenecks"* provides the Scenario II results of the ED evaluation method option Arena and Simul8 simulation models for the primary "bottlenecks" in terms of the time (see Equation 2.15) and production lost (see Equation2.16) criteria. The throughput utilisation values (see Equations 2.13 and 2.14) for the primary "bottlenecks" are also shown.

Table 4.7: Scenario II Primary "Bottlenecks"

No.	Name	Arena Simulation Model			Simul8 Simulation Model		
		ThrUtl (%)	Time (%)	PrdLst (%)	ThrUtl (%)	Time (%)	PrdLst (%)
1	Coal Processing	69,53	0,02	0,03	69,58	0,09	0,12
3	Steam	50,95	0,00	0,00	50,88	0,00	0,00
4	Gas Production	86,77	1,03	0,47	86,89	1,27	0,71
5	Temperature Regulation	81,45	0,00	0,00	81,47	0,00	0,00
6-A	Oxygen-A	79,10	0,18	0,37	79,14	0,21	0,41
6-B	Oxygen-B	76,45	0,00	0,00	76,49	0,00	0,00
6-C	Oxygen-C	68,14	0,00	0,01	68,17	0,00	0,01
8	Plant(I)	94,88	32,42	33,12	94,92	31,98	33,19
9-A	Plant(II)-A	95,13	65,57	61,40	95,25	65,75	61,32
9-B	Plant(II)-B	60,28	0,03	0,09	60,30	0,04	0,11
10	Plant(III)	85,31	0,25	1,54	85,35	0,26	1,58
11	Division Process	85,45	0,49	2,97	85,42	0,41	2,54
12	Recycling	76,87	0,00	0,00	76,90	0,00	0,00

Where:

No.	:	The plant identification number.
ThrUtl	:	The throughput utilisation value of the primary "bottleneck" (%).
Time	:	The time that the primary "bottleneck" is the "bottleneck" (%).
PrdLst	:	The production lost due to each of the primary "bottlenecks" (%).

In Section 4.2 the three most important primary "bottlenecks" are identified from the results of the Scenario I simulation runs. They are, in order of importance, Plant(II)-A, Plant(I) and Oxygen-A. Table 4.7 indicates that the Scenario II results for the throughput utilisation values of the most important Scenario I primary "bottlenecks" are the following: 95,13% (Arena) and 95,25% (Simul8) for Plant(II)-A, 94,88% (Arena) and 94,92% (Simul8) for Plant(I) and 79,10% (Arena) and 79,14% (Simul8) for Oxygen-A. The Scenario II results, according to the time criterion, of the most important Scenario I primary "bottlenecks" are the following: 65,57% (Arena) and 65,75% (Simul8) for Plant(II)-A, 32,42% (Arena) and 31,98% (Simul8) for Plant(I) and only 0,18% (Arena) and 0,21% (Simul8) for Oxygen-A. The Scenario II results, according to the production lost criterion, of the most important Scenario I primary "bottlenecks" are the following: 61,40% (Arena) and 61,32% (Simul8) for Plant(II)-A, 33,12% (Arena) and 33,19% (Simul8) for Plant(I) and only 0,37% (Arena) and 0,41% (Simul8) for Oxygen-A.

These results are presented in Table 4.8: *Scenario II Primary "Bottlenecks" Prioritised*.

Table 4.8: Scenario II Primary "Bottlenecks" Prioritised

No.	Name	Arena Simulation Model			Simul8 Simulation Model		
		ThrUtl (%)	Time (%)	PrdLst (%)	ThrUtl (%)	Time (%)	PrdLst (%)
9-A	Plant(II)-A	95,13	65,57	61,40	95,25	65,75	61,32
8	Plant(I)	94,88	32,42	33,12	94,92	31,98	33,19
6-A	Oxygen-A	79,10	0,18	0,37	79,14	0,21	0,41

Where:

No.	:	The plant identification number.
ThrUtl	:	The throughput utilisation value of the primary "bottleneck" (%).
Time	:	The time that the primary "bottleneck" is the "bottleneck" (%).
PrdLst	:	The production lost due to each of the primary "bottlenecks" (%).

Table 4.8 actually represents the results of the three most important primary "bottlenecks" that are identified from the results of the Scenario I simulation runs in Section 4.2 and not the three most important primary "bottlenecks" of the Scenario II simulation runs. The reason for this is that it allows a direct comparison of the three primary "bottleneck" identification criteria for Oxygen-A between Scenario I and II.

A discussion on the interpretation of the throughput utilisation values of Scenario II is provided in the *Magister* dissertation (Albertyn, 1995:90-94). The throughput utilisation values of the Scenario II ED evaluation method option Arena and Simul8 simulation models correlate extremely closely with those of the original simulation model (Albertyn, 1995:94). In this document, however, the time and production lost criteria are the focus of the discussion.

From Table 4.8 it follows that Plant(II)-A is the primary "bottleneck" for approximately 66% of the time and is responsible for approximately 61% of the production that is lost. Plant(I) is the primary "bottleneck" for approximately 32% of the time and is responsible for approximately 33% of the production that is lost. Oxygen-A is the primary "bottleneck" for less than 1% of the time and is responsible for less than 1% of the production that is lost.

Table 4.9: *Scenario II Secondary "Bottlenecks"* provides the Scenario II results of the ED evaluation method option Arena and Simul8 simulation models for the secondary "bottlenecks" in terms of the total volumes and mean rates of flare at the secondary "bottlenecks".

Table 4.9: Scenario II Secondary "Bottlenecks"

No.	Name	Flare	Arena Simulation Model		Simul8 Simulation Model	
			Volume (m^3, nm^3)	Rate $(m^3/h, nm^3/h)$	Volume (m^3, nm^3)	Rate $(m^3/h, nm^3/h)$
13	Plant(IV)	Flare-A	3413,9	0,395	7328,2	0,848
14	Sub(I)	Flare-C1	0,0	0,000	0,0	0,000
15	Sub(II)	Flare-C2	0,0	0,000	0,0	0,000
16	Sub(III)	Flare-C3	0,0	0,000	0,0	0,000
17	Sub(IV)	Flare-C4	0,0	0,000	0,0	0,000
18	Sub(V)	Flare-C5	0,0	0,000	0,0	0,000
19	Sub(VI)	Flare-C6	0,0	0,000	0,0	0,000
20	Plant(V)	Flare-B	19418,8	2,248	19413,0	2,247

Where:

No.   :   The plant identification number.

From Table 4.9 it is evident that there are only two secondary "bottlenecks", namely: Plant(IV) and Plant(V). The difference in the total volume and mean rate of flare values at Plant(IV) between the results of the Arena and Simul8 simulation models is immediately noticeable. The total volume and mean rate of flare values of the Arena simulation model are approximately half that of the Simul8 simulation model. The explanation for this anomaly in the results is provided in Section 4.2. There is no discernible difference in the total volume and mean rate of flare values at Plant(V) between the results of the Arena and Simul8 simulation models.

Summary

In this section the Scenario I and II results of the ED evaluation method option Arena and Simul8 simulation models are used to verify the Scenario II simulation models, to compare the Scenario I and II simulation models and to establish the 99% confidence intervals for the mean output throughput values of the Scenario I and II simulation models. The confidence intervals do not overlap and therefore the two scenarios can be assumed to represent two different outcomes. The Scenario II results are used to identify the primary and secondary "bottlenecks" and it is indicated that the two most important primary "bottlenecks" are Plant(II)-A and Plant(I). Oxygen-A is only responsible for less than 1% of the production that is lost in Scenario II. The total volume and mean rate of flare values indicate that Plant(IV) and Plant(V) are the only two secondary "bottlenecks" in Scenario II.

* * * * *

4.4   COMPARISON OF THE SCENARIO I AND II RESULTS AND THE CONCLUSIONS

This section compares the Scenario I and II results (see Sections 4.2 and 4.3) of the ED evaluation method option Arena and Simul8 simulation models and presents some logical conclusions that can be derived from these results.

Table 4.10: *Comparison of the Scenario I and II Primary "Bottlenecks"* provides a comparison between the Scenario I and II results of the ED evaluation method option Arena and Simul8 simulation models for the most important primary "bottlenecks" in terms of the time (see Equation 2.15) and production lost (see Equation 2.16) criteria.

Table 4.10: Comparison of the Scenario I and II Primary "Bottlenecks"

No.	Name	Arena Simulation Model				Simul8 Simulation Model			
		Scenario I		Scenario II		Scenario I		Scenario II	
		Time (%)	PrdLst (%)	Time (%)	PrdLst (%)	Time (%)	PrdLst (%)	Time (%)	PrdLst (%)
9-A	Plant(II)-A	57,53	47,16	65,57	61,40	57,53	46,70	65,75	61,32
8	Plant(I)	28,63	28,30	32,42	33,12	27,91	28,20	31,98	33,19
6-A	Oxygen-A	10,96	18,11	0,18	0,37	11,17	18,45	0,21	0,41
	Total	**97,12**	**93,57**	**98,17**	**94,89**	**96,61**	**93,35**	**97,94**	**94,92**

Where:

No.	:	The plant identification number.
Time	:	The time that the primary "bottleneck" is the "bottleneck" (%).
PrdLst	:	The production lost due to each of the primary "bottlenecks" (%).

Table 4.10 indicates that Plant(II)-A, Plant(I) and Oxygen-A (the three most important primary "bottlenecks") are the primary "bottlenecks" for a total of approximately 97% of the time and are responsible for a total of approximately 93% of the production that is lost in Scenario I. Oxygen-A is the primary "bottleneck" for approximately 11% of the time out of the total of 97% for the three most important primary "bottlenecks" and is responsible for approximately 18% of the production that is lost out of the total of 93% in Scenario I. Scenario II, however, presents a different picture. Plant(II)-A, Plant(I) and Oxygen-A are the primary "bottlenecks" for a total of approximately 98% of the time and are responsible for a total of approximately 95% of the

production that is lost in Scenario II. Oxygen-A, however, is the primary "bottleneck" for less than 1% of the time out of the total of 98% and is responsible for less than 1% of the production that is lost out of the total of 95% in Scenario II.

The results of the previous paragraph clearly indicate that Oxygen-A does not qualify as an important primary "bottleneck" in Scenario II. In fact, Plant(II)-A and Plant(I) together are the primary "bottlenecks" for most (98%) of the time and are responsible for most (95%) of the production that is lost in Scenario II.

These results are graphically depicted in Figure 4.1: *Comparison of the Scenario I and II Primary "Bottlenecks"* which shows the time (on the left-hand side of the graph) and production lost (on the right-hand side of the graph) of Plant(II)-A, Plant(I) and Oxygen-A.
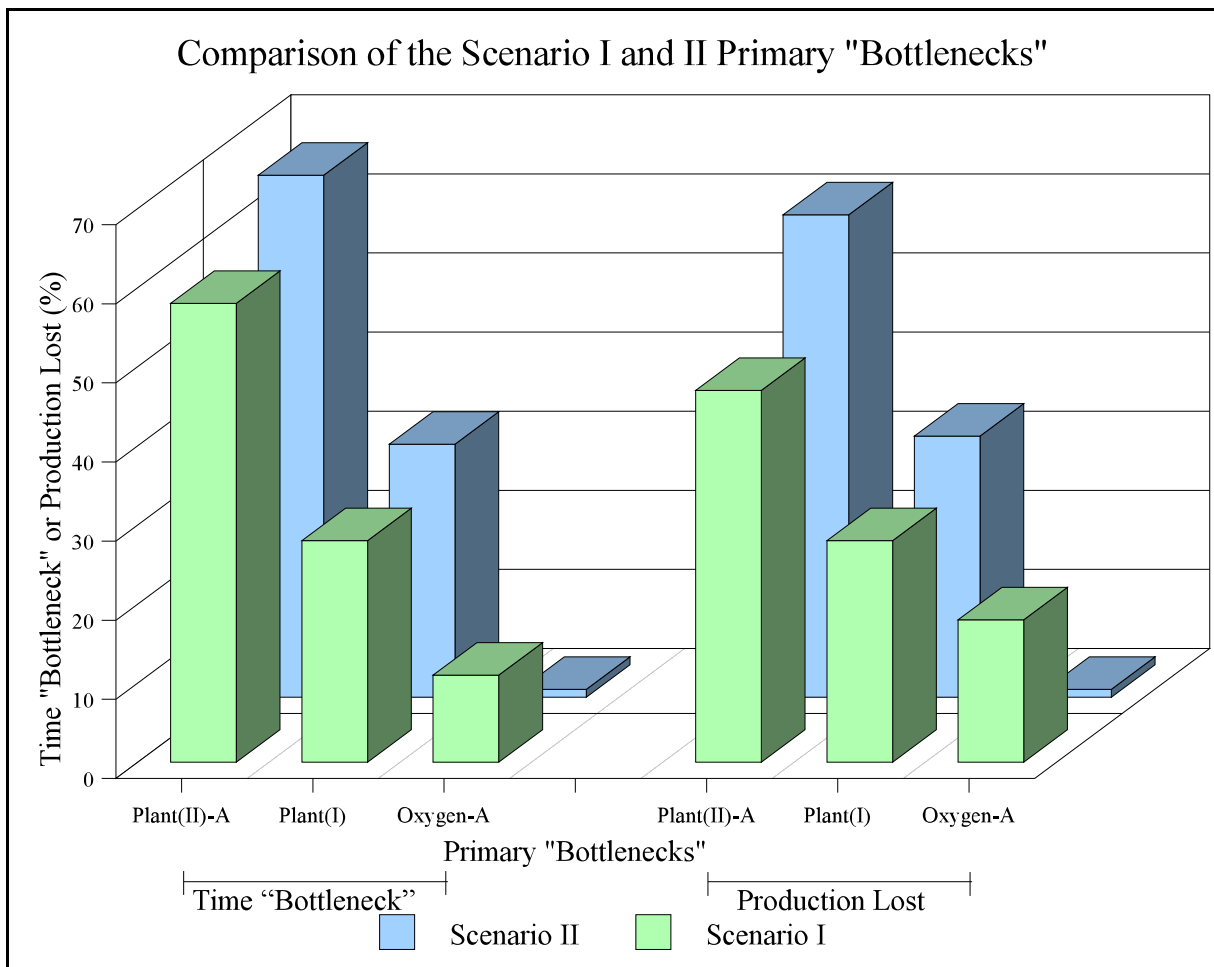
Figure 4.1: Comparison of the Scenario I and II Primary "Bottlenecks"

Oxygen-A does not qualify as an important primary "bottleneck" anymore, when an additional oxygen "train" (the Oxygen Extra plant) is incorporated into the Synthetic Fuel plant in the Scenario II ED evaluation method option Arena and Simul8 simulation models.

Table 4.11: *Comparison of the Scenario I and II Secondary "Bottlenecks"* provides a comparison between the Scenario I and II results of the ED evaluation method option Arena and Simul8 simulation models for the most important secondary "bottlenecks" in terms of the total volumes and mean rates of flare at the secondary "bottlenecks".

Table 4.11: Comparison of the Scenario I and II Secondary "Bottlenecks"

No.	Name	Flare	Arena Simulation Model				Simul8 Simulation Model			
			Scenario I		Scenario II		Scenario I		Scenario II	
			Vol (D1)	Rate (D2)	Vol (D1)	Rate (D2)	Vol (D1)	Rate (D2)	Vol (D1)	Rate (D2)
13	Plant(IV)	Flare-A	3362,1	0,389	3413,9	0,395	7264,6	0,841	7328,2	0,848
20	Plant(V)	Flare-B	17036,7	1,972	19418,8	2,248	17191,2	1,990	19413,0	2,247

Where:

No.	:	The plant identification number.
Vol (D1)	:	The total volume flared (m^3, nm^3).
Rate (D2)	:	The mean rate of flare (m^3/h, nm^3/h).

From Table 4.11 it follows that Plant(IV) and Plant(V) are the only two important secondary "bottlenecks". The difference in the total volume and mean rate of flare values at Plant(IV), between the results of the Scenario I Arena and Simul8 simulation models, is immediately noticeable. The same applies to the Scenario II simulation models. The total volume and rate of flare values of the Scenario I and II Arena simulation models are approximately half that of the Scenario I and II Simul8 simulation models. Section 4.2 indicates that this discrepancy can be attributed to that fact that the mean number of failures created at Plant(IV)-C is 0,15 for the Arena simulation model and 0,30 for the Simul8 simulation model in both Scenario I and II. The higher number of failures created by the Simul8 simulation model implies that Plant(IV)-C was less available in the Simul8 simulation run and therefore a bigger portion of the throughput was flared in both Scenario I and II. There is no discernible difference in the total volume and rate of flare values at Plant(V) between the results of the Scenario I Arena and Simul8 simulation models, and also no discernible difference in the results of the Scenario II Arena and Simul8 simulation

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models. A scrutiny of the rest of the results of the two simulation runs reveals that the mean number of failures created at Plant(V) is 11,20 for the Arena simulation model and 11,05 for the Simul8 simulation model in both Scenario I and II.

The exposition in the previous paragraph indicates that results that are in any way dependent on low failure rates should be scrutinised more carefully. This view is supported by the discussion in Section 3.6 which shows that a large deviation of the number of failures created by the Arena and Simul8 simulation models and the real-world number of failures that occur is acceptable for a point of evaluation with a low failure rate. When fewer failures occur, the effect of these failures on a system seems to be more pronounced. In such an instance the simulation run should be extended to include more replications. This should have an equalising effect on the results and could present a more balanced picture of what is actually happening at that point in the simulation model.

In Scenario II the total volume and mean rate of flare values at Plant(IV) and Plant(V) are slightly larger than in Scenario I. This result can be explained by the fact that the mean output throughput value of the Gas Production plant in Scenario II is larger than in Scenario I (see Section 4.3). The larger mean output throughput value of the Gas Production plant, in Scenario II, cascades through the simulation model and leads to larger mean throughput values at Plant(IV) and Plant(V). There is no difference between the capacities, service schedules and failure characteristics of the modules of Plant(IV) and Plant(V) in Scenario I and II. It is therefore obvious that the total volume and mean rate of flare values at Plant(IV) and Plant(V) will be larger in Scenario II.

Table 4.12: *Comparison of the Scenario I and II Output Throughput* shows the deltas, the gains and the gains, expressed as production days, of the mean output throughput values of the Gas Production plant between the Scenario I and II results of the ED evaluation method option Arena and Simul8 simulation models.

Section 4.3 indicates that the 99% confidence intervals for the mean output throughput values of the Scenario I and II Arena and Simul8 simulation models do not overlap and therefore the two scenarios can be assumed to represent two different outcomes for both the simulation models. This implies that it is valid to use the deltas between the mean output throughput values of the Scenario I and II Arena and Simul8 simulation models to determine the effect of the additional oxygen "train" on the throughput of the Synthetic Fuel plant.

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Table 4.12: Comparison of the Scenario I and II Output Throughput

Simulation Model	Scn	GasPro (nm³/h)	Delta (nm³/h)	Gain (%)	Production Days (Day)
Arena (ED)	I	1332471,8	18562,3	1,3931	5,02
Arena (ED)	II	1351034,1			
Simul8 (ED)	I	1332253,3	19231,5	1,4435	5,20
Simul8 (ED)	II	1351484,8			

Where:

Scn   :   The scenario number.

GasPro   :   The mean output throughput value of the Gas Production plant, calculated from n_{Rep} replications (nm³/h).

From Table 4.12 it follows that the deltas between the mean output throughput values of the Gas Production plant in Scenario I and II are 18562,3 nm³/h for the Arena simulation model and 19231,5 nm³/h for the Simul8 simulation model. The gains between the mean output throughput values of the Gas Production plant in Scenario I and II are 1,3931% for the Arena simulation model and 1,4435% for the Simul8 simulation model. The gains, in terms of production days, between the mean output throughput values of the Gas Production plant in Scenario I and II are 5,02 days for the Arena simulation model and 5,20 days for the Simul8 simulation model. The gains are expressed in terms of the mean output throughput values of Scenario I and in terms of the simulation model year (see Appendix L).

The gains, in terms of production days, between the mean output throughput values of the Gas Production plant in the Scenario I and II ED evaluation method option Arena and Simul8 simulation models, correlate closely with the gain of 5,15 production days of the original simulation model that is determined in the *Magister* dissertation (Albertyn, 1995:96).

The gain, in terms of production days of the Gas Production plant, is approximately five production days, when an additional oxygen "train" (the Oxygen Extra plant) is incorporated into the Synthetic Fuel plant in the Scenario II ED evaluation method option Arena and Simul8 simulation models.

Section 2.6 indicates that both primary and secondary "bottlenecks" are undesirable from the

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perspectives of increased efficiency and the realisation of profit (see Section 1.3) and therefore have to be managed with circumspection. The secondary "bottlenecks", that flare throughput that cannot be processed, are also undesirable as seen from the environmental perspective.

If the process flow of the Synthetic Fuel plant is assumed to remain unchanged, the following three strategies are available to reduce the effect of primary and secondary "bottlenecks":

a)   Increase the capacity at the primary and secondary "bottlenecks".

b)   Decrease the time that is lost due to services at the primary and secondary "bottlenecks". This is done by revisiting the service schedules of the relevant modules to see if an increase in cycle time or a decrease in service time, or both, is possible.

c)   Decrease the time that is lost due to failures at the primary and secondary "bottlenecks". This is done by embarking on reliability growth programmes that decrease the failure rate (*i.e.* increase the MTBF) of the relevant modules or by decreasing the repair time of the relevant modules, or both simultaneously.

The impact on the Synthetic Fuel plant, when an additional oxygen "train" (the Oxygen Extra plant) is incorporated, is the following:

a)   The "bottleneck" effect of Oxygen-A is removed.

b)   The output throughput of the Synthetic Fuel plant is increased.

Summary

In this section the Scenario I results of the three most important primary "bottlenecks" (*i.e.* Plant(II)-A, Plant(I) and Oxygen-A) are compared with those of Scenario II. The comparison indicates that Oxygen-A does not qualify as an important primary "bottleneck" in Scenario II. The Scenario I and II results also indicate that the total volume and mean rate of flare values at the two secondary "bottlenecks" (*i.e.* Plant(IV) and Plant(V)) are larger in Scenario II. This can be ascribed to the larger mean output throughput value of the Gas Production plant in Scenario II. The gain in Scenario II, expressed in terms of production days of the Gas Production plant, is approximately five production days. The overall impact, when an additional oxygen "train" (the Oxygen Extra plant) is incorporated into the Synthetic Fuel plant, is that the "bottleneck" effect of Oxygen-A is removed and that the output throughput of the Synthetic Fuel plant is increased.

* * * * *

CHAPTER 5

SYNOPSIS

INTRODUCTION

The term "synopsis" means a summary of the main points of an argument or theory. This chapter aims to provide a concise summary of the most important aspects of the generic simulation modelling methodology.

The most important factors that motivated this research are identified and discussed in the first section. The three main factors are the following: the shortcomings of the original simulation modelling method, the nonexistence in the literature that was surveyed of any strategy or methodology to address the simulation modelling problems that are posed by stochastic continuous systems and the fact that neither Arena nor Simul8 make provision to accommodate the simulation modelling problems that are posed by stochastic continuous systems.

The second section provides a summary of the process that was followed during the completion of the research. The main problem was dealt with by applying the complex problem solving process. This process comprises the following: identify the main problem, segregate the main problem into subproblems, conceptualise and develop methods and techniques to solve the subproblems and integrate the methods and techniques into a methodology.

All the elements of the generic simulation modelling methodology are summarised in the third section. The "toolbox" of the generic methodology contains the following eight methods and techniques: the variables technique, the ITI evaluation method, the ED evaluation method, the ERM method, the FC method, the iterative-loop technique, the time "bottleneck" identification technique and the production lost "bottleneck" identification technique.   The generic methodology comprises two parts, namely: an iterative-loop technique part and a simulation model part. The simulation model consists of a "virtual" part that is represented by the logic engine high-level building block and a "real" part that is represented by the four different high-level building blocks of the ERM method.

In the fourth section the methods, techniques and other attributes of the original simulation modelling method and the generic simulation modelling methodology are identified and

compared. The "toolbox" of the generic methodology contains eight methods and techniques of which only four are used by the original method. The comparison of the attributes indicates that the generic methodology provides effective solutions for the three most important shortcomings of the original method. The most important attributes of the original simulation model and the Arena and Simul8 simulation models are also compared.

The strengths and weaknesses of the generic simulation modelling methodology are summarised in the fifth section. The six most important strengths are the following: the use of a "toolbox" of eight methods and techniques and the identification of the secondary "bottlenecks" (flares), the use of five high-level building blocks and two hierarchical levels, the fact that no warm-up period is necessary, the use of input and output files, spreadsheet variables and preformatted output spreadsheets, the availability of both the ITI and ED evaluation methods in the same simulation model and the characteristics of simulation models that are developed with the generic methodology. The three most important weaknesses are the following: the fact that the logic engine high-level building block is not 100% generic, the need to develop the five high-level building blocks into a template format and the need to develop a concise, simplistic and user-friendly manual.

The contribution to knowledge of the research is discussed in the sixth section. The contribution to knowledge is a generic simulation modelling methodology that can be used to model stochastic continuous systems effectively. The generic methodology makes "knowledge work" more productive. The efficiency of the generic methodology can be attributed to a structured approach and the characteristics that are exhibited by simulation models that are developed with the generic methodology, namely: short development and maintenance times, user-friendliness, short simulation runtimes, compact size, robustness, accuracy and a single software application.

Some ideas on future developments, the possible range of application and different usage perspectives of the generic simulation modelling methodology are provided in the seventh section. The most important weaknesses of the generic methodology are an obvious starting point for any future developments. The possible range of application of the generic methodology is primarily in the petrochemical industry but any stochastic continuous system can readily be accommodated by the generic methodology. The three different usage perspectives within the possible range of application of the generic methodology are the following: the classic Industrial Engineering usage perspective, the training usage perspective and the Sustainable Development usage perspective.

The last section reflects on the research that is presented in this document with a few philosophical musings. Eight seemingly disjointed ideas are discussed, namely: lateral thinking can lead to innovative solutions, simplistic concepts can provide elegant solutions for complex problems, paying attention to detail does render better solutions, complex problems should be approached with the complex problem solving process, unfortunately there is no *Chemical Plant Simulation for Dummies*, the triple bottom-line approach is the future, simulation modelling is as much an art as a science and the search for the truth is the quest of the enquiring mind.

* * * * *

5.1 MOTIVATION FOR THE RESEARCH

The origins of the research that is presented in this document are detailed in Section 1.1. The background information that is provided there, however, is not the only motivation for this research. The aim of this section is to provide a concise summary of the most important factors that initiated the research.

The motivation for the research (*i.e.* the development of a generic simulation modelling methodology) can be ascribed to the following three main factors:

a) The shortcomings of the original simulation modelling method.

b) The absence in the literature that was surveyed of any complete or coherent strategy or methodology to address the simulation modelling problems that are posed by the class or type of system that is considered in this document (*i.e.* systems that exhibit the same characteristics as the Synthetic Fuel plant).

c) The lack of any provision in the simulation software packages that were scrutinised to accommodate the simulation modelling problems that are posed by the class or type of system that is considered in this document.

The following paragraphs detail the points stated above. During 1999 the feasibility of updating the final 1996 simulation model was investigated. Comprehensive changes were needed and the shortcomings of the original simulation modelling method effectively scuppered the project (see Sections 1.1 and 1.4). Even though the project was cancelled, the investigation revealed that a need existed in the industry for a generic simulation modelling methodology that could be used to develop simulation models of the class or type of system that is considered in this document. The investigation presented a unique opportunity to use the original method as a point of departure for the development of a generic methodology.

Systems of the class or type of system that is considered in this document are described as stochastic continuous systems, thereby referring to their two most distinctive characteristics and indicating that they are subject to random (stochastic) phenomena such as failures and that they are characterised by continuous processes (flow) (see Section 1.5). A survey of the available literature revealed that no complete or coherent strategy or methodology existed to address the simulation modelling problems that are posed by stochastic continuous systems. Certain aspects of the simulation modelling problems are addressed by different sources, but no single integrated or comprehensive solution or methodology is proposed, conceptualised, developed, verified and validated, used, *etc.* in the existing sources.

Section 1.6 indicates that traditionally the development of simulation software packages has focused primarily on the ability to model discrete-event systems, because most manufacturing and service systems are discrete-event systems. Continuous systems have been, and still are, neglected by both the simulation software packages and the literature. For example, Pegden *et al.* (1998) dedicate approximately 6%, Harrell and Tumay (1999) approximately 3% and Kelton *et al.* (1998) less than ½% of their respective books to the modelling of continuous systems. The *Simul8®: Manual and Simulation Guide* (1999) does not even address continuous systems.

Neither Arena nor Simul8 make provision to readily accommodate the simulation modelling problems that are posed by the class or type of system that is considered in this document. Section 1.6 indicates that the limited continuous modelling ability of Arena cannot adequately accommodate the simulation modelling problems that are posed by stochastic continuous systems. There are no ready-to-use templates with high-level building blocks (in the simulation software packages) or step-by-step guides (in the manuals) to lead prospective modellers through the process of developing simulation models of stochastic continuous systems, in either Arena or Simul8. Prospective modellers are mostly left to their own devices in both simulation software packages when simulation models of this class or type of system are encountered.

Summary

In this section the most important factors that motivated this research are identified and discussed. The three main factors are the following: the shortcomings of the original simulation modelling method, the nonexistence in the literature that was surveyed of any strategy or methodology to address the simulation modelling problems that are posed by stochastic continuous systems and the fact that neither Arena nor Simul8 make provision to accommodate the simulation modelling problems that are posed by stochastic continuous systems.

* * * * *

5.2   SUMMARY OF THE RESEARCH PROCESS

The purpose of this section is to provide a summary of the research process that was followed to complete the research that is presented in this document. It is both a concise history of the research process followed and, at the same time, a generic research process for the development of a methodology in the simulation modelling environment. In this specific instance the complex simulation modelling problem that is resolved is the development of a generic simulation modelling methodology that can be used to model stochastic continuous systems effectively.

The research process comprises the following:

a)   Identify a clearly demarcated shortcoming in the current state of knowledge to solve the problem. Use the following process:

   i)   Assimilate all the background information (see Sections 1.1 and 1.4).

   ii)   Do a preliminary literature survey (see Sections 1.2, 1.3, 1.5 and 1.6).

   iii) Investigate all additional sources of information, for example, knowledgeable persons, simulation software packages, the Internet, *etc.* (see Sections 1.6 and 3.1).

b)   Use the output of Point a) to determine if the problem is worthy of a structured research effort. If the answer is yes, continue.

c)   Identify "best practice" research tools, techniques, methods, procedures, processes, *etc.* (see Botha and du Toit (1999:1-14), Davis and Parker (1979:1-148), Leedy (1993:1-348) and *Manual for Research and Postgraduate Studies (Master's Degree and PhD)* (2000:1-30)).

d)   Prepare a research proposal. The research proposal should address at least the following topics: an introduction, an objective statement (*i.e.* a problem statement), the importance of the research, a preliminary literature survey, a proposed research method, the limitations, the risks and the contribution to knowledge (see Davis and Parker (1979:57-76), Leedy (1993:149-182) and *Manual for Research and Postgraduate Studies (Master's Degree and PhD)* (2000:3,27)). This point is sometimes regarded as the first step of the formal research process.

e)   Submit the research proposal to the appropriate Departmental Research Committee. If the research proposal is accepted, continue.

f)   Complete the required administrative procedures and continue with the formal research process under the leadership of the assigned supervisor.

g)   Develop or implement management processes for the management of the formal research process. The management processes should include at least the following concepts: a

schedule spreadsheet with the activities (*i.e.* the tasks and the task elements) and the timescale of each activity, a timekeeping spreadsheet with the activities and the man-hours spent on each activity, a literature survey spreadsheet with the relevant information about the appropriate references and a register with a list of the research related meetings and the minutes of the meetings.

h)   Prepare and submit progress reports at regular time intervals, for example, annual, biannual or quarterly progress reports. The purpose of the progress reports is to establish a credible "paper trail" that provides traceability to the formal research process. The documentation of any deviation from the research proposal is of special importance. As the research progresses, a new insight into the problem may be gained. This could lead to a deviation from the original goal of the research that is documented in the research proposal.

i)   Do a thorough literature survey (see the references that are dispersed throughout this document). This is an activity that continues unabated until the research process is completed.

j)   Compile a detailed system description of the system that is under scrutiny (see Section 1.2).

k)   Identify the system characteristics (see Section 2.1).

l)   Conceptualise and develop a solution (*i.e.* a generic simulation modelling methodology) with the complex problem solving process that is advocated by Leedy (1993:71) and *Rule Thirteen* (see Section 5.8) of Descartes (2003:164-169). Use to the following process:

    i)   Identify the main problem. In this instance the main problem is the fact that the system characteristics that are identified in Section 2.1 have to be accommodated in a simulation model that conforms to the design criteria that are stated in Section 1.5 (see Section 2.1).

    ii)   Segregate the main problem into subproblems (see Section 2.2).

    iii)   Conceptualise and develop methods and techniques to solve the subproblems (see Sections 2.2 to 2.6).

    iv)   Integrate the methods and techniques into a methodology (see Section 2.7).

m)   Develop simulation models with the methodology. Use the following process:

    i)   Investigate the simulation software packages (see Section 3.1).

    ii)   Develop a simulation model breakdown from the system description (see Section 3.2).

    iii)   Construct the simulation models and determine an appropriate iteration time interval and the minimum sufficient sample sizes (see Sections 3.3, 3.4 and 3.5).

    iv)   Verify and validate the simulation models (see Section 3.6).

v)   Enhance the simulation models, if possible (see Section 3.7).

n)   Apply the simulation models (*i.e.* conduct scenario analysis). Use the following process:

    i)   Identify and detail alternative scenarios (see Section 4.1).

    ii)   Use the simulation models to generate results for each alternative scenario (see Sections 4.2 and 4.3).

    iii)   Compare the results of the alternative scenarios and reach conclusions (see Section 4.4).

o)   Present a paper about the research at a recognised symposium or conference (see Albertyn and Kruger (16th European Simulation Multiconference, 2002:29-36)).

p)   Publish an article about the research in a recognised technical or scientific journal (see Albertyn and Kruger (2003:57-60)).

q)   Compare the research results with the research goal that is documented in the research proposal. If the research goal is met or exceeded, proceed.

r)   Document the research (see this document).

s)   Submit the document for examination purposes and complete the examination.

The *Manual for Research and Postgraduate Studies (Master's Degree and PhD)* (2000:2) provides the following guidelines for the examination of a doctoral thesis:

> "*Candidates must provide proof that they can plan, initiate and execute* [as well as document] *independent and original research.*"

Summary

This section provides a summary of the process that was followed during the completion of this research. The complex problem solving process was used to address the main problem. The complex problem solving process comprises the following: identify the main problem, segregate the main problem into subproblems, conceptualise and develop methods and techniques to solve the subproblems and integrate the methods and techniques into a methodology.

* * * * *

5.3   SUMMARY OF THE GENERIC METHODOLOGY

The purpose of this section is to provide a concise summary of all the elements of the generic simulation modelling methodology.

In Section 2.1 the characteristics of the class or type of system that is considered in this document are identified. Stochastic continuous systems are characterised by the following: continuous processes, two types of discrete events (*i.e.* the chronological services and stochastic failures) and complex interrelationships. The main problem of this research is the fact that these system characteristics have to be accommodated in a simulation model that conforms to the design criteria that are stated in Section 1.5. Seven methods and techniques to effectively accommodate these system characteristics in a simulation model are conceptualised and developed in Sections 2.2 to 2.6. The seven methods and techniques are integrated into the generic simulation modelling methodology in Section 2.7 and in Section 3.7 an additional method is added when the Arena and Simul8 simulation models are enhanced. That gives a total of eight methods and techniques that are integrated into the generic methodology.

The "toolbox" of the generic simulation modelling methodology contains the following eight methods and techniques:
a)   The variables technique uses variables to represent process flow as real numbers (see Section 2.2).
b)   The ITI evaluation method (*i.e.* the fixed time interval technique detailed in Chapter 2) uses a fixed time interval to advance a simulation model in time (see Section 2.2).
c)   The ED evaluation method advances a simulation model in time by evaluating the simulation model only when an event takes place (see Section 3.7).
d)   The ERM method determines the state of the modules in the system that is under scrutiny at any given moment in time (see Section 2.3).
e)   The FC method identifies the momentary "bottleneck" in a complex system at any given moment in time (see Section 2.4).
f)   The iterative-loop technique determines the governing parameters for every specific system description of the system that is under scrutiny, for example, the gas-feedback-loop-fraction, the steam-division-ratio, the oxygen-division-ratio and the FC method parameter set in the instance of the Synthetic Fuel plant (see Section 2.5).
g)   The time "bottleneck" identification technique identifies the primary "bottlenecks" based on the time that each primary point of evaluation is the "bottleneck" (see Section 2.6).
h)   The production lost "bottleneck" identification technique identifies the primary

"bottlenecks" based on the production that is lost due to each primary point of evaluation (see Section 2.6).

The key objective of this research is to provide a generic simulation modelling methodology that can be used to construct simulation models of stochastic continuous systems effectively. Section 2.2 indicates that the throughput of a plant is considered to be the definitive measurement of plant performance and the first rule of operation in Appendix B states that the Synthetic Fuel plant always strives to maintain the maximum possible rate of production or throughput. It is therefore clear that the determination of the maximum possible throughput, as a function of time, is of vital importance in a simulation model of a stochastic continuous system. Equation 2.4 (repeated here in a generic format for the sake of the continuity of the argument) indicates that the maximum possible throughput of a stochastic continuous system (*i.e.* the Synthetic Fuel plant) is a function of the maximum possible throughput of each of the elements of the stochastic continuous system (*i.e.* the smaller plants).

$$Throughput_{SCStmMaxPos}(t) = f(Throughput_{EmtMaxPos}(t) \: for \: No.1 \: ... \: n_{Emt}) \quad (ton, m^3, nm^3/h)(Eq.:2.4rep)$$

Where:

$Throughput_{SCStmMaxPos}(t)$	:	The maximum possible throughput of the stochastic continuous system, as a function of time, in ton/h, m^3/h or nm^3/h.
$Throughput_{EmtMaxPos}(t)$	:	The maximum possible throughput of the element, as a function of time, in ton/h, m^3/h or nm^3/h.
n_{Emt}	:	The number of elements, as a constant.

The generic format of the terms "Synthetic Fuel plant" and "smaller plant" are used throughout this section. The term "stochastic continuous system" is used instead of "Synthetic Fuel plant" and the term "element" is used instead of "smaller plant". The term "module" remains unchanged.

It is not easy to determine the maximum possible throughput of a stochastic continuous system, as a function of time, because of the continuous process, the fact that the number of available modules in each of the elements is a function of time (*i.e.* the modules are subject to services and failures) and the complex interrelationship characteristic of such a system (*i.e.* the presence of feedback-loops, the division of the output of some of the elements, *etc.*).

A scrutiny of the aforementioned "toolbox" of eight methods and techniques indicates that it provides solutions to all the problems that are posed in the previous paragraph. The variables technique uses variables to represent the process flow of the continuous process. The ERM method determines the number of available modules in each of the elements at any given moment in time and then the FC method identifies the momentary "bottleneck" and determines the maximum possible throughput of the stochastic continuous system at that specific moment in time. The FC method uses a parameter set that is determined with the iterative-loop technique. The FC method parameter set is unique for every specific system description and incorporates the influence of the complex interrelationship characteristic (*i.e.* the presence of feedback-loops, the division of the output of some of the elements, *etc.*). The ITI and ED evaluation methods are used to advance simulation models of stochastic continuous systems in time and the time and production lost "bottleneck" identification techniques are used to identify the primary "bottlenecks".

It is obvious that the eight methods and techniques are applicable at different stages during the completion of a simulation run. Most of the methods and techniques are used continuously by the simulation model during the simulation run. The only exception to this rule is the iterative-loop technique that determines the governing parameters of the system that is under scrutiny before the start of the simulation run. Therefore the generic simulation modelling methodology comprises two separate parts, namely: an iterative-loop technique part and a simulation model part. The iterative-loop technique part accommodates the specific system description of the system that is under scrutiny and the simulation model part contains the seven methods and techniques that accommodate the time dependent behaviour of the system that is under scrutiny.

This concept is graphically depicted in Figure 5.1: *Generic Simulation Modelling Methodology Parts, Methods and Techniques (Updated)*. (Figure 5.1 is an updated version of Figure 2.3 that replaces the fixed time interval technique with the ITI evaluation method and includes the ED evaluation method.)

Generic Simulation Modelling Methodology Parts,
Methods and Techniques (Updated)

Technique Used to Determine Governing
Parameters Before Start of Simulation Run
(Specific System Description of System)

Methods and Techniques Used Continuously by
Simulation Model During Simulation Run
(Time-dependent Behaviour of System)

Iterative-loop Technique
Part

Simulation Model
Part

* Iterative-loop Technique

* Variables Technique
* ITI Evaluation Method
* ED Evaluation Method
* ERM Method
* FC Method
* Time "Bottleneck" Identification
   Technique
* Production Lost "Bottleneck" Identification
   Technique

Natural Division

**Figure 5.1: Generic Simulation Modelling Methodology Parts,
Methods and Techniques (Updated)**

The simulation model itself consists of a "virtual" part that deals with the continuous processes and all the other concepts that are necessary for the simulation model to function and a "real" part that deals with the behaviour of the modules. The "virtual" part of the simulation model is represented by the logic engine high-level building block. The "real" part is represented by the four different high-level building blocks of the ERM method, namely: an element with a multiple service cycle and failures of the modules, an element with a service cycle and failures of the modules, an element with a service cycle of the modules and an element with failures of the modules. The basic structure of the simulation model is graphically depicted in Figure 5.2: *Simulation Model Parts and Building Blocks (Updated)*. (Figure 5.2 is an updated version of Figure 2.4 that replaces the fixed time interval technique with the ITI evaluation method and includes the ED evaluation method.)

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┌─────────────────────────────────────────────────────────────────────────────┐
│              Simulation Model Parts and Building Blocks (Updated)              │
│                                                                               │
│  ←—  "Virtual" Part Deals with Continuous Processes  —→ ←—  "Real" Part Deals with Behavior  —→ │
│        and Functioning of Simulation Model                  of Modules                        │
│                                                                               │
│        ┌───────────────────────────┐        ┌──────────────────────────────────────┐ │
│        │      "Virtual" Part       │        │            "Real" Part               │ │
│        │  ┌─────────────────────┐  │        │  ┌──────────────┐  ┌──────────────┐  │ │
│        │  │  Building Block     │  │        │  │Building Block│  │Building Block│  │ │
│        │  │                     │  │        │  │              │  │              │  │ │
│        │  │   Logic Engine      │  │        │  │ Element with │  │ Element with │  │ │
│        │  │                     │  │        │  │Multiple Serv.│  │Service Cycle │  │ │
│        │  └─────────────────────┘  │        │  │Cycles&Failur.│  │and Failures  │  │ │
│        └───────────────────────────┘        │  └──────────────┘  └──────────────┘  │ │
│                                              │  ┌──────────────┐  ┌──────────────┐  │ │
│  * Uses Variables Technique to Represent Process Flow │  │Building Block│  │Building Block│  │ │
│  * Uses ITI or ED Evaluation Method to Advance │  │ Element with │  │ Element with │  │ │
│    Simulation Model in Time                    │  │Service Cycle │  │ Failures     │  │ │
│  * Controls ERM Method                         │  └──────────────┘  └──────────────┘  │ │
│  * Uses FC Method to Identify Momentary "Bottleneck" └──────────────────────────────────────┘ │
│  * Determines Maximum Possible Throughput                                      │
│  * Determines Number Modules Switched On or Off  * Uses ERM Method to Determine the State of Modules │
│  * Determines Input to Identify Primary and Secondary                          │
│    "Bottleneck" Elements                                                       │
│  * Determines Variables that Keep Record of Functioning                        │
│    of Simulation Model                                                         │
│  * Determines Mean Values of Relevant Variables at                             │
│    End of Simulation Run                                                       │
│  * Identifies Primary and Secondary "Bottleneck"                               │
│    Elements at End of Simulation Run                                           │
└─────────────────────────────────────────────────────────────────────────────┘
```

Figure 5.2: Simulation Model Parts and Building Blocks (Updated)

Summary

In this section the generic simulation modelling methodology is summarised. The "toolbox" of the generic methodology contains the following eight methods and techniques: the variables technique, the ITI evaluation method, the ED evaluation method, the ERM method, the FC method, the iterative-loop technique, the time "bottleneck" identification technique and the production lost "bottleneck" identification technique. The generic methodology comprises two parts, namely: an iterative-loop technique part that determines the governing parameters of the system that is under scrutiny before the start of a simulation run and a simulation model part that uses the other seven methods and techniques continuously during the simulation run. The simulation model consists of a "virtual" part and a "real" part. The "virtual" part is represented by the logic engine high-level building block and deals with the continuous processes and all the other concepts that are necessary for the simulation model to function. The "real" part deals with the behaviour of the modules and is represented by the four different high-level building blocks of the ERM method, namely: an element with a multiple service cycle and failures of the modules, an element with a service cycle and failures of the modules, an element with a service

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cycle of the modules and an element with failures of the modules.

* * * * *

5.4 COMPARISON OF THE ORIGINAL METHOD AND THE GENERIC METHODOLOGY

The detail discussions about the differences between the original simulation modelling method and the generic simulation modelling methodology are dispersed throughout this document. This section presents the essence of these differences in tabular format and concise discussions. The methods, techniques and other attributes of the original method and generic methodology are identified and compared. Some of the attributes of the original simulation model and the Arena and Simul8 simulation models are also compared.

A comparison of the methods and techniques that are used by the original simulation modelling method and the generic simulation modelling methodology is presented in Table 5.1: *Methods and Techniques Used by the Original Method and the Generic Methodology*.

Table 5.1: Methods and Techniques Used by the Original Method and the Generic Methodology

Method or Technique	Original Simulation Modelling Method	Generic Simulation Modelling Methodology
Variables Technique	Yes	Yes
ITI Evaluation Method	Yes	Yes
ED Evaluation Method	No	Yes
ERM Method	Yes (Original version)	Yes (Enhanced version)
FC Method	No	Yes
Iterative-loop Technique	Yes (Original version)	Yes (Enhanced version)
Time "Bottleneck" Identification Technique	No	Yes
Production Lost "Bottleneck" Identification Technique	No	Yes

Table 5.1 reveals that only four of the "toolbox" of eight methods and techniques that comprise the generic simulation modelling methodology are used by the original simulation modelling method. The variables technique and the ITI evaluation method are used by both the original

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method and the generic methodology. The ED evaluation method, however, is an option that is only available in the generic methodology. The ERM method of the original method (*i.e.* the original version) is less compact and accurate than the ERM method of the generic methodology (*i.e.* the advanced version) because the latter reduces the number of queues that is used and it introduces techniques that address the "disturbed service sequence" phenomena (see Section 2.3). The FC method is unique to the generic methodology and it is the "jewel in the crown" of the generic methodology because it makes an invaluable contribution to eliminate the shortcomings of the original method. Both the original method and the generic methodology use the iterative-loop technique to determine the governing parameters of the system that is under scrutiny before the start of a simulation run. The iterative-loop technique of the original method (*i.e.* the original version) only determines the gas-feedback-loop-fraction, steam-division-ratio and oxygen-division-ratio (in the instance of the Synthetic Fuel plant), while the iterative-loop-technique of the generic methodology (*i.e.* the enhanced version) also determines the FC method parameter set.   The original method uses the throughput utilisation values to identify the primary "bottlenecks", while the generic methodology uses the time and production lost "bottleneck" identification techniques to identify the primary "bottlenecks".

Table 5.2: *Comparison of the Original Method and the Generic Methodology* provides a concise comparison of some of the most important attributes of the original simulation modelling method and the generic simulation modelling methodology.

The first three rows in Table 5.2 represent the attributes that are identified in Section 1.4 as the three most important shortcomings of the original simulation modelling method, while the next three rows represent the attributes of the generic simulation modelling methodology that counter these shortcomings. The generic methodology reduces the number of queues that is used and addresses the "disturbed service sequence" phenomena in the ERM method. The generic methodology immediately starts the simulation run while the original method uses the first time interval to set up the simulation model and only then starts the simulation run. The generic methodology also uses high-level building blocks, hierarchical levels, enhanced animation, preformatted spreadsheets, identifies the secondary "bottlenecks" (flares) and makes provision for the ITI and ED evaluation methods.

Table 5.2: Comparison of the Original Method and the Generic Methodology

Attribute	Original Simulation Modelling Method	Generic Simulation Modelling Methodology
FORTRAN subroutine with complex structures that are, to a large extent, not generic	Yes	No
Complicated structure that uses two different software packages to construct a simulation model with a complex structure and difficult interfacing, compiling and linking	Yes	No
Complex structure that complicates "debugging"	Yes	No
FC method that is, to a large extent, generic	No	Yes
Simplistic structure that accommodates a simulation model in one simulation software package	No	Yes
Simplistic "debugging" because of simplistic structure	No	Yes
Reduced number of queues used in the ERM method	No	Yes
Address the "disturbed service sequence" phenomena in the ERM method	No	Yes
Immediate start of the simulation run	No (First time interval used to set up simulation model)	Yes
High-level building blocks	No	Yes
Hierarchical levels in simulation model	No	Yes
Animation	Yes (Basic)	Yes (Enhanced)
Preformatted spreadsheets	No	Yes
Identification of the secondary "bottlenecks" (flares)	No	Yes
ITI and ED evaluation methods	No	Yes

A comparison of the original simulation modelling method and the generic simulation modelling methodology would not be complete without a comparison of the original simulation model and the Arena and Simul8 simulation models. Table 5.3: *Comparison of the Original Simulation Model and the Arena and Simul8 Simulation Models* provides a comparison of some of the attributes of the original simulation model and the Arena and Simul8 simulation models. Where applicable, values are provided for both the ITI and ED evaluation method option Arena and Simul8 simulation models.

Table 5.3: Comparison of the Original Simulation Model and the
Arena and Simul8 Simulation Models

Attribute	Original Simulation Model	Arena Simulation Model		Simul8 Simulation model	
ITI (hour)	1	(ITI)	1	(ITI)	1
n_{Rep}	10		20		20
Runtime (min)	171	(ITI)	24,0	(ITI)	17,0
		(ED)	8,6	(ED)	6,8
GasPro (nm^3/h)	1349900	(ITI)	1326773,7	(ITI)	1331462,8
		(ED)	1332471,8	(ED)	1332253,3
StdDev (nm^3/h)	6030	(ITI)	8066,6	(ITI)	7154,9
		(ED)	6620,5	(ED)	7462,5
n_{Sam}	5	(ITI)	14	(ITI)	12
		(ED)	11	(ED)	13
	(1% deviation from real-world and 99% confidence interval)	(0,5 deviation from real-world and 99% confidence interval)		(0,5 deviation from real-world and 99% confidence interval)	
Deviation (%)	0,59	(ITI)	-0,410	(ITI)	-0,058
		(ED)	0,018	(ED)	0,001
Size (KB) (Iterative-loop technique)	(FORTRAN file) 6	(FORTRAN file)	13	(FORTRAN file)	13
Size (KB) (Simulation model)	(SIMAN files) 46 (FORTRAN file) 50	(Arena file)	2438	(Simu8 file)	937

Where:

ITI	:	The iteration time interval (hour).
n_{Rep}	:	The number of replications completed.
Runtime	:	The simulation runtime for n_{Rep} replications (minute).
GasPro	:	The mean output throughput value of the Gas Production plant, calculated from n_{Rep} replications (nm^3/h).
StdDev	:	The standard deviation from the mean output throughput value (nm^3/h).
n_{Sam}	:	The minimum sufficient sample size.
Deviation	:	The deviation of the specific mean output throughput value from the mean output throughput value of the Gas Production plant during the 1993 production year (%).
Size	:	The simulation model size (kilobyte).

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All the values in Table 5.3 pertain to a simulated time period of one year (see Appendix L) and all the values about the original simulation model follow from the *Magister* dissertation (Albertyn, 1995). The simulation runtime of the original simulation model for 10 replications of a simulated period of one year and with an iteration time interval of one hour is 171 minutes and therefore it can be concluded that the simulation runtime for 20 replications of a simulated time period of one year and with an iteration time interval of one hour would be 342 minutes or 5,7 hours (see Section 3.4). This implies that the ITI evaluation method option Arena and Simul8 simulation models represent an approximate twentyfold improvement in simulation runtime over the original simulation model, while the ED evaluation method option Arena and Simul8 simulation models represent an approximate fortyfold improvement in simulation runtime over the original simulation model. The minimum sufficient sample size of the original simulation model is calculated with an allowance for a 1% deviation from the real-world output throughput value of the Gas Production plant, while the minimum sufficient sample sizes of the Arena and Simul8 simulation models are calculated with an allowance for a 0,5% deviation from the real-world output throughput value of the Gas Production plant.

It is of special significance to note that none of the original simulation model or the ITI and ED evaluation method option Arena and Simul8 simulation models deviate more than 1% from the mean output throughput value of the Gas Production plant during the 1993 production year.

Summary

This section identifies and compares the methods, techniques and other attributes of the original simulation modelling method and the generic simulation modelling methodology. The "toolbox" of the generic methodology contains eight methods and techniques of which only four are used by the original method. The generic methodology also uses more refined and enhanced versions of two of the four methods and techniques that are used by the original method. The comparison of the attributes of the original method and the generic methodology indicates that the generic methodology provides effective solutions for the three most important shortcomings of the original method. The most important attributes of the original simulation model and the Arena and Simul8 simulation models are also compared.

* * * * *

5.5 STRENGTHS AND WEAKNESSES OF THE GENERIC METHODOLOGY

The detail discussions concerning the advantages (*i.e.* the strengths) and the disadvantages (*i.e.* the weaknesses) of the concepts of the generic simulation modelling methodology are dispersed throughout this document. This section distils the strengths and weaknesses of the generic methodology into concise lists.

The strengths of the generic simulation modelling methodology are the following:

a)   The exclusion of transient behaviour reduces complexity even though, paradoxically, it can also be perceived as a possible limitation (see Section 1.7).

b)   The use of the variables technique leads to short simulation runtimes and therefore also short development and maintenance times. The variables technique also ensures high accuracy. (See Section 2.2.)

c)   The use of the ERM method leads to a compact simulation model size, total control over all the relevant aspects of the services and accuracy (see Section 2.3).

d)   The use of the FC method impacts positively on all the design criteria of the generic simulation modelling methodology, namely: short development and maintenance times, user-friendliness, short simulation runtimes, compact size, robustness, accuracy and a single software application (see Section 1.5). The FC method is, to a large extent, generic and is also principally responsible for the simplistic structure of the generic methodology that accommodates the simulation model in one simulation software package and simplifies "debugging" (see Section 2.4).

e)   The use of the iterative-loop technique provides a structured and accurate technique to determine the governing parameters of the simulation model (see Section 2.5).

f)   The time and production lost "bottleneck" identification techniques accurately identify the primary "bottlenecks" (see Section 2.6).

g)   The secondary "bottlenecks" (flares) are identified (see Section 2.6).

h)   The division of the generic simulation modelling methodology into two separate parts (*i.e.* an iterative-loop technique part and a simulation model part) leads to a compact simulation model size and support the short simulation runtime design criterion (see Section 2.7).

i)   The division of the simulation model into two separate parts (*i.e.* a "virtual" part that is represented by the logic engine high-level building block and a "real" part that is represented by the four different high-level building blocks of the ERM method) leads to a structured simulation model and therefore supports user-friendliness (see Section 2.7).

j)   The use of high-level building blocks leads to short development and maintenance times,

user-friendliness and a compact simulation model size. The compact simulation model size design criterion is supported by the fact that the four different high-level building blocks of the ERM method do not include any options that are unnecessary or unwanted. (See Sections 2.3 and 2.7.)

k)   The use of the variables technique leads to a major benefit because no warm-up period is necessary to wait for the simulation model to "fill up" with entities before the simulation run can start. No warm-up period leads to short simulation runtimes and high accuracy. (See Section 2.7.)

l)   The fact that the generic simulation modelling methodology immediately starts the simulation run (versus the original simulation modelling method where the first time interval is used to set up the simulation model) leads to a small improvement in accuracy (see Section 2.7).

m)   The fact that logic engine high-level building block is generic, to a large extent, supports the short development and maintenance times and user-friendliness design criteria (see Section 3.3).

n)   The fact that four different high-level building blocks of the ERM method are truly generic, supports the short development and maintenance times and user-friendliness design criteria (see Section 3.3).

o)   The use of input and output files and spreadsheet variables greatly simplify the manipulation of input and output variables. These input and output mechanisms enhance user-friendliness. (See Section 3.3.)

p)   The use of two hierarchical levels to represent the simulation model leads to a structured simulation model and therefore it supports user-friendliness (see Section 3.3).

q)   The animation of the output throughput graph, the momentary "bottleneck" status of the primary "bottlenecks" and the flares (secondary "bottlenecks") support user-friendliness, because the realistic representation of a simulation model in a format that is immediately recognisable is fundamental to the successful familiarisation with, orientation to, and acceptance of, the simulation model by clients and users (see Section 3.3).

r)   The use of the ITI evaluation method leads to accuracy (if an appropriate iteration time interval is used) and short simulation runtimes can be achieved by increasing the iteration time interval up to the acceptable limit (see Section 3.7).

s)   The use of the ED evaluation method leads to accuracy and there is no need to determine a bandwidth of iteration time intervals that render valid results (see Section 3.7).

t)   The availability of both the ITI and ED evaluation methods in the same simulation model and the ability to switch between the two evaluation methods at will, affords the modeller tremendous flexibility in terms of required accuracy and simulation runtimes (see

Section 3.7).

u)   The use of preformatted spreadsheets to manipulate and present the results of simulation runs supports the user-friendliness design criterion (see Section 4.1).

v)   The design criteria of the generic simulation modelling methodology lead to simulation models with the following characteristics: short development and maintenance times, user-friendliness, short simulation runtimes, compact size, robustness, accuracy and a single software application (see Section 1.5).

w)   The generic simulation modelling methodology emphatically resolves all the shortcomings of the original simulation modelling method and presents a structured approach that accommodates all the simulation modelling problems that are posed by the class or type of system (*i.e.* stochastic continuous systems) that is considered in this document (see Sections 5.3 and 5.4).

The weaknesses of the generic simulation modelling methodology are the following:

a)   The exclusion of transient behaviour is perceived as a possible limitation even though, paradoxically, it can also be perceived as a possible advantage (see Section 1.7).

b)   The logic engine high-level building block is not truly 100% generic, because the unique concepts of a specific simulation model that are usually described by the process logic or rules of operation of that specific simulation model cannot be accommodated generically and therefore a part of the logic engine high-level building block of that specific simulation model will contain certain concepts that are unique to that specific simulation model (see Section 3.3).

c)   The weakness of the ITI evaluation method is that a bandwidth of iteration time intervals that render valid results has to be determined before the simulation model can be used (see Sections 3.4 and 3.7).

d)   The weakness of the ED evaluation method is that the simulation runtime for a specific simulation model in a specific simulation software package is a given that depends on the computer hardware configuration (see Section 3.7).

e)   The five high-level building blocks of the generic simulation modelling methodology have to be developed into a template format. In a template format high-level building blocks are displayed as icons and are manipulated with the "drag and drop" functionality (to add high-level building blocks to the simulation model) and with high-level building block menus (to manipulate the parameters of the high-level building blocks). Currently the high-level building blocks are manipulated with the "copy and paste" functionality (to add high-level building blocks to the simulation model) and with the menus of the basic building blocks (to manipulate the parameters of the high-level building blocks).

f)   A concise, simplistic and user-friendly manual has to be developed to provide a summary of the basic principles of the generic simulation modelling methodology and explain how the high-level building blocks should be used to construct a simulation model.

Section 1.4 indicates that the stochastic nature of simulation models of stochastic continuous systems complicates "debugging". This was perceived as a weakness of the original simulation modelling method but, as a matter of fact, it is one of the inherent problems of all stochastic simulation models. It is therefore debatable whether it should be considered as a weakness of the generic simulation modelling methodology, or merely as an inherent characteristic.

Summary

This section summarises the strengths and weaknesses of the generic simulation modelling methodology. Twenty-three strengths and six weaknesses are identified and discussed. The six most important strengths are the following: the use of a "toolbox" of eight methods and techniques and the identification of the secondary "bottlenecks" (flares), the use of five high-level building blocks and two hierarchical levels, the fact that no warm-up period is necessary, the use of input and output files, spreadsheet variables and preformatted output spreadsheets, the availability of both the ITI and ED evaluation methods in the same simulation model and the characteristics of simulation models that are developed with the generic methodology. The three most important weaknesses are the following: the fact that the logic engine high-level building block is not 100% generic, the need to develop the five high-level building blocks into a template format and the need to develop a concise, simplistic and user-friendly manual.

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5.6   CONTRIBUTION TO KNOWLEDGE

In *The Age of Discontinuity: Guidelines to Our Changing Society* Drucker (1978:290) makes the following statement concerning knowledge and productivity:

> "*To make knowledge work productive will be the great management task of this century, just as to make manual work productive was the great management task of the last century.*"

Drucker is, of course, referring to the twentieth (*i.e.* "*... this century, ...*") and the nineteenth centuries (*i.e.* "*... the last century.*") respectively. Even though the twentieth century is something of the past now, this viewpoint can surely be projected into the first part of the twenty-first century. His viewpoint is supported by the statement in Section 1.3 that the path to understanding the behaviour of a system can be characterised as progressing through four different levels, namely: data, information, knowledge and insight. The contribution of simulation modelling, as a decision support tool, is primarily in the areas of knowledge and insight. A simulation model is ideally suited to provide knowledge about past and present system behaviour as well as insight into probable future system behaviour. The generic simulation modelling methodology can therefore be regarded as a decision support tool that, in the words of Drucker, "*make*[s] *knowledge work productive*" and hence it supports the quest for greater efficiency.

The principal contribution to knowledge is a generic simulation modelling methodology that can be used to model stochastic continuous systems effectively.

The efficiency of the generic simulation modelling methodology can be attributed to a structured approach and the characteristics that are exhibited by simulation models that are developed with the generic methodology. The characteristics of the simulation models follow directly from the design criteria of the generic methodology and therefore the characteristics and the design criteria are identical.

The characteristics (or alternatively the design criteria) of simulation models that are developed with the generic simulation modelling methodology, are the following:
a)   Short development time.
b)   Short maintenance times.
c)   User-friendliness as perceived from the development, maintenance and usage perspectives.

d)   Short simulation runtimes.

e)   Compact simulation model size.

f)   Robust modelling ability.

g)   Accurate modelling ability.

h)   Single software application.

The following points, on a one-to-one basis, provide more detail about exactly how the generic simulation modelling methodology supports the aforementioned characteristics of simulation models that are developed with the generic methodology:

a)   It is difficult to substantiate the short development time characteristic because the generic simulation modelling methodology was not used to develop a simulation model of a stochastic continuous system, other than the simulation models of the Synthetic Fuel plant, from scratch. From the timekeeping spreadsheet of the research effort (see Section 5.2) it follows that approximately 450 man-hours were spent on the development of the Arena simulation model and approximately 650 man-hours on the development of the Simul8 simulation model. These figures are misleading, however, because they include the development times of the high-level building blocks in the simulation software packages and, in the case of Simul8, the time needed to "acclimatise" to the specific concepts of the software package. If these extenuating circumstances are taken into account, the development times of the simulation models are exemplary for the development of a simulation model of a stochastic continuous system of the size and complexity of the Synthetic Fuel plant. It is therefore quite reasonable to predict that a development time of approximately 300 man-hours could be achieved for a simulation model of a stochastic continuous system that is comparable in size and complexity to the Synthetic Fuel plant.

b)   It is difficult to substantiate the short maintenance times characteristic of the generic simulation modelling methodology because no maintenance actions were carried out on the Arena and Simul8 simulation models. However, it is reasonable to predict that the maintenance times should be equally acceptable, if the short development times of the simulation models are taken as a point of reference.

c)   The user- friendliness characteristic of the generic simulation modelling methodology is supported by the following concepts:

   i)   The use of high-level building blocks (see Sections 2.3 and 2.7).

   ii)   The use of input and output files by the software programme (*i.e.* PSCALC.FOR) that determines the governing parameters (see Section 2.5).

   iii)   The use of input and output files and spreadsheet variables by the Arena and

> Simul8 simulation models respectively to manipulate the input and output variables (see Section 3.3).

iv) The use of two hierarchical levels to represent the system that is modelled (see Section 3.3).

v) The use of a layout on the higher hierarchical level that conforms closely to the configuration of the system that is modelled is fundamental to the familiarisation with, orientation to, and acceptance of, the simulation model (see Section 3.3).

vi) The use of preformatted spreadsheets for the manipulation of the input and output variables and spreadsheet variables of the Arena and Simul8 simulation models respectively (see Section 4.1).

d) The short simulation runtimes characteristic of the generic simulation modelling methodology is supported by the following concepts:

i) The use of the variables technique ensures that the simulation models that are developed with the generic simulation modelling methodology do not need a warm-up period (see Section 2.7).

ii) If the ITI evaluation method is used, short simulation runtimes can be achieved by increasing the iteration time interval up to the acceptable limit (see Section 3.7).

iii) The use of the most basic of the standard simulation software package building blocks in the respective simulation software packages (see Section 3.8).

e) The compact simulation model size characteristic of the generic simulation modelling methodology is supported by the following concepts:

i) The use of the advanced version of the ERM method that uses a reduced number of queues, basic building blocks to construct the high-level building blocks and excludes any unused and unnecessary options in the high-level building blocks (see Section 2.3).

ii) The natural division of the generic simulation modelling methodology into an iterative-loop technique part and a simulation model part (see Section 2.7).

f) It is difficult to substantiate the robustness characteristic of the generic simulation modelling methodology because it was not used to develop a simulation model of a stochastic continuous system, other than the simulation models of the Synthetic Fuel plant, from scratch. However, the ease of the simulation model construction of both the Arena and Simul8 simulation models suggests that the generic methodology is robust (see the discussions concerning the short development and maintenance times in this section).

g) The accurate modelling ability characteristic of the generic simulation modelling methodology is supported by the following concepts:

i) The use of the variables technique (see Sections 1.6, 2.2 and 2.7).

ii) The use of the advanced version of the ERM method that allows total control over all the relevant aspects of the services of the modules, including the "disturbed service sequence" phenomena (see Section 2.3).

iii) The use of double precision accuracy (*i.e.* 15 decimal digits) by the FORTRAN software programme that determines the governing parameters (see Section 2.5).

iv) The use of the time and production lost "bottleneck" identification techniques to identify the primary "bottlenecks" (see Section 2.6).

v) The use of the variables technique ensures that the simulation models that are developed with the generic simulation modelling methodology do not need a warm-up period and therefore the risk of including data from the "unstable" warm-up period into the results is negated (see Section 2.7).

vi) If the ITI evaluation method is used, high accuracy can be achieved by using an appropriate iteration time interval (see Section 3.4).

vii) The use of variables in the Arena and Simul8 simulation software packages that are accurate to 15 and 10 decimal digits respectively (see Section 3.8).

h) The single software application characteristic of the generic simulation modelling methodology is evident in the fact that both the Arena and Simul8 simulation models of the Synthetic Fuel plant were developed in a single simulation software package. The use of a FORTRAN software programme to determine the governing parameters is not perceived as a breach of the single software application characteristic or design criterion, because the FORTRAN software programme is essentially a preprocessor that only determines the governing parameters that are used in the simulation models.

It is essential to note that the use of the FC method impacts positively on all the characteristics of simulation models that are developed with the generic simulation modelling methodology. Therefore the FC method is perceived as the single method, from the "toolbox" of eight methods and techniques that comprises the generic methodology, that makes the most significant contribution to the efficiency of the generic methodology.

Summary

An exposition on the contribution to knowledge of this research is provided in this section. The contribution to knowledge is a generic simulation modelling methodology that can be used to model stochastic continuous systems effectively. The research supports the view of Drucker (1978:290) that one of the major current management challenges is to make "knowledge work"

more productive. The efficiency of the generic methodology can be attributed to a structured approach and the characteristics that are exhibited by simulation models that are developed with the generic methodology, namely: short development and maintenance times, user-friendliness, short simulation runtimes, compact size, robustness, accuracy and a single software application.

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5.7   THE FUTURE VISION

In this section some thoughts on future developments that could enrich the generic simulation modelling methodology are presented. The possible range of application and different usage perspectives of the generic methodology are also identified and discussed.

The obvious point to start any future developments is by addressing the following shortcomings (*i.e.* the three most important weaknesses) of the generic simulation modelling methodology that are identified in Section 5.5:

a)   The logic engine high-level building block is not 100% generic.

b)   The five high-level building blocks have to be developed into a template format.

c)   A concise, simplistic and user-friendly manual has to be developed.

Section 3.3 indicates that the logic engine high-level building block is to a large extent generic because most of the concepts that are necessary for the simulation model to function are basically the same for every simulation model that is developed with the generic simulation modelling methodology. However, the unique concepts of a specific simulation model that are usually described by the process logic or rules of operation of that specific simulation model are difficult to accommodate generically and therefore a part of the logic engine high-level building block of that specific simulation model will contain certain concepts that are unique to that specific simulation model. Even though it is virtually impossible to make provision to accommodate all possible combinations and permutations of such rules of operation generically in the logic engine high-level building block, some concepts, like the inclusion of a tank to buffer flow, are more universal and therefore lend themselves more readily to generic use. In the future a "library" of universal generic concepts could be developed. The "library" would greatly enhance the generic characteristic of the logic engine high-level building block, because appropriate universal generic concepts could simply be picked from the "library" and implemented in the logic engine high-level building block when a new simulation model is developed with the generic methodology.

The development of the five high-level building blocks into a template format and the development of a manual go hand in hand. A template format for the five high-level building blocks will increase the user-friendliness of the generic simulation modelling methodology immensely through the use of icons, the "drag and drop" functionality and high-level building block menus. The development of a concise, simplistic and user-friendly manual is essential because it is unrealistic to expect prospective modellers to work through this research document to familiarise themselves with the concepts of the generic methodology. In its current format the generic methodology is still very much a developer's or researcher's tool (*i.e.* a technology demonstrator) and not an industrial engineer's tool.

The possible range of application of the generic simulation modelling methodology is already touched upon in Section 1.6. The most obvious possible range of application is found within the petrochemical industry, where the oil-from-coal process, the classic crude oil refinement process and the GTL process can all be accommodated by the generic methodology without any difficulty. In South Africa alone, examples of chemical plants that use these processes abound, for instance, the Sasol Synfuels complex at Secunda (*i.e.* the oil-from-coal process), the South African Petroleum Refinery (Sapref) south of Durban (*i.e.* the classic crude oil refinement process) and the PetroSA plant at Mossel Bay (*i.e.* the GTL process). Furthermore, there are many chemical plants all over the world that use the classic crude oil refinement and GTL processes. Each of these chemical plants is a potential client for an application of the generic methodology.

The generic simulation modelling methodology is by no means restricted to only the petrochemical industry. Any plant that exhibits the same characteristics as the Synthetic Fuel plant can readily be accommodated by the generic methodology. For example, a plant that manufactures paint or liquid detergents obviously falls within this class or type of system. In fact, a simulation model of any stochastic continuous system can be developed with the generic methodology.

The following three different usage perspectives can be identified within the possible range of application of the generic simulation modelling methodology:
a)   The classic Industrial Engineering usage perspective.
b)   The training usage perspective.
c)   The Sustainable Development usage perspective.

The classical Industrial Engineering usage perspective is personified by the first rule of operation in Appendix B that states that the Synthetic Fuel plant always strives to maintain the maximum

possible rate of production or throughput. Goldratt and Cox (1992:294) also indicate that they regard the throughput as the definitive measurement of plant performance (see Section 2.2). The classical Industrial Engineering usage perspective will use a simulation model that is developed with the generic simulation modelling methodology to evaluate different options that are aimed at increasing the throughput and hence the profitability of the system that is under scrutiny. Chapter 4 of this document, where two alternative scenarios are evaluated with the Arena and Simul8 simulation models, is a prime example of the classic Industrial Engineering usage perspective of the generic methodology.

The training usage perspective is primarily aimed at the junior engineers of chemical plants and the engineering students of tertiary institutions. A simulation model of a chemical plant that is developed with the generic simulation modelling methodology can be used by junior chemical -, industrial - and mechanical engineers as a training tool to familiarise themselves with the cause and effect behaviour of that specific plant. In the same vein, a simulation model of an imaginary continuous process system that is developed with the generic methodology can be used by chemical -, industrial - and mechanical engineering students as an introduction to the concepts of simulation and modelling and to familiarise themselves with the cause and effect behaviour of a complex system.

The following basic introduction to the concept of Sustainable Development provides a context for the discussion of the Sustainable Development usage perspective. The concept of Sustainable Development became prominent in recent years as an area of interest and concern for the entire global community. The finite resources of the earth are coming under increasing strain from the ever increasing human world population and worldwide industrialisation. It is imperative that the resources have to be managed intelligently to ensure a prosperous future for all the inhabitants of the earth. This requires the use of best practice technologies to guarantee that the resources are optimally utilised. Simulation modelling has been identified as one of the key technology areas of future research by the European Union (Geril, 2002). It therefore stands to reason that simulation modelling qualifies as a best practice technology that can be used by the Sustainable Development fraternity.

The term "sustainable" is defined as "*of, relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged*" (*Merriam-Webster's Collegiate Dictionary*). The most commonly accepted definition of the term "Sustainable Development" is the one put forward by the United Nations World Commission on Environment and Development in 1987. This commission is also known as the Brundtland Commission.

According to this Commission the term "Sustainable Development" means: "*... development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs.*" (Sustainable Development, 2002).

The United Nations Conference on Environment and Development held in Rio de Janeiro, Brazil in 1992 drafted a blueprint for Sustainable Development, called Agenda 21. This conference is more commonly known as the Earth, or Rio Summit (Year in Review, 1998). The central theme of Agenda 21 is the emphasis on the improvement of the quality of life, especially for the poor (Sustainable Development, 2002). In 1997 representatives from signatory nations to the United Nations Framework Convention on Climate Change attended a meeting in Kyoto, Japan. They reached an agreement, called the Kyoto Protocol, to reduce global emissions by about 5,2% by the year 2012 (Year in Review, 1999).

In 2002 the World Summit on Sustainable Development (WSSD) was held in Johannesburg, South Africa. Two official outcomes were produced, namely the *Johannesburg Political Declaration* and the *Plan of Implementation*. The three main Sustainable Development issues identified by the *Johannesburg Political Declaration* are poverty eradication, changing consumption and production patterns and protecting and managing the natural resource base. The *Plan of Implementation* endorses water and energy as Sustainable Development concerns and reaffirms commitment to Agenda 21 of the Rio Summit (The World Summit on Sustainable Development, 2002).

A ten-point action plan to protect the environment was also signed at the WSSD by leading companies and labour organisations. The plan is called *The South African Green Paper* and it contributes towards the objectives of Sustainable Development. South African signatories include prominent companies like Sasol, Iscor, Columbus Stainless, Eskom and Telkom (WSSD, 2002).

Sustainable Development has three dimensions, namely: Economic Prosperity, Environmental Quality and Social Value (Sustainable Development, 2002). The first dimension of Economic Prosperity is comparable with the classic Industrial Engineering usage perspective that strives to increase shareholder fiscal value through the maximisation of profit. This perspective is also sometimes referred to as the "accounting" perspective and finds expression in the manufacturing environment by the pursuit of engineering to optimise the processes involved. This could lead to an increase in income or a decrease in cost (see Section 1.3). The second dimension of Environmental Quality can be compared to the so-called "green" perspective. This perspective

is concerned with the health of the environment and focuses primarily on resource efficiency, cleaner production and pollution prevention. The third dimension of Social Value is not a dimension where engineering can intrinsically make a huge contribution, except in the area of safety and health through the implementation of nonhazardous processes. This dimension represents the "human" perspective which primarily falls within the spheres of the health environment and that of the humanities (sociology).

The commitment of leading companies to *The South African Green Paper* indicates that the concept of Sustainable Development is supported and actively pursued by the business community. This commitment is also reflected in the marketing campaigns of some companies, where all three the dimensions of Sustainable Development are conspicuously engaged in advertising material (Sasol's Natural gas Project Surging Ahead in Mozambique, 2002). When a company base its management decisions on all three the dimensions of Sustainable Development, it is referred to as a triple bottom-line approach (Sustainable Development Case Studies, 2002). The shift towards more accountable corporate behaviour also finds expression in the fact that many business schools are adding courses on ethics to their Master of Business Administration (MBA) programmes (Scandals Put Ethics in the Syllabus, 2003).

The Sustainable Development usage perspective of a simulation model that is developed with the generic simulation modelling methodology is primarily concerned with the Economic Prosperity and Environmental Quality dimensions of Sustainable Development. The Economic prosperity dimension is supported by the classic Industrial Engineering usage perspective, while the Environmental Quality dimension is supported by the ability of the generic methodology to identify the secondary "bottlenecks" (*i.e.* the flares). Stricter government legislation, non-governmental organisations and other pressure groups are forcing companies to manage the Environmental Quality dimension more diligently (Hofstätter and Russouw, 2004). The third dimension of Social Value benefits indirectly, because a cleaner environment is a healthier environment.

Summary

This section provides some ideas on future developments, the possible range of application and different usage perspectives of the generic simulation modelling methodology. The most important weaknesses of the generic methodology are an obvious starting point for future developments. The important weaknesses are the fact that the logic engine high-level building block is not 100% generic, the need to develop the five high-level building blocks into a template

format and the need to develop a manual. The possible range of application of the generic methodology is primarily in the petrochemical industry, but any plant that exhibits the same characteristics as the Synthetic Fuel plant (*i.e.* any stochastic continuous system) can readily be accommodated by the generic methodology. The three different usage perspectives within the possible range of application of the generic methodology are the classic Industrial Engineering usage perspective, the training usage perspective and the Sustainable Development usage perspective.

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5.8   LESSONS LEARNT AND REINFORCED

This section contains a few philosophical musings that are related to the research that is presented in this document.

Thinking outside the confines that are dictated by the norm (*i.e.* lateral thinking) can lead to an innovative solution. For instance, the concept of the ERM method, that is used to determine the number of available modules in each of the smaller plants at any given moment in time, is counter-intuitive because it uses entities to represent the modules rather than the cumbersome *Servers* or *Work Centers* that are usually used in simulation software packages. It leads to a compact simulation model size, total control over all the aspects of the services and accuracy.

A concept that may seem simplistic can provide an elegant solution for a complex problem. For example, the simplicity of the FC method, that is used to identify the momentary "bottleneck" in a complex system at any given moment in time, contradicts the complexity of the problem that it solves. The FC method successfully addresses one of the major problem areas of the generic simulation modelling methodology and it also impacts positively on all the design criteria (or simulation model characteristics) of the generic methodology.

In *Gallows Gecko* of Leipoldt (2001:15) the character Martin Rekker makes the following remark to Brother Doremus:

> "*If I may remark, little things make perfection but perfection, Brother, is by no means a little thing.*"

Paying attention to minute detail, whenever possible, does accumulate to render a better solution in the long run. For example, the use of the advanced version of the ERM method that allows total control over all the relevant aspects of the services of the modules (including the "disturbed service sequence" phenomena), the use of double precision accuracy by the FORTRAN software programme that determines the governing parameters, *etc.* all contribute to the high accuracy of the generic simulation modelling methodology.

Complex problems should be approached with the complex problem solving process that is suggested by Leedy (1993:71) and *Rule Thirteen* of Descartes (2003:164-169). *Rule Thirteen* addresses the first part of the complex problem solving process.

> "*If we understand a question perfectly, it must be abstracted from every superfluous concept, reduced to its most simple form and divided by enumeration into the smallest parts possible.*"

The complex problem solving process comprises the following:
a)   Identify the main problem.
b)   Segregate the main problem into subproblems.
c)   Conceptualise and develop methods and techniques to solve the subproblems.
d)   Integrate the methods and techniques into a methodology.

Unfortunately there is no *Chemical Plant Simulation for Dummies*. In *The Goal* (Goldratt and Cox, 1992:43) the character Alex Rogo remarks:

> "*The complexity in this plant - in **any** manufacturing plant - is mind-boggling if you contemplate it.*"

Chemical plants are, by the very nature of the processes involved, extremely complex systems. There is no quick and easy way to develop a high quality simulation model of a chemical plant. It takes time, commitment and diligence. The generic simulation modelling methodology can be used to model stochastic continuous systems effectively.   The efficiency of the generic methodology follows from a structured approach and the characteristics of simulation models that are developed with the generic methodology, namely: short development and maintenance times, user-friendliness, short simulation runtimes, compact size, robustness, accuracy and a single software application.   The generic methodology, however, is not a magic wand that can effortlessly render high quality simulation models of complex systems.

Goldratt and Cox (1992:58) advocate the commonly held belief that monetary considerations are the sole motivation for the existence of a company.

"*The goal of a manufacturing organization is to make money.*"

This one-dimensional perspective belongs to the realm of the dinosaurs now and has to make way for a new paradigm. The new paradigm advocates that companies that want to survive and prosper have to adapt a triple bottom-line approach. Progressive companies should temper management decisions with consideration for the three dimensions of Sustainable Development, namely: Economic Prosperity, Environmental Quality and Social Value.

Simulation modelling is as much an art as a science (Kruger, 2003:39-49). Kruger uses the comparative neutral concept of simulation modelling syndromes to discuss the art of simulation modelling. For example, under the heading "*Bigger is Better*", Kruger postulates:

"*... many more* [simulation] *models suffer from too much detail than suffering from not enough detail. An attempt should be made to keep the* [simulation] *model as simple as possible ...*"

The concept to keep it as simple as possible is one of the cornerstones of the generic simulation modelling methodology. The simplicity concept may seem to contradict the paying attention to minute detail concept, but that is exactly where the art of simulation modelling comes into the picture. One aspect of the art of simulation modelling is to identify which detail should be included and which should be excluded.

In *Walden* Thoreau (1996:289) makes the following statement:

"*Rather than love, than money, than fame, give me truth.*"

This statement personifies the quest of the enquiring mind and may be interpreted differently if viewed from different perspectives. For example, the philosophical, political, religious, legal, scientific, *etc.* perspectives of the term "truth", may differ significantly. From the perspective of the scientist or engineer the term "truth" may be interpreted as the "better" solution or increased efficiency. The efficiency of the generic simulation modelling methodology follows from a structured approach and the characteristics of simulation models that are developed with the generic methodology. The generic methodology represents a "better" way to develop powerful

decision support tools. If these decision support tools are used correctly, it will lead to the more efficient utilisation of the limited resources of the earth.

This research represents but a small step in the long journey towards a better world.

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Summary

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This section concludes the research that is presented in this document with a few philosophical musings. The eight ideas that are considered may seem disconnected, but they are all relevant in the context of the research. The following philosophical ideas are discussed: lateral thinking can lead to innovative solutions, simplistic concepts can provide elegant solutions for complex problems, paying attention to detail does render better solutions, complex problems should be approached with the complex problem solving process, there is unfortunately no *Chemical Plant Simulation for Dummies,* the triple bottom-line approach is the future, simulation modelling is as much an art as a science and the search for the truth is the quest of the enquiring mind.

In the summer of 1773 Samuel Johnson and James Boswell undertook a journey to the Hebrides. During a meeting between Voltaire and Boswell, before the journey, the following conversation took place (Boswell, 2000:25):

> "*When I was at Ferney* [in France, near the Swiss border]*, in 1764, I mentioned our design to Voltaire. He looked at me, as if I had talked of going to the North Pole, and said, "You do not insist on my accompanying you?" - "No, sir." - "Then I am very willing you should go." I was not afraid that our curious expedition would be prevented by such apprehensions; ...*"

And such is the journey of the researcher, many may think the journey interesting and relevant, but few are willing to go.

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APPENDICES

APPENDIX A

SYNTHETIC FUEL PLANT DETAIL

Table A1: Number of Modules and Capacities

No.	Name	Mod.	Capacity In	(From)	Capacity Out	(To)
1	Coal Processing	14	140 ton/h Coal	(-)	94,5 ton/h Coal (Coarse)	(No. 4)
					45,5 ton/h Coal (Fine)	(No. 3)
2	Water Treatment	2	2555 ton/h Water	(-)	3150 ton/h Water	(No. 3)
			595 ton/h Recycled water	(No. 4,6,7)		
3	Steam	9	399 ton/h Water	(No. 2)	378 ton/h Steam	(No. 4)
			60,9 ton/h Coal (Fine)	(No. 1)		(No. 6-A, -C)
						(No. 7)
4	Gas Production	40	25,9 ton/h Steam	(No. 3)	39900 nm^3/h Raw gas	(No. 5)
			5530 nm^3/h Oxygen	(No. 6-C)		
			25,45 ton/h Coal (Coarse)	(No. 1)		
5	Temperature Regulation	8	210000 nm^3/h Raw gas	(No. 4)	210000 nm^3/h Raw gas	(No. 8)
					134,4 m^3/h Gas-water	(No. 13-A)
6-A	Oxygen-A	6	105 ton/h Steam	(No. 3)	269500 nm^3/h Air	(No. 6-B)
6-B	Oxygen-B	6	269500 nm^3/h Air	(No. 6-A)	46900 nm^3/h Oxygen	(No. 6-C)
6-C	Oxygen-C	7	46900 nm^3/h Oxygen	(No. 6-B)	46900 nm^3/h Oxygen	(No. 4)
			35 ton/h Steam	(No. 3)		(No. 12)
6E-A	Oxygen Extra-A	1	24,5 MW Electricity	(-)	262010 nm^3/h Air	(No. 6E-B)
6E-B	Oxygen Extra-B	1	262010 nm^3/h Air	(No. 6E-A)	51800 nm^3/h Oxygen	(No. 6E-C)
6E-C	Oxygen Extra-C	1	51800 nm^3/h Oxygen	(No. 6E-B)	51800 nm^3/h Oxygen	(No. 4)
			9,8 MW Electricity	(-)		(No. 12)
7	Electricity Generation	4	178,5 ton/h Steam	(No. 3)	42 MW Electricity	(-)
8	Plant(I)	4	365000 nm^3/h Raw gas	(No. 5)	255500 nm^3/h Pure gas	(No. 9-A)
9-A	Plant(II)-A	8	217000 nm^3/h Pure gas	(No. 8)	69440 nm^3/h Residue gas	(No. 9-B)
			(Feedback H$_2$	(No. 11))	70 m^3/h Chemical product	(No. 14)
			(Feedback recycled gas	(No. 12))		
9-B	Plant(II)-B	2	404250 nm^3/h Residue gas	(No. 9-A)	404250 nm^3/h Residue gas	(No. 10)
10	Plant(III)	2	280000 nm^3/h Residue gas	(No. 9-B)	241500 nm^3/h Down gas	(No. 11)

No.	Name	Mod.	Capacity In	(From)	Capacity Out	(To)
11	Division Process	2	241500 nm^3/h Down gas	(No. 10)	98000 nm^3/h H$_2$	(No. 9-A)
					84000 nm^3/h CH$_4$	(No. 12)
					7350 nm^3/h C$_2$	(No. 18)
					3850 nm^3/h C$_2$	(No. 19)
					77 m^3/h Condensate	(No. 20)
12	Recycling	8	24500 nm^3/h CH$_4$	(No. 11)	64750 nm^3/h Recycled gas	(No. 9-A)
			11200 nm^3/h Oxygen	(No. 6-C)		
13-A	Tank Plant(IV)-A	4	(1000 m^3 Gas-water) 245 m^3/h Gas-water	(No. 5)	(2000 m^3 Gas-water) 5,95 m^3/h NH$_3$	(No. 13-B)
					1,05 m^3/h Tar acid	(-)
13-B	Plant(IV)-B	2	11,9 m^3/h NH$_3$	(No. 13-A)	11,9 m^3/h NH$_3$	(No. 13-C)
13-C	Plant(IV)-C	1	23,8 m^3/h NH$_3$	(No. 13-B)	23,8 m^3/h NH$_3$	(-)
14	Sub(I)	2	280 m^3/h Chemical product	(No. 9-A)	3,75% Alcohol	(No. 15)
					2,5% Carbonyl	(No. 16)
15	Sub(II)	1	21 m^3/h Alcohol	(No. 14)	70% Ethanol	(-)
					30% Propanol	(-)
16	Sub(III)	1	14 m^3/h Carbonyl	(No. 14)	47,62% Acetone	(-)
					28,57% MEK	(-)
					19,05% Aldehyde	(No. 17)
					4,65% Methanol	(-)
17	Sub(IV)	1	2,8 m^3/h Aldehyde	(No. 16)	50% Heavy aldehyde	(-)
					37% N–Butanol	(-)
18	Sub(V)	1	16800 nm^3/h C$_2$	(No. 11)	40% Ethane	(-)
					0,076% Ethylene	(-)
19	Sub(VI)	1	12600 nm^3/h C$_2$	(No. 11)	40% Ethane	(-)
					0,06% Petrol	(-)
					0,04% Butene	(-)
20	Plant(V)	8	20 m^3/h Condensate	(No. 11)	6 m^3/h C$_5$C$_6$	(-)
					6,24 m^3/h Petrol	(-)
					6,24 m^3/h Diesel	(-)
					0,8 m^3/h C$_3$	(-)
					0,8 m^3/h Heavy polymer	(-)
					1,2 m^3/h C$_4$	(-)

Where:

No.   :   The plant identification number.

Mod.   :   The number of modules in the plant.

(-)   :   The external input or output.

Notes:

a) The solid phase capacities are given in tons per hour (ton/h) - except for water and steam where traditionally the capacities are always given in ton/h.

b) The liquid phase capacities are given in cubic metres per hour (m^3/h).

c) The gas phase capacities are given in normalised cubic metres per hour (nm^3/h).

d) Because the temperatures and pressures (and therefore the volumes) of gases differ at different points in the process, the volumes of gases are represented as volumes that are numerically normalised to a standard temperature and pressure. This normalisation makes it possible to compare the volumes of gases at different points in the process.

e) The plant (or plants) from which input (singular or multiple) is received and the plant (or plants) to which output (singular or multiple) is sent are indicated in brackets in Columns 4 and 5 respectively.

f) The two modules in the Water Treatment plant are arranged and connected in series and therefore the input and output capacities are given for the whole Water Treatment plant and not for a single module as per the convention that is followed for the other plants. The two values that are given for the input and output capacities incorporate the recycled water from the Gas Production, Oxygen and Electricity Generation plants and therefore the input and output capacities do not represent the conversion ratio of the Water Treatment plant as per the convention that is followed for the other plants. It is obvious that the conversion ratio of the Water Treatment plant is one (1) because the water is only filtered and demineralised and therefore the input and output throughput values of the Water Treatment plant are always exactly the same. However, the constant feedback of 595 ton/h of recycled water implies that water is only taken from the external source if the demand for water is such that the output throughput of the Water Treatment plant exceeds 595 ton/h of water.

g) The values that are given for the minimum and maximum volumes of the tank at Plant(IV) differ from the rest of the values in Columns 4 and 5 respectively because they represent volumes and not rates of flow.

* * *

Table A2: Service Schedules and Failure Characteristics

No.	Name	Service Schedule		Failure Characteristics			
		Cycle Time (hour)	Service Time (hour)	MTBF - Failure Rate Reciprocal (hour)	Repair Time (hour)		
					Mi.	Mo.	Ma.
1	Coal Processing	168 1176 10080	1 2 336	336	6	8	12
2	Water Treatment	-	-	-	-	-	-
3	Steam	1344	34	2880	24	120	168
4	Gas Production	-	-	960	3	16	25
5	Temperature Regulation	(2/"phase") 34560	408	5760	2	3	8
6-A 6-B 6-C	Oxygen-A Oxygen-B Oxygen-C	1440 17280 1440	24 336 24	1080 8640 840	1 16 1	2 24 1	10 30 8
6E-A 6E-B 6E-C	Oxygen Extra-A Oxygen Extra-B Oxygen Extra-C	(1/"phase") 8640 (1/"phase") 8640 (1/"phase") 8640	336 336 336	- - 1234	- - 0,5	- - 12	- - 24
7	Electricity Generation	34560	720	1440	0,25	1	3
8	Plant(I)	(2/"phase") 17280	408	8640	1	6	24
9-A	Plant(II)-A	720 2880 10080	24 120 360	11520	168	168	168
9-B	Plant(II)-B	(1/"phase") 17280	360	17280	1	1	5
10	Plant(III)	-	-	8640	6	8	24
11	Division Process	-	-	8640	1	18	48
12	Recycling	4320	216	-	-	-	-
13-A 13-B 13-C	Plant(IV)-A Plant(IV)-B Plant(IV)-C	- - -	- - -	34560 17280 34560	0,5 2 18	0,5 3 24	3 10 30
14	Sub(I)	-	-	-	-	-	-
15	Sub(II)	-	-	-	-	-	-
16	Sub(III)	-	-	-	-	-	-
17	Sub(IV)	-	-	-	-	-	-
18	Sub(V)	-	-	-	-	-	-

No.	Name	Service Schedule		Failure Characteristics			
		Cycle Time (hour)	Service Time (hour)	MTBF - Failure Rate Reciprocal (hour)	Repair Time (hour)		
					Mi.	Mo.	Ma.
19	Sub(VI)	-	-	-	-	-	-
20	Plant(V)	-	-	5317	300	336	408

Where:

No.	:	The plant identification number.
MTBF	:	The Mean Time Between Failure of the modules (hour).
Mi.	:	The minimum value of the triangular distribution.
Mo.	:	The mode value of the triangular distribution.
Ma.	:	The maximum value of the triangular distribution.

Notes:

a)   The service cycles assume a 24-hour day, a 7-day week, a 30-day month and a 360-day year (see Appendix L for a detailed discussion about the simulation model year).

b)   The plants that are subject to "phase" services as well as the number of modules that are serviced during each "phase" service are indicated.

c)   The MTBF values (reciprocals of the failure rates) of the modules are given because it is easier to understand and conceptualise than the small numerical values of the failure rates and because the MTBF values represent the mean values of the exponential distributions that are used to model the failure rates of the modules (see Section 1.2).

d)   The repair times are represented by three values that define the triangular distributions that are used to model the repair times of the modules (see Section 1.2).

e)   The repair time of Plant(II)-A is a constant repair time.

* * * * *

APPENDIX B

SYNTHETIC FUEL PLANT RULES OF OPERATION

a)   The Synthetic Fuel plant always strives to maintain the maximum possible rate of production or throughput.

b)   Only the smaller plants that form part of the main-gas-cycle can act as "bottlenecks" that influence the rate of production or throughput of the Synthetic Fuel plant. The main-gas-cycle comprises the following smaller plants: Coal Processing, Steam, Gas Production, Temperature Regulation, Oxygen-A, -B and -C, Plant(I), Plant(II)-A and -B, Plant(III), Division Process and Recycling. These smaller plants determine the throughput of the Synthetic Fuel plant. The throughput of the Synthetic Fuel plant is constantly adjusted to coincide with the maximum possible throughput of the specific smaller plant that act as the "bottleneck" at that specific moment in time. The Water Treatment plant actually forms part of the main-gas-cycle, but it is not considered for inclusion in the aforementioned list, because it can never act as a "bottleneck" that influences the throughput (see Point f) for an explanation). The smaller plants in the aforementioned list are sometimes referred to as the "heart " of the Synthetic Fuel plant.

c)   The Electricity Generation plant, Plant(IV), Plant(V) and Sub(I) to Sub(VI) do not form part of the main-gas-cycle and therefore they do not influence the throughput of the Synthetic Fuel plant. They are sometimes referred to as the peripheral plants. The final products of the Synthetic Fuel plant are generated by the peripheral plants.

d)   If Plant(IV), Plant(V) and Sub(I) to Sub(VI) do not have the capacity to process the throughput at their respective positions in the Synthetic Fuel plant, then the portions of the throughput that cannot be processed are flared. The flares at Plant(IV) and Plant(V) are called Flare-A and Flare-B respectively and the flares at Sub(I) to Sub(VI) are numbered progressively from Flare-C1 to Flare-C6.

e)   The Coal Processing plant separates the coal from the mines into coarse and fine coal with sieves. Coarse coal is supplied to the Gas Production plant and fine coal to the Steam plant. The ratio of this division is determined by the composition of the coal from the mines. The division ratio changes over time but it is assumed to be a fixed ratio of 67,5% coarse coal to 32,5% fine coal for the sake of this document. For the system description of the Synthetic Fuel plant that is provided in Section 1.2, this specific division ratio implies that the "bottleneck" capacity of the Coal Processing plant is determined by its capacity to supply coarse coal to the Gas Production plant and not by its capacity to

supply fine coal to the Steam plant. It therefore logically follows that there is an oversupply of fine coal to the Steam plant in this instance. This oversupply of fine coal to the Steam plant is diverted to slimes dams. If the system description or division ratio changes, the whole situation could be reversed and fine coal might then be recovered from the slimes dams to bolster the capacity of the Coal Processing plant to supply fine coal to the Steam plant. (It is assumed that the external source of coal from the mines is unlimited.)

f) The Water Treatment plant can never act as a "bottleneck" in the main-gas-cycle because there is always enough water (adequate capacity). When a breakdown occurs at the Water Treatment plant only the quality of the water that is supplied to the Steam plant is affected. The capacity of the Water Treatment plant is not affected. Water is also recycled from the Gas Production, Oxygen and Electricity Generation plants. Water is only taken from the external source if the demand for water is such that it cannot be satisfied by the recycled water. (It is assumed that the external source of water is unlimited.)

g) The output of the Steam plant is divided between three of the smaller plants. Steam is supplied to the Gas Production, Oxygen and Electricity Generation plants. Steam will only be supplied to the Electricity Generation plant once the Gas Production and Oxygen plants have been supplied. The primary function of the Steam plant is to supply steam to the Gas Production and Oxygen plants and the secondary function is to supply steam to the Electricity Generation plant. The ratio of steam that is supplied to the Gas Production plant to steam that is supplied to the Oxygen plant is referred to as the steam-division-ratio. The steam-division-ratio is a fixed ratio for a specific system description.

h) The raw gas output capacity of each gasifier in the Gas Production plant is actually 39200 nm^3/h. An electrical fan delivers an additional output capacity of 28000 nm^3/h from the piping of the Gas Production plant. The operators of the Synthetic Fuel plant claim that the additional output capacity of 28000 nm^3/h is always available, independent of the throughput of the Synthetic Fuel plant. This assumption is highly questionable because at the extreme of 0% throughput the additional output capacity obviously cannot be 28000 nm^3/h. (If any additional output capacity is available at 0% throughput, it will be contradictory to the laws of conservation of mass and energy.) It therefore seems prudent to allocate the additional output capacity of 28000 nm^3/h evenly to the 40 gasifiers and that leads to an output capacity of 39900 nm^3/h for each gasifier. This concept spreads the additional output capacity evenly over the total possible range of the throughput of the Synthetic Fuel plant.

i) The output of the Oxygen plant is divided between two of the smaller plants. Oxygen is

supplied to both the Gas Production and Recycling plants. The ratio of oxygen that is supplied to the Gas Production plant to oxygen that is supplied to the Recycling plant is referred to as the oxygen-division-ratio. The oxygen-division-ratio is a fixed ratio for a specific system description.

j) The Electricity Generation plant generates in-house electricity for the Synthetic Fuel plant to alleviate its dependence on the national electricity network. Point g) indicates that steam is only supplied to the Electricity Generation plant once the Gas Production and Oxygen plants have been supplied. In the instance where the Electricity Generation plant cannot operate at full capacity due to a shortage of steam or services and failures of modules, additional electricity is drawn from the national network to make up for the shortfall.

k) Plant(II)-A receives input from three other plants. Plant(II)-A receives pure gas directly from Plant(I), H_2 from the Division Process plant and recycled gas from the Recycling plant. From the Division Process plant there is a direct feedback-loop to Plant(II)-A and there is also an indirect feedback-loop from the Division Process plant through the Recycling plant to Plant(II)-A. The primary input of Plant(II)-A is the pure gas from Plant(I) and it is supplemented by the secondary input that consists of the H_2 and recycled gas from the Division Process and Recycling plants respectively. The volumes of H_2 and recycled gas that are supplied to Plant(II)-A obviously depends on the volume of pure gas that is supplied to Plant(II)-A from Plant(I). The ratio of the pure gas to the pure gas plus the H_2 and the recycled gas is referred to as the gas-feedback-loop-fraction. The gas-feedback-loop-fraction assumes a fixed value for a specific system description.

l) The only tank in the Synthetic Fuel plant is situated directly in front of Plant(IV) where it is used to buffer the flow of gas-water between the Temperature Regulation plant and Plant(IV). The minimum and maximum allowable volumes of gas-water in the tank are specified. If the maximum allowable volume of gas-water in the tank is surpassed, all addition gas-water is flared and if the minimum allowable volume of gas-water is reached, the processing capacity of Plant(IV) is curtailed to maintain at least the minimum allowable volume of gas-water in the tank.

* * * * *

APPENDIX C

PSCALC.IN
(Governing Parameters Determination Input File)

```
GOVERNING PARAMETERS CALCULATION INPUT
COAL PROCESSING
14                94.5
STEAM
 9               378.0
GAS PRODUCTION
40      25.9   39900.0
      5530.0
       25.45
TEMPERATURE REGULATION
 8   210000.0  210000.0
OXYGEN-A
 6      105.0  269500.0
OXYGEN-B
 6   269500.0   46900.0
OXYGEN-C
 7    46900.0   46900.0
         35.0
PLANT(I)
 4   365000.0  255500.0
PLANT(II)-A
 8   217000.0   69440.0
PLANT(II)-B
 2   404250.0  404250.0
PLANT(III)
 2   280000.0  241500.0
DIVISION PROCESS
 2   241500.0   98000.0
                84000.0
RECYCLING
 8    24500.0   64750.0
      11200.0
```

* * * * *

APPENDIX D

PSCALC.OUT
(Governing Parameters Determination Output File)

```
GOVERNING PARAMETERS CALCULATION OUTPUT
   FO08A    FI09AA    FI10A     FI11A     FI12A     FO12A
   725961.   725961.  232307.  200365.   69692.  184187.
   725961.   991455.  317265.  273641.   95180.  251546.
   725961.  1088550.  348336.  300440.  104501.  276181.
   725961.  1124059.  359699.  310240.  107910.  285190.
   725961.  1137045.  363854.  313824.  109156.  288485.
   725961.  1141794.  365374.  315135.  109612.  289689.
   725961.  1143531.  365930.  315615.  109779.  290130.
   725961.  1144166.  366133.  315790.  109840.  290291.
   725961.  1144398.  366207.  315854.  109862.  290350.
   725961.  1144483.  366235.  315877.  109870.  290372.
   725961.  1144514.  366245.  315886.  109873.  290380.
   725961.  1144526.  366248.  315889.  109874.  290383.
   725961.  1144530.  366250.  315890.  109875.  290384.
   725961.  1144531.  366250.  315891.  109875.  290384.
   725961.  1144532.  366250.  315891.  109875.  290384.
   725961.  1144532.  366250.  315891.  109875.  290384.
GAS-FEEDBACK-LOOP-FRACTION
   .634286
   1.576576
OXYGEN-DIV-RATIO (GAS PRODUCTION - RECYCLING)
   .741043   .258957
   1.349449  3.861647
STEAM-DIV-RATIO (GAS PRODUCTION - OXYGEN)
   .537612   .462388
   1.860077  2.162687
FRACTION METHOD PARAMETER SET
COAL PROCESSING
   931.253
STEAM
   1762.830
GAS PRODUCTION
  1460000.0
TEMPERATURE REGULATION
  1460000.0
OXYGEN-A
  1569088.9
OXYGEN-B
   273062.2
```

```
OXYGEN-C
  273062.2
PLANT(I)
 1022000.0
PLANT(II)-A
  515603.6
PLANT(II)-B
  515603.6
PLANT(III)
  444708.1
DIVISION PROCESS
  180461.2
RECYCLING
  408800.0
```

* * * * *

APPENDIX E

SERVIC.DAT
(Arena Simulation Model Service Schedules Input File)

```
Servic.dat
Coal Processing
   84    168      1
  588   1176      2
 5040  10080    336
Steam
  672   1344     34
Temperature Regulation
 1440  34560    408
Oxygen-A
  720   1440     24
Oxygen-B
 8640  17280    336
Oxygen-C
  720   1440     24
Electricity Generation
17280  34560    720
Plant(I)
 1440  17280    408
Plant(II)-A
  360    720     24
 1440   2880    120
 5040  10080    360
Plant(II)-B
 1440  17280    360
Recycling
 2160   4320    216
Oxygen Extra-A
 1440   8640    336
Oxygen Extra-B
 1440   8640    336
Oxygen Extra-C
 1440   8640    336
```

* * * * *

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APPENDIX F

PRIORI.WKS

(Arena Simulation Model "Bottleneck" Identification Output File)

(See next page for landscape view)

* * * * *

1	0.000000	0.000000	0.016531	0.000000	1.494756	0.318729	0.020431	2.427662	4.597664	0.004999	0.063465	0.312036	0.000000
2	0.000000	0.000000	0.080944	0.000000	1.646589	0.134029	0.036776	2.494213	3.637738	0.007499	0.052887	0.222127	0.000000
3	0.000000	0.000000	0.013707	0.000000	1.694225	0.297208	0.031600	2.395833	4.964954	0.012498	0.237993	0.163951	0.000000
4	0.000000	0.000000	0.060130	0.000000	1.504276	0.035142	0.017162	2.442130	4.336630	0.000000	0.259148	0.111064	0.000000
5	0.000000	0.000000	0.003555	0.000000	1.560866	0.121771	0.017162	2.447917	5.857306	0.004999	0.174528	0.306747	0.000000
6	0.000000	0.000000	0.009622	0.006342	1.705564	0.071918	0.031873	2.595486	4.460826	0.007499	0.047599	0.000000	0.000000
7	0.002007	0.000000	0.017895	0.000000	1.362671	0.258252	0.059659	2.528935	5.300241	0.000000	0.021155	0.396655	0.000000
8	0.004015	0.000000	0.026327	0.000000	1.754510	0.148740	0.059659	2.395833	3.997820	0.017497	0.174528	0.449543	0.000000
9	0.007025	0.000000	0.043076	0.000000	1.578558	0.204313	0.050206	2.447917	4.229393	0.019997	0.216838	0.195683	0.000000
10	0.000000	0.000000	0.057169	0.001585	1.811497	0.331805	0.040045	2.662037	3.700619	0.000000	0.306747	0.100486	0.000000
11	0.000000	0.000000	0.028354	0.000000	1.469134	0.195323	0.021249	2.392940	4.398884	0.007499	0.195683	0.095197	0.000000
12	0.000000	0.000000	0.128139	0.000000	1.787642	0.211669	0.044132	2.549190	4.326427	0.017497	0.095197	0.116352	0.000000
13	0.000000	0.000000	0.015787	0.000000	1.622955	0.156913	0.026969	2.624421	4.674228	0.007499	0.153373	0.121641	0.000000
14	0.010036	0.000000	0.034011	0.000000	1.579640	0.125040	0.015528	2.471065	4.024167	0.000000	0.042310	0.222127	0.000000
15	0.000000	0.000000	0.111107	0.000000	1.736597	0.259069	0.031873	2.459491	3.899594	0.019997	0.179817	0.105775	0.000000
16	0.001004	0.000000	0.025837	0.000000	1.524553	0.439682	0.026152	2.485532	4.876162	0.017497	0.280303	0.179817	0.000000
17	0.000000	0.000000	0.030626	0.000000	1.638726	0.180613	0.026152	2.459491	4.083803	0.009998	0.312036	0.174528	0.000000
18	0.000000	0.000000	0.002575	0.000000	1.646523	0.204313	0.016345	2.523148	3.520856	0.007499	0.179817	0.301458	0.000000
19	0.004015	0.000000	0.083122	0.000000	1.679765	0.179796	0.017162	2.427662	4.172465	0.000000	0.058176	0.153373	0.000000
20	0.006022	0.000000	0.002993	0.000000	1.676209	0.254983	0.033044	2.581019	4.282333	0.000000	0.206261	0.137507	0.000000

* * * * *

APPENDIX G

SIMULATION WINDOW OF THE HIGHER HIERARCHICAL LEVEL
(Simul8 Simulation Model)
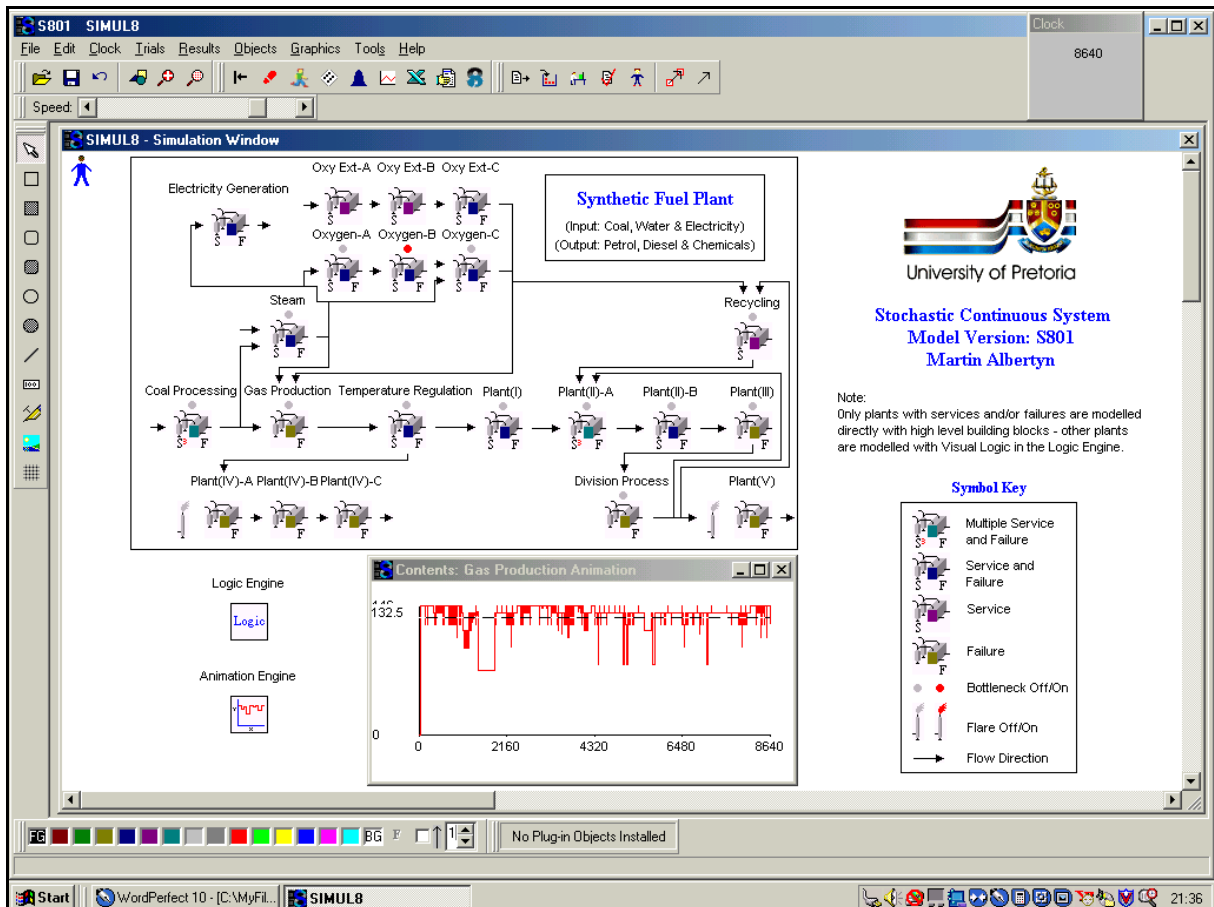
* * * * *

APPENDIX H

SIMULATION WINDOW OF THE LOWER HIERARCHICAL LEVEL
(Arena Simulation Model - Example No.1)

* * * * *

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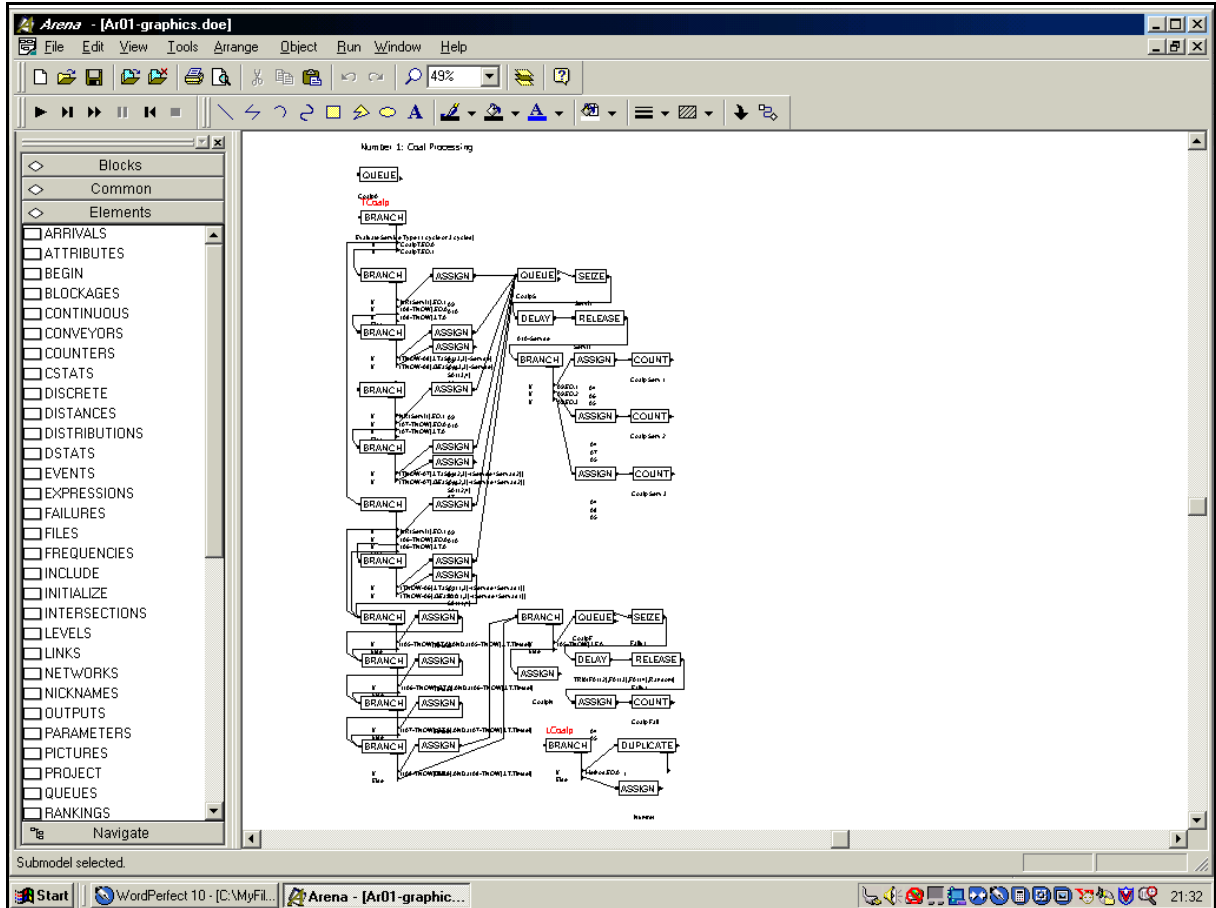
APPENDIX I

SIMULATION WINDOW OF THE LOWER HIERARCHICAL LEVEL
(Arena Simulation Model - Example No.2)

* * * * *

APPENDIX J

N.IN
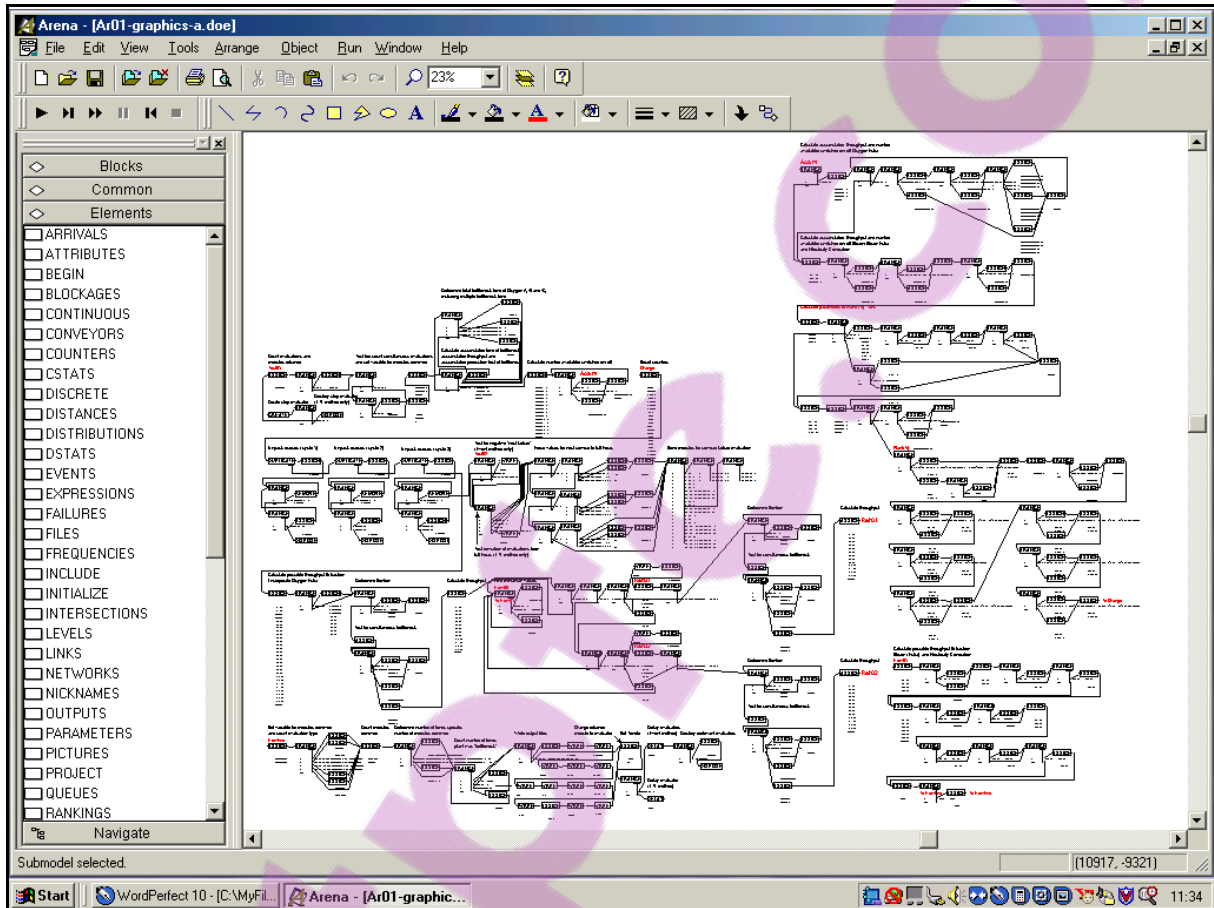
(Sample Size Determination Input File)

```
SAMPLE SIZE CALCULATION INPUT
CONFIDENCE INTERVAL (90%, 95% OR 99%)
   99.0
FAULT ALLOWED (HALF LENGTH OF CONFIDENCE INT)
 6661.2
IDENTIFIER  STDDEV
  0.125     7185.9
  0.250     7185.6
  0.500     7159.0
  1.000     7154.9
  2.000     7131.7
  3.000     7112.1
  4.000     7153.3
  6.000     7204.7
 12.000     7087.1
 24.000     7781.5
```

* * * * *

APPENDIX K

N.OUT
(Sample Size Determination Output File)

```
SAMPLE SIZE CALCULATION OUTPUT
CONFIDENCE INTERVAL
      99.0
FAULT ALLOWED (HALF LENGTH OF CONFIDENCE INT)
    6661.2
IDENTIFIER    STDDEV    N(INT)    N(CALC)
      .125    7185.9     12.      11.227
      .250    7185.6     12.      11.226
      .500    7159.0     12.      11.143
     1.000    7154.9     12.      11.130
     2.000    7131.7     12.      11.058
     3.000    7112.1     12.      10.997
     4.000    7153.3     12.      11.125
     6.000    7204.7     12.      11.286
    12.000    7087.1     12.      10.920
    24.000    7781.5     13.      12.736
```

* * * * *

APPENDIX L

SYNTHETIC FUEL PLANT SIMULATION MODEL YEAR

The Synthetic Fuel plant simulation model year is considered to consist of 360 days or 8640 hours (360 multiplied by 24 hours). This assumption is made to make provision for the easy subdivision of the simulation model year into equal smaller parts. The simulation model year can easily be subdivided into equal halves of six months each (*i.e.* 180 days each), equal quarters of three months each (*i.e.* 90 days each) and 12 equal months of 30 days each. That leaves only the seven-day week out of synchronisation with the other subdivisions of the simulation model year.

This simplification is incorporated to accommodate the service schedules of the modules of the Synthetic Fuel plant. The service schedules are expressed in terms of hours, days, weeks, months and sometimes even in terms of years by the maintenance division of the Synthetic Fuel plant. The hours, days, weeks, months and years that characterise the service schedules are all expressed in terms of hours in Table A2 and Appendix E and can readily by accommodated by the simulation model year. The only small aberration is created by weeks that are slightly out of synchronisation with the other subdivisions of the simulation model year.

The simplification of the 360 days simulation model year, however, does have an impact on the failure rates of the modules of the Synthetic Fuel plant. The failure rates of the modules are usually expressed in terms of the number of failures per year by the maintenance division of the Synthetic Fuel plant. The mean values of the exponential distributions that represent the failure rates of the modules are expressed in terms of hours in Table A2 (see Section 1.2 for a detailed explanation). The mean values of the exponential distributions that represent the failure rates of the modules are the MTBF values of the modules and they are derived by dividing the number of hours in the simulation model year by the number of failures per year of the modules. For example, at the Steam plant there are usually approximately 27 failures per year. That is approximately three failures per year (approximately one failure every four months) for each of the nine modules of the Steam plant (27 divided by nine). This implies that the MTBF of a Steam plant module in the simulation model year is 2880 hours (8640 hours divided by three). In contrast to this, the MTBF of a Steam plant module in the real-world year of 365 days is 2920 hours (8760 hours divided by three). Therefore the failures that are generated in the simulation model year (with an MTBF of 2880 hours) will be spaced slightly closer together than those that occur in the real-world situation (with an MTBF of 2920 hours). This may adversely affect the

output throughput of the Synthetic Fuel plant in a simulation model. The difference between the simulation model year MTBF and the real-world situation MTBF, however, is only 1,4% and therefore it is assumed that the effect of the simulation model year on the output throughput is negligible (40 hours divided by 2920 hours and multiplied by 100).

The output throughput values of the simulation model of the Synthetic Fuel plant are usually expressed as mean hourly rates that are calculated over the time period of the simulation run. For example, Table 3.2 indicates that the mean output throughput value of the Gas Production plant, for a simulation run consisting of 20 replications of a simulated time period of one simulation model year with an iteration time interval of one hour, is 1331462,8 nm^3/h. The total output throughput of the Gas Production plant during one real-world year can easily be determined by simply multiplying the average hourly rate by the number of hours in one real-world year and that is 11663614128,0 (1,17E+10) nm^3 (1331462,8 nm^3/h times 8760 hours).

It is therefore evident that the results that are generated by a simulation run of the Synthetic Fuel plant of one simulation model year can easily be "manipulated" or "extrapolated" to represent the results of one real-world year.

* * * * *

APPENDIX M

SYNTHETIC FUEL PLANT RAW GAS PRODUCTION - 1993

Table M1: Gas Production Plant Output Throughput -1993

Month	Days (day)	Hours (hour)	Monthly Mean Output Throughput (nm³/h)	Total Monthly Output Throughput (nm³)
January	31	744	1362200	1013476800
February	28	672	1365700	917750400
March	31	744	975100	725474400
April	30	720	1381100	994392000
May	31	744	1374800	1022851200
June	30	720	1374800	989856000
July	31	744	1365000	1015560000
August	31	744	1362900	1013997600
September	30	720	1339800	964656000
October	31	744	1365700	1016080800
November	30	720	1365000	982800000
December	31	744	1362200	1013476800
			Total Output Throughput (nm³)	11670372000
			Mean Output Throughput (nm³/h)	1332234,2

Notes:

a)   The Synthetic Fuel plant is actually a "scale model" of the real Sasol East plant (see Section 1.2) and therefore the monthly mean output throughput values of the Sasol East plant during the 1993 production year are adjusted with the same constant scale factor to find the values that are presented in Column 4 of Table M1. This is done to protect the client confidentiality of Sasol Synfuels. The fact that the same constant scale factor is used to adjust the capacities of the Sasol East plant and the monthly mean output throughput values of the Sasol East plant implies that Table M1 can be used to validate simulation models of the Synthetic Fuel plant.

b) The effect of a "phase" service is clearly visible in the monthly mean output throughput value of March that is appreciably less than those of the other months.

c) In this document the minimum sufficient sample sizes are calculated with an allowance for a 0,5% deviation from the real-world mean output throughput value of the Gas Production plant. From Table M1 it is clear that a 0,5% deviation from the real-world mean output throughput value is 6661,2 nm^3/h (1332234,2 nm^3/h multiplied by 0,005).

<p style="text-align:center">* * * * *</p>

APPENDIX N

DETERMINATION OF THE CONFIDENCE INTERVAL

Miller *et al.* (1990:212) indicate that if an estimate of the standard deviation is available, Equation N1 can be used to determine the confidence interval for a population mean for a small sample size (sample size less than 30).

$$x - t_{(\alpha/2)}(s/\sqrt{n}) < \mu < x + t_{(\alpha/2)}(s/\sqrt{n}) \qquad (Eq.:N1)$$

Where:

x	:	The sample mean.
t	:	The upper percentage point of the *t* distribution value.
100(1-α)	:	The confidence interval, as a percentage.
s	:	The estimate of the standard deviation.
n	:	The sample size.
μ	:	The population mean.

An interval of this kind is referred to as a confidence interval for the population mean that has a *100(1-α)*% degree of confidence. The endpoints of the interval are referred to as the lower and upper confidence limits.

The *t* distribution value is read from Table 4 in *Probability and Statistics for Engineers* (Miller *et al.*, 1990:570) for *n-1* degrees of freedom.

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APPENDIX O

FIRST-ORDER ESTIMATE OF THE NUMBER OF SERVICES AND FAILURES

Table O1: Number of Services and Failures (8640-hour year)

No.	Name	Mod.	No. Service Estimate				No. Failure Estimate	
			Start Time (hour)	Cycle Time (hour)	Service Time (hour)	No. Service	MTBF (hour)	No. Failure
1	Coal Processing	14	84	168	1	686	336	360
			588	1176	2	98		
			5040	10080	336	14		
3	Steam	9	672	1344	34	54	2880	27
4	Gas Production	40	-	-	-	-	960	360
5	Temperature Regulation	8	1440	34560	408	2/"phase"	5760	12
6-A	Oxygen-A	6	720	1440	24	36	1080	48
6-B	Oxygen-B	6	8640	17280	336	0	8640	6
6-C	Oxygen-C	7	720	1440	24	42	840	72
6E-A	Oxygen Extra-A	1	1440	8640	336	1/"phase"	-	-
6E-B	Oxygen Extra-B	1	1440	8640	336	1/"phase"	-	-
6E-C	Oxygen Extra-C	1	1440	8640	336	1/"phase"	1234	7
7	Electricity Generation	4	17280	34560	720	0	1440	24
8	Plant(I)	4	1440	17280	408	2/"phase"	8640	4
9-A	Plant(II)-A	8	360	720	24	11	11520	6
			1440	2880	120	2		
			5040	10080	360	1		
9-B	Plant(II)-B	2	1440	17280	360	1/"phase"	17280	1
10	Plant(III)	2	-	-	-	-	8640	2
11	Division Process	2	-	-	-	-	8640	2
12	Recycling	8	2160	4320	216	16	-	-

No.	Name	Mod.	No. Service Estimate				No. Failure Estimate	
			Start Time (hour)	Cycle Time (hour)	Service Time (hour)	No. Service	MTBF (hour)	No. Failure
13-A	Plant(IV)-A	4	-	-	-	-	34560	1
13-B	Plant(IV)-B	2	-	-	-	-	17280	1
13-C	Plant(IV)-C	1	-	-	-	-	34560	0
20	Plant(V)	8	-	-	-	-	5317	12
					Total No. Service	1066	Total No. Failure	945

Where:

No.	:	The plant identification number.
Mod.	:	The number of modules in the plant.
MTBF	:	The Mean Time Between Failure of the modules (hour).

Notes:

a)   The number of services is calculated as an integer value in each instance by using the INT function of the spreadsheet software package (INT drops the fractional portion of a variable, returning its integer value).

b)   The effect of the multiple service cycles is incorporated into the calculation of the number of services for the smaller plants that are subject to multiple service cycles.

c)   The number of failures is calculated as an integer value in each instance by using the INT function of the spreadsheet software package.

d)   From Point c) it follows that the number of failures of Plant(V) for an 8640-hour year is given as an integer value of 12 in Table O1 but as a real value of 13,00 in Table 3.3.

* * * * *

APPENDIX P

RANDOM NUMBER GENERATION TEST

Various authors provide methods that can be used to test the randomness of a string of random numbers (Miller *et al.*, 1990:313-316; Steyn *et al.*, 1989:509-511). Miller *et al.* (1990:313-314) indicate that Equations P1 to P3 can be used to test a string of random numbers for randomness.

They state that if a sequence contains n_1 symbols of one kind and n_2 symbols of another kind (and neither n_1 nor n_2 is less than 10), the sampling distribution of the total number of runs, u, can be approximated closely by a normal distribution with the following:

Mean and standard deviation of u:

$$\mu_u = (2n_1n_2 / (n_1 + n_2)) + 1 \qquad\qquad (Eq.:P1)$$

$$\sigma_u = \sqrt{((2n_1n_2(2n_1n_2 - n_1 - n_2)) / ((n_1 + n_2)^2(n_1 + n_2 - 1)))} \qquad (Eq.:P2)$$

Where:

u	:	The number of runs where a run is a group of similar symbols in a sequence of two kinds of symbols, where the symbols are arranged in the order of observance or occurrence.
μ_u	:	The mean of u.
n_1	:	The number of symbols of one kind (or runs below the median).
n_2	:	The number of symbols of another kind (or runs above the median).
σ_u	:	The standard deviation of u.

Therefore, the test of the null hypothesis (that the arrangement of the symbols is random) can be based on the following statistic:

Statistic for test of randomness:

$$z = (u - \mu_u) / \sigma_u \qquad\qquad (Eq.:P3)$$

This test can also be used to test the randomness of samples consisting of numerical data by counting runs above and below the median. A string of random numbers between zero and one was generated with both the Arena and Simul8 simulation software packages and then subjected to the random number generation test. The results are presented in Table P1: *Random Number Generation Test Results*.

Table P1: Random Number Generation Test Results

Attribute	Arena Simulation Software Package	Simul8 Simulation Software Package
Null hypothesis	Arrangement of sample values is random	Arrangement of sample values is random
Alternative hypothesis	Arrangement of sample values is not random	Arrangement of sample values is not random
Level of significance	0,05 (95%)	0,05 (95%)
Criterion	Accept null hypothesis if: -1,960 < z < 1,960 (see t-distribution)	Accept null hypothesis if: -1,960 < z < 1,960 (see t-distribution)
Number of random numbers in string	280	280
Median	0,550625	0,524858
n_1 (runs below the median)	140	140
n_2 (runs above the median)	140	140
u (number of runs)	133	132
Mean of u (Equation P1)	141	141
Standard deviation of u (Equation P2)	8,352	8,352
Statistic for test of randomness (z) (Equation P3)	-0,958	-1,078
Decision according to test criterion	Accept null hypothesis because: -0,958 > –1,960 and -0,958 < 1,960	Accept null hypothesis because: -1,078 > –1,960 and -1,078 < 1,960
Result	Arrangement of sample values is random	Arrangement of sample values is random

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APPENDIX Q

ED EVALUATION METHOD OPTION ARENA
SIMULATION MODEL RESULTS
(Scenario I)

(See next pages for landscape view)

* * * * *

Model AR01, ED Method, 8640 Hours, Oxygen Extra Off, Runtime = 8,6 Minutes (20 replications)
Throughput Primary Plants (ton/h, nm³/h) (output.wks)

N	Coalp	Steam	Gaspr	Tempr	OxygA	OxygB	OxygC	Plan1	Pla2A	Pla2B	Plan3	Divip	Recyc
1	848.806	1606.761	1330741.6	1330741.6	1430172.5	248887.1	248887.1	931519.1	469955.6	469955.6	405336.7	164484.4	372607.6
2	841.524	1592.976	1319324.5	1319324.5	1417902.3	246751.8	246751.8	923527.1	465923.6	465923.6	401859.1	163073.2	369410.9
3	848.056	1605.341	1329565.3	1329565.3	1428908.4	248667.1	248667.1	930695.7	469540.2	469540.2	404978.4	164339.0	372278.3
4	850.423	1609.821	1333276.2	1333276.2	1432896.5	249361.2	249361.2	933293.4	470850.7	470850.7	406108.7	164797.7	373317.3
5	849.241	1607.585	1331423.6	1331423.6	1430905.5	249014.7	249014.7	931996.5	470196.4	470196.4	405544.4	164568.7	372798.6
6	849.954	1608.934	1332541.5	1332541.5	1432106.9	249223.8	249223.8	932779.1	470591.2	470591.2	405884.9	164706.9	373111.6
7	850.128	1609.263	1332813.9	1332813.9	1432399.7	249274.7	249274.7	932969.7	470687.4	470687.4	405967.9	164740.5	373187.9
8	850.290	1609.569	1333067.1	1333067.1	1432671.8	249322.1	249322.1	933147.0	470776.8	470776.8	406045.0	164771.8	373258.8
9	856.749	1621.797	1343194.4	1343194.4	1443555.7	251216.2	251216.2	940236.1	474353.3	474353.3	409129.7	166023.6	376094.4
10	847.716	1604.698	1329033.1	1329033.1	1428336.4	248567.6	248567.6	930323.2	469352.2	469352.2	404816.3	164273.2	372129.3
11	850.683	1610.314	1333683.8	1333683.8	1433334.5	249437.4	249437.4	933578.7	470994.6	470994.6	406232.9	164848.1	373431.5
12	853.113	1614.914	1337493.7	1337493.7	1437429.1	250150.0	250150.0	936245.6	472340.1	472340.1	407393.3	165319.0	374498.2
13	849.417	1607.916	1331698.4	1331698.4	1431200.8	249066.1	249066.1	932188.9	470293.5	470293.5	405628.1	164602.7	372875.6
14	856.086	1620.541	1342154.5	1342154.5	1442438.2	251021.7	251021.7	939508.2	473986.1	473986.1	408813.0	165895.1	375803.3
15	848.938	1607.011	1330948.6	1330948.6	1430395.0	248925.9	248925.9	931664.1	470028.7	470028.7	405399.8	164510.0	372665.6
16	851.576	1612.005	1335084.6	1335084.6	1434840.0	249699.4	249699.4	934559.2	471489.3	471489.3	406659.5	165021.2	373823.7
17	849.647	1608.352	1332059.4	1332059.4	1431588.8	249133.6	249133.6	932441.6	470421.0	470421.0	405738.1	164647.3	372976.6
18	838.716	1587.661	1314922.7	1314922.7	1413171.6	245928.5	245928.5	920445.9	464369.1	464369.1	400518.3	162529.1	368178.3
19	855.337	1619.124	1340981.1	1340981.1	1441177.1	250802.2	250802.2	938686.7	473571.7	473571.7	408455.6	165750.0	375474.7
20	851.795	1612.419	1335428.0	1335428.0	1435209.0	249763.6	249763.6	934799.6	471610.6	471610.6	406764.1	165063.7	373919.8
Mean	849.910	1608.850	1332471.8	1332471.8	1432032.0	249210.7	249210.7	932730.3	470566.6	470566.6	405863.7	164698.3	373092.1

0.018	Deviation
6620.5	StdDev

* * *

Throughput Secondary Plants (ton/h, MW/h, m³/h, nm³/h) (output2.wks)

N	Steam Ext	Elecg	Pla4A	Pla4B	Pla4C	Plan5	Sub1	Sub2	Sub3	Sub4	Sub5	Sub6	OxyeA	OxyeB	OxyeC
1	712.902	167.742	20.627	20.627	20.627	37.526	17.765	12.436	5.640	1.128	4934.5	2584.8	0.0	0.0	0.0
2	706.328	166.195	20.507	20.507	20.507	37.997	17.613	12.329	5.592	1.118	4892.2	2562.6	0.0	0.0	0.0
3	710.664	167.215	20.667	20.667	20.667	38.240	17.750	12.425	5.635	1.127	4930.2	2582.5	0.0	0.0	0.0
4	709.038	166.832	20.724	20.724	20.724	37.977	17.799	12.460	5.651	1.130	4943.9	2589.7	0.0	0.0	0.0
5	710.633	167.208	20.643	20.643	20.643	38.417	17.775	12.442	5.643	1.129	4937.1	2586.1	0.0	0.0	0.0
6	712.985	167.761	20.710	20.710	20.710	38.013	17.789	12.453	5.648	1.130	4941.2	2588.3	0.0	0.0	0.0
7	713.072	167.782	20.664	20.664	20.664	38.651	17.793	12.455	5.649	1.130	4942.2	2588.8	0.0	0.0	0.0
8	710.984	167.290	20.721	20.721	20.721	38.506	17.797	12.458	5.650	1.130	4943.2	2589.3	0.0	0.0	0.0
9	712.769	167.710	20.876	20.876	20.876	37.675	17.932	12.552	5.693	1.139	4980.7	2608.9	0.0	0.0	0.0
10	712.109	167.555	20.654	20.654	20.654	38.699	17.743	12.420	5.633	1.127	4928.2	2581.4	0.0	0.0	0.0
11	713.253	167.824	20.731	20.731	20.731	38.763	17.805	12.463	5.652	1.131	4945.4	2590.5	0.0	0.0	0.0
12	712.529	167.654	20.787	20.787	20.787	38.539	17.856	12.499	5.669	1.134	4959.6	2597.9	0.0	0.0	0.0
13	712.864	167.733	20.700	20.700	20.700	38.554	17.778	12.445	5.644	1.129	4938.1	2586.6	0.0	0.0	0.0
14	713.365	167.851	20.862	20.862	20.862	38.854	17.918	12.542	5.688	1.138	4976.9	2606.9	0.0	0.0	0.0
15	713.284	167.832	20.683	20.683	20.683	38.196	17.768	12.438	5.641	1.128	4935.3	2585.2	0.0	0.0	0.0
16	713.306	167.837	20.751	20.751	20.751	36.659	17.823	12.476	5.658	1.132	4950.6	2593.2	0.0	0.0	0.0
17	712.239	167.586	20.705	20.705	20.705	38.620	17.783	12.448	5.646	1.129	4939.4	2587.3	0.0	0.0	0.0
18	712.891	167.739	20.439	20.439	20.439	37.771	17.554	12.288	5.573	1.115	4875.9	2554.0	0.0	0.0	0.0
19	713.189	167.809	20.840	20.840	20.840	38.488	17.902	12.532	5.683	1.137	4972.5	2604.6	0.0	0.0	0.0
20	713.107	167.790	20.756	20.756	20.756	38.456	17.828	12.480	5.660	1.132	4951.9	2593.9	0.0	0.0	0.0
Mean	712.076	167.547	20.702	20.702	20.702	38.230	17.789	12.452	5.647	1.130	4940.9	2588.1	0.0	0.0	0.0

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Time "Bottleneck" (%) (bottle.wks)

N	Coalp	Steam	Gaspr	Tempr	OxygA	OxygB	OxygC	Plan1	Pla2A	Pla2B	Plan3	Divip	Recyc	Total	OxygA	OxygB	OxygC
1	0.00	0.00	30.34	0.00	902.10	100.45	21.58	2524.11	5003.15	0.00	12.11	46.16	0.00	8640.00	916.45	104.15	32.23
2	0.00	0.00	30.25	0.00	958.16	151.49	13.61	2308.28	5107.78	9.26	8.44	52.74	0.00	8640.00	994.48	180.29	21.14
3	2.71	0.00	58.03	0.00	1033.36	124.40	8.92	2288.95	5049.17	0.00	9.61	64.84	0.00	8640.00	1052.87	135.25	17.59
4	0.00	0.00	60.29	0.00	996.04	162.60	12.85	2643.90	4696.03	4.84	17.51	45.93	0.00	8640.00	1011.01	169.86	20.56
5	0.00	0.00	41.56	0.00	831.29	37.79	13.10	2434.31	5206.67	0.00	21.94	53.35	0.00	8640.00	836.17	37.79	17.98
6	0.00	0.00	13.23	0.00	950.74	75.58	25.97	2387.37	5107.59	1.14	65.46	12.92	0.00	8640.00	997.27	105.26	45.96
7	0.00	0.00	5.01	0.00	955.70	37.88	29.38	2680.08	4878.29	0.00	24.07	29.60	0.00	8640.00	977.04	48.85	39.74
8	0.00	0.00	35.06	0.00	1071.71	194.36	17.26	2516.67	4708.10	6.51	22.04	68.30	0.00	8640.00	1093.86	205.00	28.76
9	4.88	0.00	75.01	0.00	929.96	137.58	23.41	2662.25	4773.52	1.64	0.00	31.74	0.00	8640.00	939.51	138.54	32.00
10	0.00	0.00	52.87	0.00	1037.76	176.87	13.33	2690.06	4583.85	0.00	61.14	24.12	0.00	8640.00	1047.91	176.87	23.48
11	0.24	0.00	73.00	0.00	973.34	16.75	6.41	2598.56	4907.14	1.98	15.80	46.76	0.00	8640.00	981.01	19.30	11.53
12	0.00	0.00	31.69	0.00	993.91	65.61	7.77	2442.85	5044.19	2.69	9.23	42.06	0.00	8640.00	1001.13	66.25	14.34
13	3.91	0.00	66.81	0.00	890.15	130.23	11.39	2087.36	5432.71	3.10	14.32	0.00	0.00	8640.00	899.38	134.15	16.71
14	0.00	0.00	42.99	1.75	982.95	95.93	14.42	2679.33	4789.45	0.00	33.17	0.00	0.00	8640.00	1009.81	111.69	25.53
15	0.00	0.00	65.10	0.00	947.83	154.75	14.65	2179.46	5216.64	0.00	0.00	61.57	0.00	8640.00	962.22	158.55	25.23
16	0.00	0.00	89.19	0.00	991.31	75.92	19.50	2505.95	4876.64	7.49	30.65	43.34	0.00	8640.00	995.39	75.92	23.59
17	19.13	0.00	21.33	1.82	910.98	119.22	20.28	2530.70	4961.66	0.00	17.35	37.51	0.00	8640.00	934.92	123.52	39.92
18	0.00	0.00	212.58	0.00	685.48	23.69	16.03	2480.42	5077.44	3.88	24.60	115.88	0.00	8640.00	693.92	23.69	24.47
19	0.00	0.00	209.64	0.00	918.08	14.00	13.09	2426.02	5003.18	6.57	20.47	28.96	0.00	8640.00	943.66	28.53	25.19
20	0.00	0.00	110.13	0.00	974.43	69.01	15.65	2410.76	4996.28	3.95	27.34	32.44	0.00	8640.00	986.26	71.16	25.32
Mean	1.54	0.00	66.21	0.18	946.76	98.21	15.93	2473.87	4970.97	2.65	21.76	41.91	0.00	8640.00	963.71	105.73	25.56
Time %	0.02	0.00	0.77	0.00	10.96	1.14	0.18	28.63	57.53	0.03	0.25	0.49	0.00	100.00	11.15	1.22	0.30

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Production Lost "Bottleneck" (%) (priori.wks)

N	Coalp	Steam	Gaspr	Tempr	OxygA	OxygB	OxygC	Plan1	Pla2A	Pla2B	Plan3	Divip	Recyc	
1	0.0000	0.0000	0.0057	0.0000	1.4988	0.2012	0.0353	2.3673	4.4368	0.0000	0.0641	0.2441	0.0000	
2	0.0000	0.0000	0.0117	0.0000	1.6316	0.2476	0.0222	2.4420	4.9335	0.0231	0.0446	0.2789	0.0000	
3	0.0027	0.0000	0.0123	0.0000	1.7049	0.2033	0.0146	2.4551	4.1472	0.0000	0.0508	0.3429	0.0000	
4	0.0000	0.0000	0.0114	0.0000	1.6575	0.2658	0.0210	2.4181	3.9582	0.0121	0.0926	0.2429	0.0000	
5	0.0000	0.0000	0.0347	0.0000	1.3810	0.0618	0.0214	2.4461	4.4634	0.0000	0.1160	0.2822	0.0000	
6	0.0000	0.0000	0.0025	0.0000	1.5885	0.1235	0.0488	2.4637	4.0856	0.0028	0.3462	0.0683	0.0000	
7	0.0000	0.0000	0.0009	0.0000	1.5840	0.0619	0.0480	2.5793	4.1533	0.0000	0.1273	0.1565	0.0000	
8	0.0000	0.0000	0.0069	0.0000	1.7847	0.3177	0.0282	2.5152	3.5472	0.0163	0.1166	0.3612	0.0000	
9	0.0049	0.0000	0.0489	0.0000	1.5850	0.2249	0.0383	2.5026	3.4240	0.0041	0.0000	0.1679	0.0000	
10	0.0000	0.0000	0.0107	0.0000	1.7407	0.2891	0.0218	2.4888	3.9683	0.0000	0.3234	0.1276	0.0000	
11	0.0002	0.0000	0.0282	0.0000	1.6240	0.0274	0.0105	2.4216	4.2041	0.0050	0.0836	0.2473	0.0000	
12	0.0000	0.0000	0.0143	0.0000	1.6650	0.1072	0.0127	2.6318	3.6817	0.0067	0.0488	0.2225	0.0000	
13	0.0039	0.0000	0.0162	0.0000	1.5076	0.2129	0.0186	2.3947	4.5504	0.0078	0.0757	0.0000	0.0000	
14	0.0000	0.0000	0.0080	0.0028	1.6296	0.1568	0.0236	2.4149	3.6605	0.0000	0.1754	0.0000	0.0000	
15	0.0000	0.0000	0.0143	0.0000	1.5909	0.2529	0.0257	2.5453	4.0843	0.0000	0.0000	0.3256	0.0000	
16	0.0000	0.0000	0.0292	0.0000	1.6655	0.1241	0.0319	2.4646	3.8305	0.0187	0.1621	0.2292	0.0000	
17	0.0262	0.0000	0.0040	0.0029	1.5074	0.1949	0.0331	2.4345	4.2699	0.0000	0.0918	0.1984	0.0000	
18	0.0000	0.0000	0.0609	0.0000	1.1537	0.0387	0.0262	2.5497	5.3550	0.0097	0.1301	0.6128	0.0000	
19	0.0000	0.0000	0.1772	0.0000	1.5164	0.0229	0.0214	2.4614	3.6749	0.0164	0.1083	0.1531	0.0000	
20	0.0000	0.0000	0.0498	0.0000	1.6148	0.1128	0.0256	2.4479	3.9554	0.0099	0.1446	0.1716	0.0000	
Mean	**0.0019**	**0.0000**	**0.0274**	**0.0003**	**1.5816**	**0.1624**	**0.0264**	**2.4722**	**4.1192**	**0.0066**	**0.1151**	**0.2217**	**0.0000**	**8.7348**
Lost %	**0.0217**	**0.0000**	**0.3136**	**0.0032**	**18.1067**	**1.8589**	**0.3027**	**28.3032**	**47.1585**	**0.0759**	**1.3177**	**2.5376**	**0.0000**	**100.0000**

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Tank and Flares (m³, nm³, m³/h, nm³/h) (flares.wks)

N	Tank	FlareA		FlareB		FlareC1		FlareC2		FlareC3		FlareC4		FlareC5		FlareC6	
1	1004.0	20684.9	2.394	35871.2	4.152	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
2	1000.2	0.0	0.000	12707.4	1.471	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
3	1000.1	0.0	0.000	14306.4	1.656	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
4	1001.9	186.8	0.022	24992.1	2.893	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
5	1003.5	18716.1	2.166	10781.3	1.248	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
6	1001.5	923.6	0.107	23335.8	2.701	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
7	1005.3	18902.0	2.188	5211.8	0.603	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
8	1000.2	0.0	0.000	9592.6	1.110	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
9	1001.1	830.3	0.096	42020.2	4.863	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
10	1002.1	1583.5	0.183	639.3	0.074	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
11	1000.1	0.0	0.000	2698.2	0.312	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
12	1002.2	907.5	0.105	12367.0	1.431	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
13	1000.2	0.0	0.000	7065.0	0.818	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
14	1000.2	0.0	0.000	7183.9	0.831	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
15	1001.3	1876.2	0.217	16747.2	1.938	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
16	1001.2	530.0	0.061	64476.7	7.463	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
17	1000.2	0.0	0.000	5449.6	0.631	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
18	1000.5	0.0	0.000	15541.7	1.799	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
19	1001.3	1326.0	0.153	16738.7	1.937	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
20	1001.0	775.4	0.090	13008.5	1.506	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000
Mean	1001.4	3362.1	0.389	17036.7	1.972	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0	0.000

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Number Modules Available, Switched On/Off (number) (sonoff.wks)

N	Coalp			Steam			Gaspr			Tempr			OxygA			OxygB			OxygC		
1	13.133	9.444	3.689	8.397	6.684	1.713	39.030	33.841	5.188	7.896	6.633	1.264	5.878	5.652	0.226	5.979	5.639	0.340	6.851	5.639	1.212
2	13.133	9.375	3.758	8.401	6.619	1.782	39.173	33.556	5.617	7.898	6.584	1.314	5.875	5.606	0.269	5.976	5.591	0.384	6.858	5.591	1.267
3	13.104	9.466	3.638	8.394	6.668	1.726	39.157	33.815	5.343	7.901	6.633	1.267	5.871	5.655	0.216	5.981	5.642	0.339	6.856	5.642	1.214
4	13.110	9.464	3.646	8.357	6.664	1.693	38.942	33.904	5.038	7.899	6.633	1.266	5.874	5.659	0.215	5.980	5.641	0.340	6.856	5.641	1.215
5	13.113	9.467	3.646	8.421	6.687	1.734	38.874	33.857	5.017	7.902	6.650	1.251	5.879	5.664	0.215	5.993	5.659	0.334	6.857	5.659	1.198
6	13.152	9.489	3.663	8.601	6.705	1.896	39.158	33.891	5.268	7.897	6.650	1.248	5.878	5.666	0.212	5.985	5.660	0.325	6.857	5.660	1.197
7	13.044	9.464	3.580	8.425	6.695	1.730	39.061	33.895	5.166	7.897	6.643	1.254	5.881	5.654	0.226	5.994	5.649	0.345	6.853	5.649	1.204
8	13.140	9.492	3.648	8.458	6.681	1.778	39.054	33.904	5.150	7.899	6.638	1.261	5.868	5.670	0.198	5.973	5.648	0.325	6.857	5.648	1.209
9	13.109	9.564	3.545	8.452	6.740	1.712	38.984	34.156	4.827	7.896	6.692	1.204	5.880	5.713	0.166	5.983	5.696	0.288	6.845	5.696	1.149
10	13.111	9.429	3.682	8.429	6.658	1.771	38.978	33.797	5.181	7.901	6.610	1.291	5.874	5.641	0.233	5.977	5.620	0.357	6.855	5.620	1.235
11	13.153	9.470	3.683	8.392	6.701	1.691	39.017	33.912	5.105	7.899	6.645	1.253	5.879	5.655	0.224	5.996	5.653	0.342	6.856	5.653	1.203
12	13.132	9.539	3.593	8.431	6.723	1.708	39.033	34.017	5.015	7.899	6.678	1.221	5.876	5.692	0.184	5.992	5.684	0.308	6.860	5.684	1.175
13	13.113	9.487	3.626	8.344	6.706	1.638	38.907	33.871	5.036	7.898	6.659	1.239	5.880	5.676	0.204	5.984	5.660	0.324	6.855	5.660	1.194
14	13.116	9.543	3.574	8.435	6.731	1.704	39.030	34.129	4.901	7.901	6.680	1.221	5.879	5.694	0.185	5.987	5.685	0.302	6.858	5.685	1.173
15	13.096	9.495	3.601	8.436	6.706	1.730	39.103	33.852	5.251	7.893	6.651	1.242	5.876	5.676	0.199	5.982	5.658	0.323	6.855	5.658	1.197
16	13.112	9.500	3.612	8.481	6.711	1.770	38.943	33.950	4.993	7.901	6.655	1.246	5.880	5.674	0.206	5.991	5.663	0.328	6.856	5.663	1.193
17	13.090	9.460	3.630	8.369	6.684	1.685	39.056	33.875	5.181	7.899	6.640	1.259	5.876	5.660	0.216	5.982	5.646	0.336	6.855	5.646	1.208
18	13.068	9.318	3.750	8.466	6.647	1.819	38.949	33.424	5.524	7.900	6.568	1.332	5.879	5.588	0.291	5.994	5.584	0.410	6.851	5.584	1.267
19	13.090	9.558	3.532	8.366	6.745	1.622	38.942	34.092	4.851	7.901	6.697	1.204	5.880	5.703	0.177	5.994	5.703	0.291	6.856	5.703	1.153
20	13.183	9.507	3.676	8.612	6.714	1.897	39.103	33.958	5.145	7.901	6.662	1.239	5.880	5.677	0.203	5.992	5.669	0.323	6.860	5.669	1.191
Mean	13.115	9.477	3.639	8.433	6.693	1.740	39.025	33.885	5.140	7.899	6.645	1.254	5.877	5.664	0.213	5.986	5.653	0.333	6.855	5.653	1.203

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Number Modules Available, Switched On/Off (number) (sonoff.wks - continue)

N	Plan1			Pla2A			Pla2B			Plan3			Divip			Recyc		
1	3.905	3.895	0.010	7.214	7.006	0.208	1.958	1.942	0.016	1.999	1.951	0.047	1.995	1.946	0.049	7.600	6.136	1.464
2	3.902	3.876	0.027	7.148	6.941	0.207	1.957	1.922	0.035	1.999	1.952	0.047	1.994	1.946	0.048	7.600	6.088	1.512
3	3.902	3.892	0.010	7.203	6.998	0.206	1.958	1.939	0.019	1.999	1.952	0.047	1.992	1.944	0.048	7.600	6.104	1.496
4	3.903	3.894	0.009	7.236	7.040	0.196	1.958	1.941	0.017	1.998	1.951	0.047	1.995	1.945	0.049	7.600	6.150	1.450
5	3.902	3.892	0.010	7.197	6.992	0.205	1.958	1.940	0.019	1.997	1.950	0.047	1.994	1.944	0.050	7.600	6.115	1.485
6	3.901	3.890	0.011	7.215	7.008	0.207	1.958	1.938	0.020	1.992	1.945	0.047	1.999	1.944	0.055	7.600	6.107	1.493
7	3.897	3.889	0.007	7.236	7.022	0.214	1.958	1.937	0.022	1.997	1.950	0.047	1.997	1.947	0.050	7.600	6.138	1.462
8	3.899	3.887	0.012	7.267	7.039	0.229	1.958	1.933	0.024	1.997	1.950	0.047	1.992	1.942	0.050	7.600	6.118	1.482
9	3.900	3.892	0.007	7.292	7.080	0.212	1.958	1.939	0.019	2.000	1.953	0.047	1.996	1.949	0.047	7.600	6.146	1.454
10	3.900	3.888	0.012	7.236	7.027	0.209	1.958	1.935	0.023	1.993	1.946	0.047	1.997	1.943	0.054	7.600	6.143	1.457
11	3.903	3.893	0.010	7.226	7.027	0.199	1.958	1.941	0.017	1.998	1.951	0.047	1.991	1.946	0.046	7.600	6.144	1.456
12	3.895	3.886	0.008	7.253	7.035	0.218	1.958	1.933	0.025	1.999	1.952	0.047	1.995	1.947	0.048	7.600	6.107	1.493
13	3.904	3.899	0.005	7.155	6.980	0.174	1.958	1.946	0.012	1.998	1.951	0.047	1.998	1.951	0.047	7.600	6.098	1.502
14	3.902	3.898	0.004	7.275	7.077	0.198	1.958	1.945	0.013	1.996	1.949	0.047	2.000	1.949	0.051	7.600	6.160	1.440
15	3.898	3.887	0.011	7.196	6.993	0.203	1.958	1.934	0.024	2.000	1.953	0.047	1.993	1.946	0.047	7.600	6.085	1.515
16	3.901	3.890	0.011	7.253	7.037	0.215	1.957	1.937	0.021	1.995	1.949	0.046	1.995	1.944	0.051	7.600	6.129	1.471
17	3.903	3.895	0.007	7.217	7.014	0.203	1.958	1.942	0.016	1.998	1.951	0.047	1.996	1.946	0.049	7.600	6.134	1.466
18	3.898	3.861	0.037	7.142	6.923	0.219	1.958	1.908	0.050	1.997	1.950	0.047	1.987	1.937	0.050	7.600	6.100	1.500
19	3.902	3.895	0.007	7.253	7.053	0.200	1.958	1.941	0.016	1.998	1.950	0.047	1.997	1.947	0.050	7.600	6.127	1.473
20	3.902	3.894	0.008	7.239	7.029	0.210	1.958	1.941	0.017	1.997	1.950	0.047	1.993	1.946	0.047	7.600	6.124	1.476
Mean	**3.901**	**3.890**	**0.011**	**7.223**	**7.016**	**0.207**	**1.958**	**1.937**	**0.021**	**1.997**	**1.950**	**0.047**	**1.995**	**1.945**	**0.049**	**7.600**	**6.123**	**1.477**

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Number Modules Available, Switched On/Off (number) (sonoff2.wks)

N	Elecg			Pla4A			Pla4B			Pla4C			Plan5			OxyeA			OxyeB			OxyeC		
1	3.996	3.996	0.000	4.000	3.883	0.117	2.000	1.947	0.053	0.997	0.997	0.000	7.088	6.590	0.497	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2	3.996	3.974	0.022	4.000	3.875	0.125	2.000	1.953	0.047	1.000	1.000	0.000	7.390	6.736	0.654	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3	3.996	3.992	0.004	4.000	3.892	0.108	2.000	1.953	0.047	1.000	1.000	0.000	7.389	6.815	0.574	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	3.997	3.985	0.012	4.000	3.892	0.107	1.999	1.952	0.047	1.000	1.000	0.000	7.313	6.709	0.604	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	3.998	3.988	0.010	4.000	3.880	0.120	1.999	1.946	0.053	0.997	0.997	0.000	7.459	6.832	0.627	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	3.996	3.994	0.001	4.000	3.888	0.112	1.999	1.952	0.047	1.000	1.000	0.000	7.469	6.731	0.739	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	3.995	3.995	0.000	4.000	3.878	0.122	1.999	1.947	0.052	0.998	0.998	0.000	7.560	6.860	0.700	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	3.997	3.989	0.008	4.000	3.886	0.114	2.000	1.953	0.047	1.000	1.000	0.000	7.408	6.840	0.568	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	3.995	3.995	0.000	4.000	3.891	0.109	1.999	1.952	0.047	1.000	1.000	0.000	7.150	6.595	0.555	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	3.995	3.995	0.000	4.000	3.886	0.114	1.999	1.952	0.047	1.000	1.000	0.000	7.750	6.967	0.783	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
11	3.996	3.996	0.000	4.000	3.893	0.107	2.000	1.953	0.047	1.000	1.000	0.000	7.609	6.971	0.638	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
12	3.997	3.997	0.000	4.000	3.885	0.115	1.999	1.952	0.047	1.000	1.000	0.000	7.323	6.819	0.503	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
13	3.995	3.995	0.000	4.000	3.899	0.101	2.000	1.953	0.047	1.000	1.000	0.000	7.447	6.856	0.591	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
14	3.996	3.996	0.000	4.000	3.898	0.102	2.000	1.953	0.047	1.000	1.000	0.000	7.631	6.921	0.709	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
15	3.997	3.997	0.000	4.000	3.885	0.115	1.999	1.952	0.047	1.000	1.000	0.000	7.348	6.743	0.605	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
16	3.996	3.996	0.000	4.000	3.889	0.111	2.000	1.952	0.047	1.000	1.000	0.000	6.684	6.338	0.346	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
17	3.994	3.994	0.000	4.000	3.895	0.105	2.000	1.953	0.047	1.000	1.000	0.000	7.526	6.867	0.659	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
18	3.995	3.995	0.000	4.000	3.860	0.140	2.000	1.952	0.047	1.000	1.000	0.000	7.396	6.656	0.740	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
19	3.997	3.997	0.000	3.999	3.893	0.107	1.999	1.952	0.047	1.000	1.000	0.000	7.570	6.888	0.682	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	3.995	3.995	0.000	4.000	3.892	0.107	1.999	1.952	0.047	1.000	1.000	0.000	7.461	6.840	0.621	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mean	**3.996**	**3.993**	**0.003**	**4.000**	**3.887**	**0.113**	**2.000**	**1.952**	**0.048**	**1.000**	**1.000**	**0.000**	**7.399**	**6.779**	**0.620**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**

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Number Evaluations, Services Completed/Missed, Failures Repaired (number) (verify.wks)

N	Eval	CoalS1		CoalS2		CoalS3		CoalF	SteamS		SteamF	GasprF	TemprS		TempF	OxyAS		OxyAF	OxyBS		OxyBF	OxyCS		OxyCF	ElecgS	
1	0	356	342	56	42	10	0	333	51	3	28	353	2	0	19	36	0	44	0	0	7	42	0	82	0	0
2	0	355	343	55	43	10	0	328	54	0	24	335	2	0	16	36	0	52	0	0	9	42	0	70	0	0
3	0	359	341	53	45	10	0	336	49	5	28	324	2	0	11	36	0	56	0	0	7	42	0	66	0	0
4	0	358	340	53	45	10	0	336	50	4	29	361	2	0	12	36	0	51	0	0	7	42	0	66	0	0
5	0	352	348	54	44	10	0	352	53	1	26	369	2	0	8	36	0	45	0	0	3	42	0	70	0	0
6	0	352	346	55	43	10	0	321	54	0	14	329	2	0	14	36	0	41	0	0	6	42	0	65	0	0
7	0	351	347	56	42	10	0	356	54	0	25	332	2	0	15	36	0	39	0	0	2	42	0	71	0	0
8	0	357	343	53	45	10	0	325	51	3	22	338	2	0	13	36	0	57	0	0	10	42	0	66	0	0
9	0	353	345	54	44	10	0	337	53	1	25	358	2	0	18	36	0	39	0	0	6	42	0	97	0	0
10	0	353	347	56	42	10	0	333	53	1	27	350	2	0	8	36	0	49	0	0	9	42	0	71	0	0
11	0	356	344	51	47	10	0	313	53	1	30	338	2	0	14	36	0	43	0	0	2	42	0	73	0	0
12	0	353	347	56	42	10	0	328	51	3	24	334	2	0	12	36	0	54	0	0	3	42	0	64	0	0
13	0	357	343	55	43	10	0	334	53	1	30	383	2	0	16	36	0	38	0	0	6	42	0	75	0	0
14	0	353	347	54	44	10	0	337	52	2	25	345	2	0	10	36	0	42	0	0	5	42	0	60	0	0
15	0	351	347	54	44	10	0	358	54	0	24	319	2	0	25	36	0	49	0	0	7	42	0	77	0	0
16	0	346	354	52	46	10	0	342	54	0	23	366	2	0	11	36	0	47	0	0	3	42	0	71	0	0
17	0	350	350	56	42	10	0	343	52	2	27	337	2	0	14	36	0	46	0	0	7	42	0	77	0	0
18	0	356	344	54	44	10	0	362	53	1	24	357	2	0	11	36	0	47	0	0	2	42	0	77	0	0
19	0	353	347	54	44	10	0	363	51	3	30	332	2	0	9	36	0	45	0	0	2	42	0	68	0	0
20	0	360	340	53	45	10	0	301	54	0	16	331	2	0	9	36	0	43	0	0	3	42	0	66	0	0
Mean	0.0	354.1	345.3	54.2	43.8	10.0	0.0	336.9	52.5	1.6	25.1	344.6	2.0	0.0	13.3	36.0	0.0	46.4	0.0	0.0	5.3	42.0	0.0	71.6	0.0	0.0

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Number Evaluations, Services Completed/Missed, Failures Repaired (number) (verify.wks - continue)

N	ElecgF	Plan1S		Plan1F	Pl2AS1		Pl2AS2		Pl2AS3		Pla2AF	Pla2BS		Pla2BF	Plan3F	DivipF	RecycS		Pla4AF	Pla4BF	Pla4CF	Plan5F	OxyeAS		OxyeBS	
1	28	2	0	1	48	48	16	8	8	0	5	1	0	0	1	2	16	0	1	1	1	15	1	0	1	0
2	19	2	0	2	46	50	16	8	8	0	7	1	0	5	1	3	16	0	1	0	0	12	1	0	1	0
3	24	2	0	4	48	48	16	8	8	0	6	1	0	0	1	2	16	0	1	0	0	12	1	0	1	0
4	20	2	0	2	47	49	16	8	8	0	4	1	0	2	1	2	16	0	1	2	0	12	1	0	1	0
5	11	2	0	3	47	49	16	8	8	0	6	1	0	0	2	2	16	0	1	1	1	11	1	0	1	0
6	24	2	0	3	48	48	16	8	8	0	5	1	0	1	5	1	16	0	0	2	0	9	1	0	1	0
7	28	2	0	6	47	49	16	8	8	0	4	1	0	0	2	1	16	0	0	2	1	10	1	0	1	0
8	21	2	0	5	51	45	16	8	8	0	2	1	0	2	1	3	16	0	0	0	0	12	1	0	1	0
9	35	2	0	4	48	48	16	8	8	0	1	1	0	1	0	2	16	0	2	1	0	12	1	0	1	0
10	31	2	0	4	47	49	16	8	8	0	4	1	0	0	5	1	16	0	1	2	0	6	1	0	1	0
11	25	2	0	2	48	48	16	8	8	0	4	1	0	1	1	3	16	0	1	0	0	9	1	0	1	0
12	20	2	0	8	48	48	16	8	8	0	3	1	0	1	1	2	16	0	2	2	0	14	1	0	1	0
13	32	2	0	1	48	48	16	8	8	0	8	1	0	2	1	1	16	0	2	0	0	12	1	0	1	0
14	21	2	0	3	47	49	16	8	8	0	2	1	0	0	3	0	16	0	1	0	0	8	1	0	1	0
15	16	2	0	8	47	49	16	8	8	0	6	1	0	0	0	2	16	0	1	1	0	12	1	0	1	0
16	24	2	0	4	48	48	16	8	8	0	3	1	0	3	4	2	16	0	1	1	0	18	1	0	1	0
17	28	2	0	4	47	49	16	8	8	0	5	1	0	0	2	1	16	0	0	0	0	10	1	0	1	0
18	29	2	0	6	51	45	15	9	8	0	8	1	0	1	2	5	16	0	0	1	0	12	1	0	1	0
19	21	2	0	3	48	48	16	8	8	0	3	1	0	3	2	1	16	0	3	1	0	7	1	0	1	0
20	26	2	0	3	46	50	16	8	8	0	4	1	0	3	2	2	16	0	2	1	0	11	1	0	1	0
Mean	24.2	2.0	0.0	3.8	47.8	48.3	16.0	8.1	8.0	0.0	4.5	1.0	0.0	1.3	1.9	1.9	16.0	0.0	1.1	0.9	0.2	11.2	1.0	0.0	1.0	0.0

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Number Evaluations, Services Completed/Missed, Failures Repaired (number) (verify.wks - continue, verify2.wks)

N	OxyeCS		OxeCF	Cmpltd	Md Ex	Md Rm	Ev Ex	Ev Rm	Rmvd	Rtrnd	Multpl	Dstryd	1	2	3	4	5	6	7	8	9	10	10+	Crr A6	Crr A7	Crr A8
1	1	0	9	3310	1575	2	224	1509	1584	1577	50	1577	1460	40	6	4	0	0	0	0	0	1	0	126	38	0
2	1	0	8	3234	1536	2	230	1466	1543	1538	50	1538	1415	42	6	4	0	0	0	0	0	1	0	123	38	0
3	1	0	4	3207	1525	2	225	1455	1530	1527	50	1526	1405	41	7	3	0	0	0	0	0	1	0	122	36	0
4	1	0	6	3266	1554	4	223	1485	1564	1558	50	1557	1436	42	6	4	0	0	0	0	0	1	0	125	36	0
5	1	0	5	3269	1553	5	229	1482	1562	1558	50	1558	1434	42	6	4	0	0	0	0	0	1	0	123	36	0
6	1	0	7	3139	1488	4	229	1418	1495	1492	50	1491	1370	42	5	4	0	0	0	0	0	1	0	122	38	0
7	1	0	5	3239	1540	3	225	1471	1548	1543	50	1543	1421	43	5	4	0	0	0	0	0	1	0	119	38	0
8	1	0	8	3212	1527	6	222	1457	1537	1533	50	1532	1411	41	6	4	0	0	0	0	0	1	0	128	35	0
9	1	0	9	3340	1590	1	228	1521	1597	1591	50	1591	1469	42	6	4	0	0	0	0	0	1	0	121	37	0
10	1	0	7	3263	1551	2	229	1481	1557	1553	50	1553	1431	41	6	4	0	0	0	0	0	1	0	124	38	0
11	1	0	6	3173	1508	1	225	1439	1515	1509	50	1509	1387	42	6	4	0	0	0	0	0	1	0	126	34	0
12	1	0	4	3196	1516	4	229	1447	1525	1520	50	1520	1399	41	6	4	0	0	0	0	0	1	0	125	38	0
13	1	0	5	3338	1593	2	222	1521	1598	1595	50	1594	1470	42	6	4	0	0	0	0	0	1	0	125	37	0
14	1	0	9	3171	1509	4	218	1440	1518	1513	50	1513	1392	41	6	4	0	0	0	0	0	1	0	124	36	0
15	1	0	9	3262	1553	3	223	1483	1560	1556	50	1556	1434	41	6	4	0	0	0	0	0	1	0	123	37	0
16	1	0	7	3291	1563	3	229	1496	1573	1566	49	1566	1447	41	6	4	0	0	0	0	0	1	0	123	35	0
17	1	0	4	3240	1544	2	220	1474	1550	1546	49	1546	1424	41	6	4	0	0	0	0	0	1	0	126	38	0
18	1	0	9	3362	1601	1	226	1534	1611	1602	51	1602	1481	43	6	4	0	0	0	0	0	1	0	125	35	0
19	1	0	3	3226	1533	5	226	1462	1541	1538	50	1538	1415	41	6	4	0	0	0	0	0	1	0	123	37	0
20	1	0	6	3107	1477	1	223	1406	1482	1478	50	1478	1354	42	6	4	0	0	0	0	0	1	0	124	35	0
Mean	1.0	0.0	6.5	3242.3	1541.8	2.9	225.3	1472.4	1549.5	1544.7	50.0	1544.4	1422.8	41.6	6.0	4.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	123.9	36.6	0.0

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Number Times "Bottleneck" (number) (verify2.wks - continue)

N	Coalp	Steam	Gaspr	Tempr	OxygA	OxygB	OxygC	Plan1	Pla2A	Pla2B	Plan3	Divip	Recyc	Total
1	0.0	0.0	7.0	1.0	387.5	83.5	16.0	991.0	1773.0	0.0	6.0	44.0	0.0	3309
2	0.0	0.0	12.0	1.0	456.5	51.0	6.5	950.0	1729.0	12.0	2.0	13.0	0.0	3233
3	2.0	0.0	45.0	1.0	451.5	47.5	4.0	949.0	1652.0	0.0	22.0	32.0	0.0	3206
4	0.0	0.0	22.0	0.0	463.5	50.5	5.0	1125.0	1572.0	5.0	9.0	13.0	0.0	3265
5	0.0	0.0	29.0	1.0	359.5	13.0	13.5	967.0	1837.0	0.0	29.0	19.0	0.0	3268
6	0.0	0.0	6.0	1.0	412.8	30.8	12.3	979.0	1663.0	1.0	25.0	7.0	0.0	3138
7	0.0	0.0	4.0	1.0	418.5	10.0	16.5	1096.0	1676.0	0.0	10.0	6.0	0.0	3238
8	0.0	0.0	10.0	0.0	482.5	101.5	8.0	1003.0	1549.0	6.0	6.0	45.0	0.0	3211
9	1.0	0.0	23.0	1.0	397.0	58.0	24.0	1105.0	1718.0	1.0	0.0	11.0	0.0	3339
10	0.0	0.0	36.0	1.0	469.5	58.0	13.5	1092.0	1562.0	0.0	21.0	9.0	0.0	3262
11	1.0	0.0	35.0	1.0	423.0	12.5	3.5	1035.0	1640.0	3.0	5.0	13.0	0.0	3172
12	0.0	0.0	32.0	1.0	452.0	14.5	3.5	974.0	1688.0	1.0	11.0	18.0	0.0	3195
13	2.0	0.0	51.0	1.0	414.0	48.5	7.5	844.0	1963.0	3.0	3.0	0.0	0.0	3337
14	0.0	0.0	16.0	6.0	437.5	65.0	10.5	1056.0	1557.0	0.0	22.0	0.0	0.0	3170
15	0.0	0.0	18.0	1.0	438.0	58.5	8.5	912.0	1766.0	0.0	0.0	59.0	0.0	3261
16	0.0	0.0	32.0	1.0	460.5	17.0	8.5	1111.0	1625.0	4.0	13.0	18.0	0.0	3290
17	10.0	0.0	28.0	2.0	443.5	45.0	19.5	942.0	1723.0	0.0	5.0	21.0	0.0	3239
18	0.0	0.0	93.0	1.0	334.5	6.0	8.5	1042.0	1834.0	3.0	4.0	35.0	0.0	3361
19	0.0	0.0	103.0	1.0	449.2	4.7	9.2	990.0	1627.0	10.0	7.0	24.0	0.0	3225
20	0.0	0.0	24.0	1.0	428.0	22.5	14.5	936.0	1660.0	3.0	12.0	5.0	0.0	3106
Mean	**0.8**	**0.0**	**31.3**	**1.2**	**429.0**	**39.9**	**10.7**	**1005.0**	**1690.7**	**2.6**	**10.6**	**19.6**	**0.0**	**3241**

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"Throughput Vector" (ton/h, nm³/h, m³/h, MW/h) (tvector.wks)

Product	Coal	CoalCourse	CoalFine	CoalFine	Water	Water	Steam	Steam	Steam	Steam	Raw gas	Raw gas	Gas-water	Air	Oxygen
From	-	Coalp	Coalp	Coalp	-	Watet	Steam	Steam	Steam	Steam	Gaspr	Tempr	Tempr	OxygA	OsygB
To	Coalp	Gaspr	Steam	Slimesdam	Watet	Steam	Gaspr	OxygA	OxygB	Elecg	Tempr	Plan1	Pla4A	OsygB	OxygC
1	1257.491	848.806	373.724	34.961	1853.533	2448.533	863.815	557.210	185.737	712.902	1330741.6	1330741.6	851.675	1430172.5	248887.1
2	1246.702	841.524	370.443	34.735	1832.043	2427.043	856.404	552.429	184.143	706.328	1319324.5	1319324.5	844.368	1417902.3	246751.8
3	1256.379	848.056	373.134	35.189	1849.672	2444.672	863.051	556.717	185.572	710.664	1329565.3	1329565.3	850.922	1428908.4	248667.1
4	1259.886	850.423	373.594	35.869	1852.685	2447.685	865.460	558.271	186.090	709.038	1333276.2	1333276.2	853.297	1432896.5	249361.2
5	1258.135	849.241	373.491	35.403	1852.007	2447.007	864.257	557.495	185.832	710.633	1331423.6	1331423.6	852.111	1430905.5	249014.7
6	1259.192	849.954	374.087	35.150	1855.915	2450.915	864.983	557.963	185.988	712.985	1332541.5	1332541.5	852.827	1432106.9	249223.8
7	1259.449	850.128	374.154	35.167	1856.354	2451.354	865.160	558.078	186.026	713.072	1332813.9	1332813.9	853.001	1432399.7	249274.7
8	1259.688	850.290	373.867	35.532	1854.473	2449.473	865.324	558.184	186.061	710.984	1333067.1	1333067.1	853.163	1432671.8	249322.1
9	1269.258	856.749	376.125	36.384	1869.264	2464.264	871.898	562.424	187.475	712.769	1343194.4	1343194.4	859.644	1443555.7	251216.2
10	1255.876	847.716	373.263	34.896	1850.519	2445.519	862.706	556.494	185.498	712.109	1329033.1	1329033.1	850.581	1428336.4	248567.6
11	1260.271	850.683	374.352	35.236	1857.654	2452.654	865.725	558.442	186.147	713.253	1333683.8	1333683.8	853.558	1433334.5	249437.4
12	1263.871	853.113	374.977	35.781	1861.745	2456.745	868.198	560.037	186.679	712.529	1337493.7	1337493.7	855.996	1437429.1	250150.0
13	1258.395	849.417	373.903	35.075	1854.712	2449.712	864.436	557.610	185.870	712.864	1331698.4	1331698.4	852.287	1431200.8	249066.1
14	1268.275	856.086	376.018	36.171	1868.568	2463.568	871.223	561.989	187.330	713.365	1342154.5	1342154.5	858.979	1442438.2	251021.7
15	1257.686	848.938	373.825	34.923	1854.200	2449.200	863.949	557.296	185.765	713.284	1330948.6	1330948.6	851.807	1430395.0	248925.9
16	1261.595	851.576	374.633	35.385	1859.495	2454.495	866.634	559.028	186.343	713.306	1335084.6	1335084.6	854.454	1434840.0	249699.4
17	1258.736	849.647	373.873	35.216	1854.513	2449.513	864.670	557.762	185.921	712.239	1332059.4	1332059.4	852.518	1431588.8	249133.6
18	1242.543	838.716	370.644	33.182	1833.360	2428.360	853.546	550.586	183.529	712.891	1314922.7	1314922.7	841.551	1413171.6	245928.5
19	1267.167	855.337	375.762	36.068	1866.886	2461.886	870.461	561.497	187.166	713.189	1340981.1	1340981.1	858.228	1441177.1	250802.2
20	1261.919	851.795	374.668	35.456	1859.723	2454.723	866.857	559.172	186.391	713.107	1335428.0	1335428.0	854.674	1435209.0	249763.6
Mean	1259.126	849.910	373.927	35.289	1854.866	2449.866	864.938	557.934	185.978	712.076	1332471.8	1332471.8	852.782	1432032.0	249210.7

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"Throughput Vector" (ton/h, nm³/h, m³/h, MW/h) (tvector.wks - continue)

Product	Oxygen	Oxygen	Electricity	Pure gas	Res gas	Chem Prod	Res gas	Down gas	H2	CH4	C2	C2	Condensate	Recyc gas	NH3
From	OxygC	OxygC	Elecg	Plan1	Pla2A	Pla2A	Pla2B	Plan3	Divip	Divip	Divip	Divip	Divip	Recyc	Pla4A
To	Gaspr	Recyc	-	Pla2A	Pla2B	Sub1	Plan3	Divip	Pla2A	Recyc	Sub5	Sub6	Plan5	Pla2A	Pla4B
1	184436.1	64451.1	167.742	931519.1	469955.6	473.746	469955.6	405336.7	164484.4	140986.6	12336.3	6461.9	129.238	372607.6	20.627
2	182853.7	63898.1	166.195	923527.1	465923.6	469.681	465923.6	401859.1	163073.2	139777.0	12230.5	6406.4	128.129	369410.9	20.507
3	184273.1	64394.1	167.215	930695.7	469540.2	473.327	469540.2	404978.4	164339.0	140862.0	12325.4	6456.2	129.124	372278.3	20.667
4	184787.4	64573.8	166.832	933293.4	470850.7	474.648	470850.7	406108.7	164797.7	141255.2	12359.8	6474.2	129.484	373317.3	20.724
5	184530.6	64484.1	167.208	931996.5	470196.4	473.988	470196.4	405544.4	164568.7	141058.9	12342.7	6465.2	129.304	372798.6	20.643
6	184685.6	64538.2	167.761	932779.1	470591.2	474.386	470591.2	405884.9	164706.9	141177.3	12353.0	6470.6	129.413	373111.6	20.710
7	184723.3	64551.4	167.782	932969.7	470687.4	474.483	470687.4	405967.9	164740.5	141206.2	12355.5	6471.9	129.439	373187.9	20.664
8	184758.4	64563.7	167.290	933147.0	470776.8	474.573	470776.8	406045.0	164771.8	141233.0	12357.9	6473.2	129.464	373258.8	20.721
9	186162.0	65054.2	167.710	940236.1	474353.3	478.179	474353.3	409129.7	166023.6	142305.9	12451.8	6522.4	130.447	376094.4	20.876
10	184199.3	64368.3	167.555	930323.2	469352.2	473.137	469352.2	404816.3	164273.2	140805.6	12320.5	6453.6	129.072	372129.3	20.654
11	184843.9	64593.6	167.824	933578.7	470994.6	474.793	470994.6	406232.9	164848.1	141298.3	12363.6	6476.2	129.523	373431.5	20.731
12	185371.9	64778.1	167.654	936245.6	472340.1	476.149	472340.1	407393.3	165319.0	141702.0	12398.9	6494.7	129.893	374498.2	20.787
13	184568.7	64497.4	167.733	932188.9	470293.5	474.086	470293.5	405628.1	164602.7	141088.0	12345.2	6466.5	129.331	372875.6	20.700
14	186017.9	65003.8	167.851	939508.2	473986.1	477.809	473986.1	408813.0	165895.1	142195.8	12442.1	6517.3	130.346	375803.3	20.862
15	184464.8	64461.1	167.832	931664.1	470028.7	473.819	470028.7	405399.8	164510.0	141008.6	12338.2	6462.9	129.258	372665.6	20.683
16	185038.0	64661.4	167.837	934559.2	471489.3	475.292	471489.3	406659.5	165021.2	141446.8	12376.6	6483.0	129.660	373823.7	20.751
17	184618.8	64514.9	167.586	932441.6	470421.0	474.215	470421.0	405738.1	164647.3	141126.3	12348.5	6468.3	129.366	372976.6	20.705
18	182243.7	63684.9	167.739	920445.9	464369.1	468.114	464369.1	400518.3	162529.1	139310.7	12189.7	6385.1	127.701	368178.3	20.439
19	185855.3	64947.0	167.809	938686.7	473571.7	477.391	473571.7	408455.6	165750.0	142071.5	12431.3	6511.6	130.232	375474.7	20.840
20	185085.6	64678.0	167.790	934799.6	471610.6	475.414	471610.6	406764.1	165063.7	141483.1	12379.8	6484.6	129.693	373919.8	20.756
Mean	184675.9	64534.9	167.547	932730.3	470566.6	474.362	470566.6	405863.7	164698.3	141169.9	12352.4	6470.3	129.406	373092.1	20.702

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"Throughput Vector" (ton/h, nm³/h, m³/h, MW/h) (tvector.wks - continue)

Product	Tar acid	NH3	NH3	Alcohol	Carbonyl	Ethanol	Propanol	Acetone	MEK	Aldehyde	Methanol	H Aldehyde	N–Butanol	Ethane	Ethylene
From	Pla4A	Pla4B	Pla4C	Sub1	Sub1	Sub2	Sub2	Sub3	Sub3	Sub3	Sub3	Sub4	Sub4	Sub5	Sub5
To	-	Pla4C	-	Sub2	Sub3	-	-	-	-	Sub4	-	-	-	-	-
1	3.640	20.627	20.627	17.765	11.844	12.436	5.330	5.640	3.384	2.256	0.551	1.128	0.835	4934.5	9.376
2	3.619	20.507	20.507	17.613	11.742	12.329	5.284	5.592	3.355	2.237	0.546	1.118	0.828	4892.2	9.295
3	3.647	20.667	20.667	17.750	11.833	12.425	5.325	5.635	3.381	2.254	0.550	1.127	0.834	4930.2	9.367
4	3.657	20.724	20.724	17.799	11.866	12.460	5.340	5.651	3.390	2.261	0.552	1.130	0.836	4943.9	9.393
5	3.643	20.643	20.643	17.775	11.850	12.442	5.332	5.643	3.385	2.257	0.551	1.129	0.835	4937.1	9.380
6	3.655	20.710	20.710	17.789	11.860	12.453	5.337	5.648	3.388	2.259	0.551	1.130	0.836	4941.2	9.388
7	3.647	20.664	20.664	17.793	11.862	12.455	5.338	5.649	3.389	2.260	0.552	1.130	0.836	4942.2	9.390
8	3.657	20.721	20.721	17.797	11.864	12.458	5.339	5.650	3.390	2.260	0.552	1.130	0.836	4943.2	9.392
9	3.684	20.876	20.876	17.932	11.954	12.552	5.380	5.693	3.415	2.277	0.556	1.139	0.843	4980.7	9.463
10	3.645	20.654	20.654	17.743	11.828	12.420	5.323	5.633	3.379	2.253	0.550	1.127	0.834	4928.2	9.364
11	3.658	20.731	20.731	17.805	11.870	12.463	5.341	5.652	3.391	2.261	0.552	1.131	0.837	4945.4	9.396
12	3.668	20.787	20.787	17.856	11.904	12.499	5.357	5.669	3.401	2.268	0.554	1.134	0.839	4959.6	9.423
13	3.653	20.700	20.700	17.778	11.852	12.445	5.333	5.644	3.386	2.258	0.551	1.129	0.835	4938.1	9.382
14	3.682	20.862	20.862	17.918	11.945	12.542	5.375	5.688	3.413	2.276	0.555	1.138	0.842	4976.9	9.456
15	3.650	20.683	20.683	17.768	11.845	12.438	5.330	5.641	3.384	2.257	0.551	1.128	0.835	4935.3	9.377
16	3.662	20.751	20.751	17.823	11.882	12.476	5.347	5.658	3.395	2.264	0.553	1.132	0.838	4950.6	9.406
17	3.654	20.705	20.705	17.783	11.855	12.448	5.335	5.646	3.387	2.258	0.551	1.129	0.836	4939.4	9.385
18	3.607	20.439	20.439	17.554	11.703	12.288	5.266	5.573	3.344	2.229	0.544	1.115	0.825	4875.9	9.264
19	3.678	20.840	20.840	17.902	11.935	12.532	5.371	5.683	3.410	2.274	0.555	1.137	0.841	4972.5	9.448
20	3.663	20.756	20.756	17.828	11.885	12.480	5.348	5.660	3.396	2.264	0.553	1.132	0.838	4951.9	9.409
Mean	3.653	20.702	20.702	17.789	11.859	12.452	5.337	5.647	3.388	2.259	0.551	1.130	0.836	4940.9	9.388

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Product	Ethane	Petrol	Butene	C5C6	Petrol	Diesel	C3	H Polymer	C4	Electricity	(Air)	(Oxygen)	(Oxygen)	Electricity	Steam (T)	Oxygen (T)
From	Sub6	Sub6	Sub6	Plan5	Plan5	Plan5	Plan5	Plan5	Plan5	-	OxyeA	OxyeB	OxyeC	-	Steam	OxygC
To	-	-	-	-	-	-	-	-	-	OxyeA	OxyeB	OxyeC	Gaspr/Recyc	OxyeC	GP/OA,C/EG	GP/R
1	2584.8	3.877	2.585	37.526	39.027	39.027	5.003	5.003	7.505	0.000	0.0	0.0	0.0	0.000	2319.663	248887.1
2	2562.6	3.844	2.563	37.997	39.517	39.517	5.066	5.066	7.599	0.000	0.0	0.0	0.0	0.000	2299.304	246751.8
3	2582.5	3.874	2.582	38.240	39.770	39.770	5.099	5.099	7.648	0.000	0.0	0.0	0.0	0.000	2316.005	248667.1
4	2589.7	3.885	2.590	37.977	39.496	39.496	5.064	5.064	7.595	0.000	0.0	0.0	0.0	0.000	2318.859	249361.2
5	2586.1	3.879	2.586	38.417	39.954	39.954	5.122	5.122	7.683	0.000	0.0	0.0	0.0	0.000	2318.217	249014.7
6	2588.3	3.882	2.588	38.013	39.534	39.534	5.068	5.068	7.603	0.000	0.0	0.0	0.0	0.000	2321.919	249223.8
7	2588.8	3.883	2.589	38.651	40.197	40.197	5.153	5.153	7.730	0.000	0.0	0.0	0.0	0.000	2322.335	249274.7
8	2589.3	3.884	2.589	38.506	40.046	40.046	5.134	5.134	7.701	0.000	0.0	0.0	0.0	0.000	2320.553	249322.1
9	2608.9	3.913	2.609	37.675	39.182	39.182	5.023	5.023	7.535	0.000	0.0	0.0	0.0	0.000	2334.566	251216.2
10	2581.4	3.872	2.581	38.699	40.247	40.247	5.160	5.160	7.740	0.000	0.0	0.0	0.0	0.000	2316.807	248567.6
11	2590.5	3.886	2.590	38.763	40.314	40.314	5.168	5.168	7.753	0.000	0.0	0.0	0.0	0.000	2323.567	249437.4
12	2597.9	3.897	2.598	38.539	40.080	40.080	5.138	5.138	7.708	0.000	0.0	0.0	0.0	0.000	2327.443	250150.0
13	2586.6	3.880	2.587	38.554	40.096	40.096	5.141	5.141	7.711	0.000	0.0	0.0	0.0	0.000	2320.780	249066.1
14	2606.9	3.910	2.607	38.854	40.409	40.409	5.181	5.181	7.771	0.000	0.0	0.0	0.0	0.000	2333.906	251021.7
15	2585.2	3.878	2.585	38.196	39.724	39.724	5.093	5.093	7.639	0.000	0.0	0.0	0.0	0.000	2320.295	248925.9
16	2593.2	3.890	2.593	36.659	38.125	38.125	4.888	4.888	7.332	0.000	0.0	0.0	0.0	0.000	2325.311	249699.4
17	2587.3	3.881	2.587	38.620	40.165	40.165	5.149	5.149	7.724	0.000	0.0	0.0	0.0	0.000	2320.591	249133.6
18	2554.0	3.831	2.554	37.771	39.282	39.282	5.036	5.036	7.554	0.000	0.0	0.0	0.0	0.000	2300.552	245928.5
19	2604.6	3.907	2.605	38.488	40.028	40.028	5.132	5.132	7.698	0.000	0.0	0.0	0.0	0.000	2332.313	250802.2
20	2593.9	3.891	2.594	38.456	39.994	39.994	5.127	5.127	7.691	0.000	0.0	0.0	0.0	0.000	2325.527	249763.6
Mean	2588.1	3.882	2.588	38.230	39.759	39.759	5.097	5.097	7.646	0.000	0.0	0.0	0.0	0.000	2320.926	249210.7

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Resource Utilisation (fraction) (utiliz.wks)

N	CoalpS	CoalpF	SteamS	SteamF	GasprF	TemprS	TemprF	OxygAS	OxygAF	OxygBS	OxygBF	OxygCS	OxygCF	ElecgS	ElecgF	Plan1S	Plan1F
1	0.4708	0.3332	0.2007	0.3196	0.6060	0.0944	0.0091	0.0999	0.0219	0.0000	0.0186	0.1167	0.0316	0.0000	0.0041	0.0944	0.0002
2	0.4703	0.3312	0.2125	0.2911	0.5512	0.0944	0.0078	0.1000	0.0242	0.0000	0.0245	0.1167	0.0251	0.0000	0.0035	0.0944	0.0032
3	0.4704	0.3377	0.1928	0.3440	0.5407	0.0944	0.0049	0.0996	0.0295	0.0000	0.0190	0.1167	0.0270	0.0000	0.0041	0.0944	0.0038
4	0.4699	0.3358	0.1968	0.3592	0.6133	0.0944	0.0063	0.1000	0.0254	0.0000	0.0197	0.1167	0.0266	0.0000	0.0033	0.0944	0.0023
5	0.4696	0.3502	0.2049	0.3068	0.6412	0.0944	0.0039	0.1000	0.0208	0.0000	0.0072	0.1167	0.0266	0.0000	0.0016	0.0944	0.0034
6	0.4678	0.3215	0.2125	0.1741	0.5454	0.0944	0.0081	0.1000	0.0216	0.0000	0.0152	0.1167	0.0256	0.0000	0.0044	0.0944	0.0041
7	0.4701	0.3602	0.2125	0.3100	0.5718	0.0944	0.0083	0.1000	0.0195	0.0000	0.0057	0.1167	0.0294	0.0000	0.0052	0.0944	0.0087
8	0.4700	0.3224	0.2006	0.2698	0.5738	0.0944	0.0070	0.0997	0.0317	0.0000	0.0267	0.1167	0.0257	0.0000	0.0033	0.0944	0.0062
9	0.4698	0.3396	0.2086	0.3199	0.5887	0.0944	0.0091	0.1000	0.0197	0.0000	0.0167	0.1167	0.0376	0.0000	0.0049	0.0944	0.0057
10	0.4704	0.3372	0.2037	0.3153	0.5884	0.0944	0.0043	0.1000	0.0259	0.0000	0.0231	0.1167	0.0287	0.0000	0.0054	0.0944	0.0051
11	0.4696	0.3165	0.2060	0.3685	0.5874	0.0944	0.0068	0.1000	0.0203	0.0000	0.0045	0.1167	0.0269	0.0000	0.0042	0.0944	0.0024
12	0.4702	0.3312	0.2007	0.3050	0.5810	0.0944	0.0064	0.1000	0.0238	0.0000	0.0077	0.1167	0.0236	0.0000	0.0032	0.0944	0.0108
13	0.4706	0.3380	0.2086	0.3599	0.6626	0.0944	0.0075	0.1000	0.0194	0.0000	0.0155	0.1167	0.0287	0.0000	0.0050	0.0944	0.0013
14	0.4698	0.3381	0.2014	0.3194	0.5934	0.0944	0.0044	0.1000	0.0209	0.0000	0.0132	0.1167	0.0249	0.0000	0.0036	0.0944	0.0038
15	0.4696	0.3575	0.2115	0.3025	0.5457	0.0944	0.0124	0.1000	0.0241	0.0000	0.0184	0.1167	0.0281	0.0000	0.0029	0.0944	0.0074
16	0.4685	0.3423	0.2116	0.2866	0.6145	0.0944	0.0048	0.1000	0.0197	0.0000	0.0088	0.1167	0.0270	0.0000	0.0039	0.0944	0.0041
17	0.4700	0.3429	0.2046	0.3411	0.5828	0.0944	0.0067	0.1000	0.0238	0.0000	0.0179	0.1167	0.0287	0.0000	0.0056	0.0944	0.0029
18	0.4702	0.3613	0.2086	0.2766	0.6017	0.0944	0.0058	0.1000	0.0213	0.0000	0.0058	0.1167	0.0316	0.0000	0.0047	0.0944	0.0075
19	0.4684	0.3644	0.2007	0.3568	0.5574	0.0944	0.0044	0.1000	0.0203	0.0000	0.0058	0.1167	0.0268	0.0000	0.0031	0.0944	0.0040
20	0.4698	0.3030	0.2125	0.1746	0.5704	0.0944	0.0048	0.1000	0.0195	0.0000	0.0082	0.1167	0.0236	0.0000	0.0050	0.0944	0.0035
Mean	0.4698	0.3382	0.2056	0.3050	0.5859	0.0944	0.0066	0.1000	0.0227	0.0000	0.0141	0.1167	0.0277	0.0000	0.0040	0.0944	0.0045

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Resource Utilisation (fraction) (utiliz.wks - continue)

N	Pla2AS	Pla2AF	Pla2BS	Pla2BF	Plan3F	DivipF	RecycS	Pla4AF	Pla4BF	Pla4CF	Plan5F	OxyeAS	OxyeBS	OxyeCS	OxyeCF
1	0.6889	0.0972	0.0417	0.0000	0.0014	0.0053	0.4000	0.0001	0.0005	0.0028	0.6220	0.0389	0.0389	0.0389	0.0117
2	0.6833	0.1524	0.0417	0.0011	0.0010	0.0061	0.4000	0.0002	0.0000	0.0000	0.4817	0.0389	0.0389	0.0389	0.0129
3	0.6801	0.1167	0.0417	0.0000	0.0011	0.0075	0.4000	0.0001	0.0000	0.0000	0.4945	0.0389	0.0389	0.0389	0.0061
4	0.6861	0.0778	0.0417	0.0006	0.0020	0.0053	0.4000	0.0003	0.0006	0.0000	0.5016	0.0389	0.0389	0.0389	0.0070
5	0.6861	0.1167	0.0417	0.0000	0.0030	0.0062	0.4000	0.0002	0.0007	0.0028	0.4369	0.0389	0.0389	0.0389	0.0055
6	0.6878	0.0972	0.0417	0.0001	0.0076	0.0015	0.4000	0.0000	0.0011	0.0000	0.3617	0.0389	0.0389	0.0389	0.0099
7	0.6861	0.0778	0.0417	0.0000	0.0028	0.0034	0.4000	0.0000	0.0013	0.0023	0.4015	0.0389	0.0389	0.0389	0.0065
8	0.6817	0.0509	0.0417	0.0008	0.0026	0.0079	0.4000	0.0000	0.0000	0.0000	0.5165	0.0389	0.0389	0.0389	0.0130
9	0.6889	0.0194	0.0417	0.0002	0.0000	0.0037	0.4000	0.0002	0.0005	0.0000	0.5196	0.0389	0.0389	0.0389	0.0120
10	0.6861	0.0778	0.0417	0.0000	0.0071	0.0028	0.4000	0.0001	0.0010	0.0000	0.2499	0.0389	0.0389	0.0389	0.0082
11	0.6889	0.0778	0.0417	0.0002	0.0018	0.0087	0.4000	0.0001	0.0000	0.0000	0.3636	0.0389	0.0389	0.0389	0.0079
12	0.6889	0.0583	0.0417	0.0003	0.0011	0.0049	0.4000	0.0004	0.0008	0.0000	0.5656	0.0389	0.0389	0.0389	0.0053
13	0.6889	0.1556	0.0417	0.0004	0.0017	0.0019	0.4000	0.0002	0.0000	0.0000	0.4772	0.0389	0.0389	0.0389	0.0091
14	0.6861	0.0389	0.0417	0.0000	0.0038	0.0000	0.4000	0.0001	0.0000	0.0000	0.3261	0.0389	0.0389	0.0389	0.0162
15	0.6857	0.1167	0.0417	0.0000	0.0000	0.0071	0.4000	0.0001	0.0009	0.0000	0.4982	0.0389	0.0389	0.0389	0.0102
16	0.6889	0.0583	0.0417	0.0009	0.0051	0.0050	0.4000	0.0001	0.0004	0.0000	0.7641	0.0389	0.0389	0.0389	0.0118
17	0.6861	0.0972	0.0417	0.0000	0.0020	0.0043	0.4000	0.0000	0.0000	0.0000	0.4203	0.0389	0.0389	0.0389	0.0061
18	0.6833	0.1556	0.0417	0.0004	0.0028	0.0134	0.4000	0.0000	0.0004	0.0000	0.4812	0.0389	0.0389	0.0389	0.0103
19	0.6889	0.0583	0.0417	0.0008	0.0024	0.0034	0.4000	0.0006	0.0006	0.0000	0.2914	0.0389	0.0389	0.0389	0.0042
20	0.6833	0.0778	0.0417	0.0005	0.0032	0.0071	0.4000	0.0002	0.0005	0.0000	0.4302	0.0389	0.0389	0.0389	0.0088
Mean	0.6862	0.0889	0.0417	0.0003	0.0026	0.0053	0.4000	0.0002	0.0005	0.0004	0.4602	0.0389	0.0389	0.0389	0.0091

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Comparison

8640 Simulation time

Service (Compare ((number of services completed*service time)/simulation time) with (resource utilisation))

Plant	Service	Service Time	Hours	H/Time	Util	% Delta
Coalp	354.05	1	354.05			
	54.20	2	108.4			
	10.00	336	3360			
		Total	3822.45	0.4424	0.4698	-2.7382
Steam	52.45	34	1783.3	0.2064	0.2056	0.0821
Tempr	2.00	408	816	0.0944	0.0944	0.0000
OxygA	36.00	24	864	0.1000	0.1000	0.0041
OxygB	0.00	336	0	0.0000	0.0000	0.0000
OxygC	42.00	24	1008	0.1167	0.1167	0.0005
Elecg	0.00	720	0	0.0000	0.0000	0.0000
Plan1	2.00	408	816	0.0944	0.0944	0.0000
Pla2A	47.75	24	1146			
	15.95	120	1914			
	8.00	360	2880			
		Total	5940	0.6875	0.6862	0.1296
Pla2B	1.00	360	360	0.0417	0.0417	0.0000
Recyc	16.00	216	216	0.4000	0.4000	0.0002
OxyeA	1.00	336	336	0.0389	0.0389	0.0000
OxyeB	1.00	336	336	0.0389	0.0389	0.0000
OxyeC	1.00	336	336	0.0389	0.0389	0.0000

Failure (Compare ((number of failures repaired*repair time)/simulation time) with (resource utilisation))

Plant	Failure	Repair Time	Hour	H/Time	Util	% Delta
Coalp	336.90	8	2695.2	0.3119	0.3382	-2.6264
Steam	25.05	120	3006	0.3479	0.3050	4.2874
Gaspr	344.55	16	5512.8	0.6381	0.5859	5.2186
Tempr	13.25	3	39.75	0.0046	0.0066	-0.2043
OxygA	46.35	2	92.7	0.0107	0.0227	-1.1940
OxygB	5.30	24	127.2	0.0147	0.0141	0.0616
OxygC	71.60	1	71.6	0.0083	0.0277	-1.9408
Elecg	24.15	1	24.15	0.0028	0.0040	-0.1252
Plan1	3.80	6	22.8	0.0026	0.0045	-0.1886
Pla2A	4.50	168	756	0.0875	0.0889	-0.1416
Pla2B	1.25	1	1.25	0.0001	0.0003	-0.0162
Plan3	1.85	8	14.8	0.0017	0.0026	-0.0908
Divip	1.90	18	34.2	0.0040	0.0053	-0.1319
Pla4A	1.05	0.5	0.525	0.0001	0.0002	-0.0090
Pla4B	0.90	3	2.7	0.0003	0.0005	-0.0151
Pla4C	0.15	24	3.6	0.0004	0.0004	0.0025
Plan5	11.20	336	3763.2	0.4356	0.4602	-2.4623
OxyeC	6.50	12	78	0.0090	0.0091	-0.0103

Evaluations

			Number	(Removed histogram)	
Completed	3242.25		1	1422.75	1422.75
			2	41.55	83.1
Mod Extra	1541.80	Modules returned that removed no modules	3	5.95	17.85
Mod Rem	2.85	Modules returned that removed modules	4	3.95	15.8
Eva Extra	225.25	Evaluators that removed no modules	5	0.00	0
Eva Rem	1472.35	Evaluators that removed modules	6	0.00	0
Total	3242.25		7	0.00	0
			8	0.00	0
Removed	1549.50		9	0.00	0
Returned	1544.65		10	1.00	10
Multiple	49.95		10+	0.00	
Destroyed	1544.40		Total	1549.5	

* * * * *

APPENDIX R

ED EVALUATION METHOD OPTION SIMUL8
SIMULATION MODEL RESULTS
(Scenario I)

(See next pages for landscape view)

* * * * *

Model S801, ED Method, 8640 Hours, Oxygen Extra Off, Runtime = 6,8 Minutes (20 replications)
Primary Plants: Throughput, Time and Production Lost "Bottleneck" (ton/h, nm^3/h, %)

Throughput	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean	Deviation
Coal Processing	852.210	847.721	850.665	845.807	838.928	855.199	851.532	849.268	848.049	857.526	849.630	848.190	846.430	855.957	854.517	848.456	854.538	852.511	840.941	847.335	**849.770**	
Steam	1613.204	1604.707	1610.280	1601.084	1588.062	1618.862	1611.920	1607.635	1605.328	1623.267	1608.321	1605.595	1602.262	1620.297	1617.571	1606.099	1617.612	1613.774	1591.872	1603.975	**1608.586**	
Gas Production	1336077.8	1329040.0	1333656.3	1326039.6	1315254.9	1340763.6	1335014.5	1331465.1	1329555.1	1344412.3	1332033.3	1329776.0	1327015.8	1341951.9	1339694.3	1330193.1	1339728.2	1336550.0	1318410.6	1328434.3	**1332253.3**	0.001
Temperature Regulation	1336077.8	1329040.0	1333656.3	1326039.6	1315254.9	1340763.6	1335014.5	1331465.1	1329555.1	1344412.3	1332033.3	1329776.0	1327015.8	1341951.9	1339694.3	1330193.1	1339728.2	1336550.0	1318410.6	1328434.3	**1332253.3**	7273.6
Oxygen A	1435907.4	1428343.8	1433305.0	1425119.2	1413528.7	1440943.4	1434764.6	1430950.1	1428897.4	1444864.6	1431560.7	1429134.7	1426168.3	1442220.4	1439794.1	1429583.1	1439830.6	1436414.9	1416920.2	1427692.8	**1431797.2**	7462.5
Oxygen B	249885.2	248568.9	249432.3	248007.7	245990.7	250761.5	249686.3	249022.5	248665.2	251444.0	249128.7	248706.5	248190.3	250983.8	250561.6	248784.6	250567.9	249973.5	246580.9	248455.6	**249169.9**	
Oxygen C	249885.2	248568.9	249432.3	248007.7	245990.7	250761.5	249686.3	249022.5	248665.2	251444.0	249128.7	248706.5	248190.3	250983.8	250561.6	248784.6	250567.9	249973.5	246580.9	248455.6	**249169.9**	
Plant(I)	935254.5	930328.0	933559.4	928227.7	920678.4	938534.5	934510.1	932025.6	930688.6	941088.6	932423.3	930843.2	928911.1	939366.3	937786.0	931135.2	937809.8	935585.0	922887.4	929904.0	**932577.3**	
Plant(II) A	471840.1	469354.7	470984.9	468295.1	464486.4	473494.9	471464.6	470211.1	469536.6	474783.4	470411.8	469614.6	468639.8	473914.5	473117.3	469761.9	473129.2	472006.8	465600.9	469140.8	**470489.5**	
Plant(II) B	471840.1	469354.7	470984.9	468295.1	464486.4	473494.9	471464.6	470211.1	469536.6	474783.4	470411.8	469614.6	468639.8	473914.5	473117.3	469761.9	473129.2	472006.8	465600.9	469140.8	**470489.5**	
Plant(III)	406962.1	404818.4	406224.5	403904.5	400619.5	408389.3	406638.2	405557.1	404975.3	409500.7	405730.1	405042.6	404201.8	408751.3	408063.6	405169.6	408074.0	407105.9	401580.7	404633.9	**405797.2**	
Division Process	165144.0	164274.1	164844.7	163903.2	162570.2	165723.2	165012.5	164573.8	164337.7	166174.1	164644.1	164365.0	164023.9	165870.0	165591.0	164416.6	165595.2	165203.2	162960.2	164199.2	**164671.3**	
Recycling	374101.8	372131.2	373423.8	371291.1	368271.4	375413.8	373804.1	372810.2	372275.4	376435.4	372969.3	372337.3	371564.4	375746.5	375114.4	372454.1	375123.9	374234.0	369155.0	371961.6	**373030.9**	
Bottleneck Time %																						
Coal Processing	0.00	0.01	0.00	0.55	0.25	0.00	0.13	0.00	0.00	0.00	0.11	0.00	0.16	0.28	0.08	0.03	0.01	0.00	0.01	0.00	**0.08**	
Steam	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	
Gas Production	0.73	0.51	1.37	0.76	1.53	0.59	2.40	1.27	2.24	0.73	0.59	0.78	1.08	0.79	0.88	0.45	1.24	0.74	1.21	1.85	**1.09**	
Temperature Regulation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	
Oxygen A	12.39	10.30	10.21	10.17	10.00	12.40	11.73	10.76	10.78	11.36	11.92	11.45	10.70	11.68	11.85	10.49	11.26	11.48	11.43	11.13	**11.17**	
Oxygen B	1.43	1.35	1.81	1.27	0.82	1.61	1.22	2.06	1.52	1.43	1.59	0.68	0.34	1.49	0.54	0.91	0.90	1.87	2.17	1.46	**1.32**	
Oxygen C	0.23	0.20	0.13	0.18	0.22	0.26	0.14	0.09	0.19	0.42	0.19	0.20	0.22	0.14	0.15	0.28	0.10	0.09	0.15	0.15	**0.19**	
Plant(I)	28.77	27.77	28.99	27.42	25.48	28.84	30.31	28.33	28.07	30.63	26.17	28.78	23.44	28.96	28.89	29.03	29.93	28.73	23.63	26.07	**27.91**	
Plant(II) A	56.10	57.96	56.54	59.20	61.24	55.60	53.41	56.46	56.39	55.04	58.62	57.82	63.34	56.51	57.38	58.66	55.69	55.80	60.38	58.41	**57.53**	
Plant(II) B	0.06	0.00	0.09	0.04	0.00	0.04	0.02	0.00	0.10	0.00	0.05	0.04	0.00	0.04	0.02	0.00	0.07	0.00	0.07	0.05	**0.04**	
Plant(III)	0.10	0.83	0.51	0.18	0.09	0.12	0.11	0.40	0.22	0.00	0.13	0.00	0.32	0.11	0.00	0.14	0.17	0.73	0.58	0.39	**0.26**	
Division Process	0.19	1.06	0.33	0.22	0.36	0.54	0.54	0.62	0.49	0.39	0.63	0.25	0.39	0.00	0.21	0.00	0.64	0.56	0.38	0.49	**0.41**	
Recycling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**	
																					100.00	
Bottleneck Production Lost %																						
Coal Processing	0.0000	0.0007	0.0003	0.0707	0.0219	0.0000	0.0119	0.0000	0.0000	0.0000	0.0098	0.0000	0.0135	0.0245	0.0068	0.0023	0.0008	0.0000	0.0007	0.0000	**0.0082**	0.0937
Steam	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**	0.0000
Gas Production	0.0264	0.0153	0.0307	0.0143	0.0876	0.0365	0.2254	0.0282	0.0724	0.0188	0.0138	0.0171	0.0677	0.0307	0.0293	0.0109	0.0252	0.0152	0.0377	0.0942	**0.0449**	0.5127
Temperature Regulation	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**	0.0000
Oxygen A	1.7680	1.4643	1.4493	1.4841	1.4667	1.7735	1.6896	1.5514	1.6030	1.6426	1.7534	1.6645	1.5710	1.6784	1.7196	1.4926	1.6236	1.6312	1.6717	1.5890	**1.6144**	18.4504
Oxygen B	0.2014	0.1912	0.2559	0.1790	0.1157	0.2274	0.1718	0.2905	0.2149	0.2021	0.2247	0.0963	0.0483	0.2102	0.0756	0.1291	0.1267	0.2640	0.3068	0.2056	**0.1869**	2.1356
Oxygen C	0.0326	0.0289	0.0189	0.0256	0.0313	0.0371	0.0193	0.0130	0.0264	0.0587	0.0274	0.0278	0.0314	0.0203	0.0219	0.0475	0.0144	0.0126	0.0211	0.0210	**0.0269**	0.3070
Plant(I)	2.4958	2.4931	2.4845	2.4722	2.4581	2.5626	2.4845	2.4977	2.4564	2.4042	2.4652	2.4767	2.3868	2.4035	2.3978	2.4242	2.4961	2.4107	2.6109	2.4629	**2.4672**	28.1974
Plant(II) A	3.8157	3.9111	4.0093	4.7371	5.5244	3.2213	3.6570	3.9557	4.2162	3.4136	3.9145	4.5161	4.6673	3.6585	3.8900	4.7189	3.5515	3.5320	4.5956	4.2256	**4.0866**	46.7048
Plant(II) B	0.0122	0.0000	0.0199	0.0123	0.0000	0.0084	0.0051	0.0000	0.0223	0.0000	0.0100	0.0088	0.0000	0.0049	0.0000	0.0000	0.0312	0.0000	0.0149	0.0115	**0.0085**	0.0969
Plant(III)	0.0474	0.3815	0.2326	0.0800	0.0427	0.0529	0.0487	0.1849	0.1009	0.0000	0.0589	0.0000	0.1454	0.0513	0.0000	0.0655	0.0762	0.3358	0.2643	0.1774	**0.1173**	1.3409
Division Process	0.0884	0.4838	0.1523	0.1001	0.1657	0.2472	0.2474	0.2822	0.2221	0.1769	0.2870	0.1122	0.1770	0.0000	0.0943	0.0000	0.2922	0.2539	0.1742	0.2241	**0.1890**	2.1606
Recycling	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	**0.0000**	0.0000
																					8.7498	100.00

* * *

Primary Plants: Number Available, Number Switched On/Off (number)

Number Available	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean
Coal Processing	13.107	13.134	13.088	13.099	13.087	13.144	13.076	13.172	13.086	13.114	13.111	13.164	13.071	13.061	13.076	13.154	13.140	13.123	13.107	13.093	**13.110**
Steam	8.524	8.393	8.435	8.421	8.436	8.367	8.425	8.509	8.459	8.513	8.361	8.484	8.496	8.411	8.373	8.411	8.458	8.513	8.391	8.562	**8.447**
Gas Production	38.870	39.019	39.069	39.186	38.804	38.971	38.886	39.058	38.982	38.988	38.889	39.042	38.822	38.788	39.002	39.129	39.115	39.057	39.124	38.884	**38.984**
Temperature Regulation	7.901	7.903	7.900	7.899	7.897	7.901	7.901	7.898	7.901	7.899	7.900	7.897	7.897	7.899	7.901	7.899	7.902	7.900	7.901	7.900	**7.900**
Oxygen A	5.871	5.875	5.877	5.872	5.877	5.866	5.878	5.880	5.884	5.878	5.869	5.878	5.873	5.880	5.873	5.877	5.878	5.876	5.877	5.881	**5.876**
Oxygen B	5.985	5.983	5.975	5.987	5.989	5.984	5.986	5.979	5.983	5.984	5.981	5.987	5.995	5.985	5.991	5.990	5.987	5.978	5.975	5.981	**5.984**
Oxygen C	6.850	6.849	6.861	6.858	6.858	6.856	6.852	6.857	6.855	6.851	6.857	6.850	6.859	6.857	6.862	6.851	6.860	6.860	6.850	6.855	**6.856**
Plant(I)	3.900	3.900	3.900	3.901	3.902	3.897	3.900	3.900	3.899	3.903	3.901	3.901	3.905	3.904	3.904	3.903	3.900	3.902	3.893	3.900	**3.901**
Plant(II) A	7.246	7.231	7.253	7.173	7.095	7.269	7.253	7.233	7.217	7.292	7.229	7.170	7.137	7.239	7.214	7.191	7.275	7.272	7.129	7.202	**7.216**
Plant(II) B	1.958	1.958	1.957	1.958	1.958	1.958	1.958	1.958	1.957	1.958	1.958	1.958	1.958	1.958	1.958	1.958	1.958	1.958	1.957	1.958	**1.958**
Plant(III)	1.999	1.992	1.995	1.998	1.997	1.999	1.997	1.996	1.998	2.000	1.999	2.000	1.997	1.999	2.000	1.999	1.998	1.993	1.994	1.996	**1.997**
Division Process	1.996	1.989	1.997	1.998	1.996	1.995	1.995	1.994	1.995	1.996	1.994	1.998	1.996	2.000	1.998	2.000	1.994	1.994	1.996	1.993	**1.996**
Recycling	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	7.600	**7.600**
Number Switched On																					
Coal Processing	9.508	9.475	9.481	9.408	9.339	9.569	9.486	9.472	9.445	9.570	9.495	9.444	9.454	9.553	9.531	9.452	9.538	9.523	9.391	9.469	**9.480**
Steam	6.706	6.703	6.703	6.672	6.652	6.737	6.693	6.685	6.685	6.742	6.706	6.689	6.698	6.733	6.728	6.700	6.731	6.717	6.652	6.699	**6.701**
Gas Production	33.979	33.797	33.910	33.723	33.447	34.100	33.941	33.857	33.805	34.187	33.880	33.817	33.750	34.127	34.068	33.827	34.065	33.988	33.535	33.780	**33.879**
Temperature Regulation	6.655	6.633	6.648	6.620	6.577	6.683	6.656	6.638	6.629	6.691	6.648	6.630	6.643	6.687	6.677	6.633	6.676	6.658	6.593	6.634	**6.645**
Oxygen A	5.674	5.666	5.674	5.637	5.591	5.707	5.675	5.668	5.652	5.710	5.669	5.640	5.652	5.703	5.685	5.645	5.692	5.689	5.624	5.656	**5.666**
Oxygen B	5.660	5.652	5.656	5.624	5.582	5.690	5.663	5.648	5.636	5.695	5.656	5.633	5.650	5.688	5.680	5.634	5.684	5.671	5.603	5.642	**5.652**
Oxygen C	5.660	5.652	5.656	5.624	5.582	5.690	5.663	5.648	5.636	5.695	5.656	5.633	5.650	5.688	5.680	5.634	5.684	5.671	5.603	5.642	**5.652**
Plant(I)	3.896	3.876	3.892	3.894	3.873	3.890	3.892	3.888	3.890	3.898	3.890	3.888	3.894	3.901	3.899	3.881	3.889	3.890	3.883	3.879	**3.889**
Plant(II) A	7.040	7.000	7.029	6.973	6.901	7.067	7.047	7.020	7.010	7.091	7.008	7.000	6.953	7.067	7.053	6.996	7.065	7.050	6.930	6.989	**7.014**
Plant(II) B	1.945	1.923	1.938	1.941	1.920	1.936	1.939	1.935	1.936	1.945	1.937	1.934	1.941	1.948	1.946	1.928	1.936	1.937	1.929	1.926	**1.936**
Plant(III)	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	1.953	**1.953**
Division Process	1.950	1.934	1.944	1.949	1.948	1.946	1.946	1.943	1.946	1.949	1.945	1.950	1.946	1.952	1.951	1.951	1.944	1.940	1.943	1.944	**1.946**
Recycling	6.132	6.086	6.134	6.120	6.077	6.117	6.138	6.121	6.131	6.157	6.097	6.129	6.077	6.146	6.145	6.124	6.139	6.123	6.062	6.089	**6.117**
Number Switched Off																					
Coal Processing	3.599	3.659	3.606	3.691	3.748	3.574	3.590	3.700	3.641	3.545	3.616	3.720	3.616	3.508	3.546	3.702	3.603	3.601	3.716	3.624	**3.630**
Steam	1.818	1.690	1.732	1.750	1.784	1.630	1.732	1.824	1.773	1.771	1.655	1.795	1.799	1.678	1.645	1.711	1.728	1.796	1.739	1.862	**1.746**
Gas Production	4.891	5.222	5.159	5.463	5.358	4.871	4.945	5.201	5.178	4.801	5.009	5.225	5.072	4.661	4.934	5.302	5.050	5.070	5.590	5.104	**5.105**
Temperature Regulation	1.246	1.270	1.252	1.278	1.320	1.217	1.245	1.260	1.272	1.208	1.252	1.267	1.254	1.212	1.224	1.267	1.226	1.242	1.308	1.267	**1.254**
Oxygen A	0.197	0.209	0.202	0.235	0.286	0.160	0.204	0.212	0.232	0.168	0.200	0.237	0.221	0.177	0.189	0.233	0.186	0.187	0.252	0.225	**0.211**
Oxygen B	0.325	0.331	0.319	0.363	0.407	0.294	0.324	0.331	0.347	0.289	0.325	0.354	0.345	0.297	0.312	0.356	0.303	0.308	0.372	0.339	**0.332**
Oxygen C	1.190	1.197	1.205	1.233	1.276	1.166	1.189	1.209	1.218	1.156	1.201	1.218	1.209	1.169	1.183	1.217	1.177	1.190	1.247	1.213	**1.203**
Plant(I)	0.004	0.024	0.008	0.007	0.029	0.007	0.007	0.012	0.009	0.005	0.011	0.013	0.011	0.003	0.005	0.022	0.010	0.012	0.011	0.020	**0.012**
Plant(II) A	0.206	0.231	0.223	0.200	0.195	0.203	0.206	0.213	0.206	0.201	0.221	0.170	0.184	0.172	0.161	0.195	0.210	0.222	0.198	0.213	**0.201**
Plant(II) B	0.012	0.035	0.019	0.017	0.038	0.022	0.019	0.023	0.021	0.013	0.021	0.024	0.017	0.010	0.012	0.031	0.021	0.021	0.028	0.032	**0.022**
Plant(III)	0.046	0.039	0.042	0.045	0.045	0.046	0.044	0.043	0.045	0.047	0.046	0.047	0.044	0.046	0.047	0.046	0.046	0.040	0.041	0.043	**0.044**
Division Process	0.046	0.056	0.052	0.049	0.048	0.048	0.048	0.051	0.049	0.047	0.049	0.047	0.050	0.048	0.047	0.049	0.049	0.055	0.053	0.049	**0.050**
Recycling	1.468	1.514	1.466	1.480	1.523	1.483	1.462	1.479	1.469	1.443	1.503	1.471	1.523	1.454	1.455	1.476	1.461	1.477	1.538	1.511	**1.483**

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Secondary Plants: Throughput, Number Available, Number Switched On/Off (ton/h, MW/h, m³/h, nm³/h, number)

Throughput	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean
Steam (Extra - Elec)	711.540	713.412	711.776	711.228	713.345	711.096	706.566	708.163	711.605	713.375	713.348	712.933	713.462	711.424	713.208	709.360	711.824	712.907	712.619	713.193	**711.819**
Electricity Generation	167.421	167.862	167.477	167.348	167.846	167.317	166.251	166.627	167.436	167.853	167.847	167.749	167.873	167.394	167.814	166.908	167.488	167.743	167.675	167.810	**167.487**
Plant(IV) A	20.763	20.658	20.730	20.607	20.444	20.836	20.747	20.696	20.666	20.894	20.705	20.602	20.621	20.859	20.652	20.671	20.816	20.655	20.489	20.649	**20.688**
Plant(IV) B	20.763	20.658	20.730	20.607	20.444	20.836	20.747	20.696	20.666	20.894	20.705	20.602	20.621	20.859	20.652	20.671	20.816	20.655	20.489	20.649	**20.688**
Plant(IV) C	20.763	20.658	20.730	20.607	20.444	20.836	20.747	20.696	20.666	20.894	20.705	20.602	20.621	20.859	20.652	20.671	20.816	20.655	20.489	20.649	**20.688**
Plant(V)	38.290	38.343	38.364	38.557	37.875	37.774	38.046	38.592	38.708	38.436	38.636	37.488	38.501	38.032	38.071	36.665	38.644	38.768	37.934	38.644	**38.218**
Number Available																					
Electricity Generation	3.996	3.997	3.996	3.996	3.996	3.997	3.995	3.995	3.995	3.996	3.996	3.998	3.997	3.995	3.997	3.997	3.996	3.998	3.997	3.995	**3.996**
Plant(IV) A	4.000	4.000	4.000	3.999	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	4.000	**4.000**
Plant(IV) B	1.999	2.000	2.000	1.999	2.000	1.999	1.999	2.000	2.000	1.999	2.000	1.999	1.999	2.000	2.000	1.998	1.999	1.999	1.999	2.000	**1.999**
Plant(IV) C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.997	1.000	1.000	0.992	1.000	1.000	0.994	1.000	1.000	**0.999**
Plant(V)	7.336	7.379	7.616	7.735	7.419	7.188	7.100	7.624	7.717	7.208	7.548	7.171	7.510	7.488	7.329	6.790	7.400	7.599	7.421	7.597	**7.409**
Number Switched On																					
Electricity Generation	3.996	3.997	3.989	3.996	3.996	3.995	3.966	3.977	3.988	3.996	3.996	3.997	3.997	3.994	3.997	3.994	3.989	3.998	3.995	3.995	**3.992**
Plant(IV) A	3.893	3.876	3.891	3.891	3.873	3.888	3.889	3.888	3.889	3.895	3.889	3.874	3.891	3.901	3.866	3.877	3.887	3.864	3.879	3.879	**3.884**
Plant(IV) B	1.951	1.953	1.953	1.952	1.953	1.952	1.951	1.953	1.953	1.952	1.953	1.946	1.951	1.953	1.936	1.951	1.951	1.940	1.952	1.953	**1.950**
Plant(IV) C	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.997	1.000	1.000	0.992	1.000	1.000	0.994	1.000	1.000	**0.999**
Plant(V)	6.795	6.839	6.855	6.897	6.685	6.635	6.663	6.908	6.942	6.779	6.897	6.575	6.829	6.742	6.700	6.457	6.841	6.893	6.679	6.888	**6.775**
Number Switched Off																					
Electricity Generation	0.000	0.000	0.008	0.000	0.000	0.002	0.030	0.018	0.007	0.000	0.000	0.001	0.000	0.001	0.000	0.003	0.007	0.000	0.001	0.000	**0.004**
Plant(IV) A	0.107	0.124	0.109	0.108	0.127	0.112	0.111	0.112	0.111	0.104	0.111	0.126	0.109	0.099	0.134	0.123	0.113	0.136	0.121	0.121	**0.116**
Plant(IV) B	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.053	0.047	0.047	0.064	0.047	0.047	0.060	0.047	0.047	**0.049**
Plant(IV) C	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Plant(V)	0.542	0.541	0.761	0.838	0.734	0.553	0.438	0.716	0.774	0.429	0.651	0.596	0.681	0.745	0.630	0.332	0.559	0.706	0.741	0.709	**0.634**
Throughput																					
Oxygen Extra A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Oxygen Extra B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Oxygen Extra C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Number Available																					
Oxygen Extra A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Oxygen Extra B	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Oxygen Extra C	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Number Switched On																					
Oxygen Extra A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Oxygen Extra B	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Oxygen Extra C	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Number Switched Off																					
Oxygen Extra A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Oxygen Extra B	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Oxygen Extra C	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**

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Tank and Flares, Throughput (Tertiary Plants), Time "Bottleneck" (m^3, nm^3, m^3/h, nm^3/h, %)

Tanks (Mean Volume)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean
Plant(IV) Tank	1002.8	1000.2	1000.1	1002.4	1000.2	1001.6	1002.3	1000.0	1000.0	1001.6	1000.0	1004.7	1002.0	1000.1	1011.3	1003.1	1001.8	1007.5	1001.8	1000.1	**1002.2**
Flares (Volume - Accumulated Throughput)																					
Flare A	1573.2	0.0	0.0	1862.1	0.0	1666.4	1523.4	0.0	0.0	1345.1	0.0	24342.5	2199.2	0.0	61325.2	2088.4	3151.2	42606.8	1607.8	0.0	**7264.6**
Flare B	18334.6	10896.7	14166.9	2217.6	12805.6	37129.4	24480.9	5770.2	817.0	21123.4	4974.6	36162.7	4656.9	30702.9	27682.5	60205.1	11216.1	4971.5	13775.4	1734.9	**17191.2**
Flare C1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Flare C2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Flare C3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Flare C4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Flare C5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Flare C6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Flares (Rate - Throughput)																					
Flare A	0.182	0.000	0.000	0.216	0.000	0.193	0.176	0.000	0.000	0.156	0.000	2.817	0.255	0.000	7.098	0.242	0.365	4.931	0.186	0.000	**0.841**
Flare B	2.122	1.261	1.640	0.257	1.482	4.297	2.833	0.668	0.095	2.445	0.576	4.185	0.539	3.554	3.204	6.968	1.298	0.575	1.594	0.201	**1.990**
Flare C1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Flare C2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Flare C3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Flare C4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Flare C5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Flare C6	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Throughput																					
Sub(I)	17.837	17.743	17.804	17.703	17.559	17.899	17.823	17.775	17.750	17.948	17.783	17.753	17.716	17.915	17.885	17.758	17.885	17.843	17.601	17.735	**17.786**
Sub(II)	12.486	12.420	12.463	12.392	12.291	12.529	12.476	12.443	12.425	12.564	12.448	12.427	12.401	12.541	12.519	12.431	12.520	12.490	12.321	12.414	**12.450**
Sub(III)	5.663	5.633	5.652	5.620	5.574	5.682	5.658	5.643	5.635	5.698	5.645	5.636	5.624	5.687	5.678	5.638	5.678	5.665	5.588	5.630	**5.646**
Sub(IV)	1.133	1.127	1.131	1.124	1.115	1.137	1.132	1.129	1.127	1.140	1.129	1.127	1.125	1.138	1.136	1.128	1.136	1.133	1.118	1.126	**1.129**
Sub(V)	4954.3	4928.2	4945.3	4917.1	4877.1	4971.7	4950.4	4937.2	4930.1	4985.2	4939.3	4931.0	4920.7	4976.1	4967.7	4932.5	4967.9	4956.1	4888.8	4926.0	**4940.1**
Sub(VI)	2595.1	2581.4	2590.4	2575.6	2554.7	2604.2	2593.1	2586.2	2582.5	2611.3	2587.3	2582.9	2577.5	2606.5	2602.1	2583.7	2602.2	2596.0	2560.8	2580.3	**2587.7**
Test Bottleneck Time (%)																					
Oxygen A	12.62	10.45	10.35	10.31	10.09	12.58	11.88	10.90	10.95	11.77	12.36	11.57	11.04	11.79	12.04	10.63	11.47	11.56	11.61	11.38	**11.37**
Oxygen B	1.49	1.37	1.82	1.27	0.82	1.61	1.23	2.11	1.52	1.58	1.87	0.74	0.46	1.49	0.59	0.91	1.02	1.87	2.28	1.61	**1.38**
Oxygen C	0.40	0.34	0.26	0.32	0.31	0.45	0.27	0.18	0.35	0.69	0.36	0.27	0.44	0.25	0.29	0.42	0.19	0.16	0.23	0.25	**0.32**

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Number Failures Repaired, Services Completed (number)

Failure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean	
Coal Processing	340	328	350	333	341	321	366	318	349	338	349	305	351	352	355	315	336	326	331	342	337.30	
Steam	20	29	22	25	26	33	24	19	23	23	31	25	25	26	28	27	25	22	27	18	24.90	
Gas Production	371	356	348	325	369	357	357	334	357	371	365	349	361	372	362	334	338	339	322	359	352.30	
Temperature Regulation	9	7	10	13	16	10	10	15	8	12	10	17	18	13	9	13	8	11	8	10	11.35	
Oxygen A	57	44	43	52	40	60	41	41	35	42	59	46	46	40	52	50	46	42	47	42	46.25	
Oxygen B	6	6	9	5	4	6	5	8	6	6	7	5	2	5	3	4	5	8	9	7	5.80	
Oxygen C	86	85	64	69	65	74	87	70	71	86	64	79	61	71	55	79	58	63	81	73	72.05	
Electricity Generation	24	22	22	24	21	18	26	30	30	23	23	14	19	31	20	20	22	15	28	24	22.80	
Plant(I)	4	5	5	3	3	8	4	4	5	2	4	3	1	3	1	3	4	3	9	5	3.95	
Plant(II) A	4	4	3	7	9	3	3	4	5	1	4	7	9	4	5	6	2	2	9	5	4.80	
Plant(II) B	2	0	3	2	0	1	1	0	3	0	1	2	0	1	1	0	3	0	3	2	1.25	
Plant(III)	1	5	3	2	2	1	2	3	2	0	1	0	2	1	0	1	1	5	3	4	1.95	
Division Process	2	4	1	1	2	2	3	4	2	2	2	1	2	0	1	0	2	2	1	2	1.80	
Plant(IV) A	0	0	1	4	0	0	0	0	0	2	2	0	0	0	1	1	3	1	0	3	0.90	
Plant(IV) B	3	0	0	2	0	1	3	0	0	2	1	1	2	0	0	4	1	1	2	0	1.15	
Plant(IV) C	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3	0	0	2	0	0	0.30	
Plant(V)	13	13	7	6	12	13	16	8	7	15	10	13	10	8	11	16	13	9	11	10	11.05	
Oxygen Extra C	9	9	6	6	6	4	12	11	7	4	12	5	6	8	6	12	11	4	4	6	7.40	907.30
Service																						
Coal Processing	356	361	357	355	357	358	349	358	358	354	359	354	355	360	356	358	356	356	352	360	356.45	
	54	53	51	56	55	55	54	56	56	54	52	56	55	55	56	55	56	55	56	53	54.65	
	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10.00	
Steam	51	54	53	51	53	52	51	53	53	53	54	52	54	54	54	50	53	52	51	53	52.55	
Temperature Regulation	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.00	
Oxygen A	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36	36.00	
Oxygen B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00	
Oxygen C	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42.00	
Electricity Generation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00	
Plant(I)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2.00	
Plant(II) A	47	47	48	47	44	47	48	48	47	48	48	47	48	46	48	48	47	48	47	47	47.25	
	16	16	16	18	16	15	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16.05	
	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8.00	
Plant(II) B	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1.00	
Recycling	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16.00	
Oxygen Extra A	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1.00	
Oxygen Extra B	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1.00	
Oxygen Extra C	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1.00	646.95

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Number Services Missed, Evaluations (number)

Missed	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean
Coal Processing	344	337	343	345	343	342	351	340	340	340	341	346	343	340	342	342	342	338	346	340	342.25
	44	45	47	42	43	43	44	42	42	44	46	42	43	43	42	43	42	43	42	45	43.35
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Steam	3	0	1	3	1	2	3	1	1	1	0	2	0	0	0	4	1	2	3	1	1.45
Temperature Regulation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Oxygen A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Oxygen B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Oxygen C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Electricity Generation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Plant(I)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Plant(II) A	49	49	48	49	52	49	48	48	49	48	48	49	48	50	48	48	49	48	49	49	48.75
	8	8	8	6	8	9	8	8	8	8	8	8	8	8	8	8	8	8	8	8	7.95
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Plant(II) B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Recycling	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Oxygen Extra A	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Oxygen Extra B	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
Oxygen Extra C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00

443.75

Evaluation	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean
Completed	3347	3288	3232	3202	3269	3270	3348	3195	3266	3295	3334	3188	3276	3326	3286	3213	3200	3155	3230	3271	3259.55
Module Extra	1594	1565	1540	1519	1559	1556	1596	1517	1557	1572	1588	1515	1559	1583	1560	1527	1522	1500	1532	1559	1551.00
Module Removed	1	3	2	7	2	3	2	3	3	2	6	3	4	3	3	3	5	4	2	5	3.25
Evaluator Extra	226	223	218	226	220	225	223	227	219	218	222	225	222	226	229	224	222	224	228	221	223.40
Evaluator Removed	1526	1497	1472	1450	1488	1486	1527	1448	1487	1503	1518	1445	1491	1514	1494	1457	1452	1429	1465	1489	1481.90
Removed	1601	1574	1548	1530	1565	1563	1604	1525	1564	1579	1598	1522	1568	1590	1572	1536	1531	1506	1544	1564	1559.20
Returned	1595	1568	1542	1526	1561	1559	1598	1520	1560	1574	1594	1518	1563	1586	1563	1532	1526	1502	1537	1561	1554.25
Multiple	49	50	50	50	49	50	49	50	49	49	50	50	50	50	50	50	50	50	50	50	49.75
Destroyed	1596	1569	1543	1527	1562	1560	1599	1521	1561	1575	1595	1519	1564	1587	1564	1533	1527	1503	1538	1562	1555.25
1	1474	1448	1421	1406	1437	1437	1476	1399	1438	1452	1471	1396	1443	1466	1444	1409	1403	1378	1418	1440	1432.80
2	43	41	42	40	42	41	42	41	41	42	43	41	41	40	42	42	42	42	41	40	41.45
3	5	6	6	6	6	6	6	6	6	7	5	6	7	6	6	7	6	6	6	6	6.05
4	4	4	4	4	4	4	4	4	4	3	4	4	3	4	4	3	4	4	4	4	3.85
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00
9	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.05
10	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0.95
10+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.00

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Number Times "Bottleneck" (number)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean
No Bottleneck																					
Coal Processing	0.00	1.00	1.00	20.00	9.00	0.00	6.00	0.00	0.00	0.00	4.00	0.00	8.00	11.00	3.00	1.00	1.00	0.00	1.00	0.00	**3.30**
Steam	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Gas Production	38.00	15.00	53.00	14.00	91.00	15.00	68.00	46.00	84.00	22.00	42.00	29.00	45.00	34.00	50.00	13.00	45.00	34.00	45.00	74.00	**42.85**
Temperature Regulation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Oxygen A	458.00	409.50	401.00	380.50	371.00	453.50	446.50	367.00	410.00	448.33	456.00	378.50	395.00	424.50	397.00	379.50	411.00	397.00	375.50	391.50	**407.54**
Oxygen B	62.00	37.50	92.50	81.00	44.00	34.00	25.00	71.50	32.00	52.33	44.50	29.50	4.00	58.00	8.00	26.00	42.00	40.00	97.50	45.50	**46.34**
Oxygen C	18.00	11.00	10.50	9.50	8.00	15.50	7.50	3.50	14.00	29.33	11.50	11.00	15.00	8.50	9.00	15.50	6.00	7.00	10.00	11.00	**11.57**
Plant(I)	1029.00	977.00	1023.00	963.00	888.00	1036.00	1065.00	1002.00	996.00	1053.00	984.00	1048.00	794.00	1067.00	1020.00	1038.00	1003.00	1049.00	852.00	953.00	**992.00**
Plant(II) A	1721.00	1757.00	1627.00	1714.00	1842.00	1683.00	1703.00	1667.00	1697.00	1671.00	1745.00	1663.00	1988.00	1720.00	1795.00	1735.00	1634.00	1579.00	1814.00	1758.00	**1725.65**
Plant(II) B	2.00	0.00	3.00	4.00	0.00	2.00	1.00	0.00	4.00	0.00	2.00	2.00	0.00	1.00	1.00	0.00	4.00	0.00	9.00	3.00	**1.90**
Plant(III)	8.00	41.00	8.00	6.00	2.00	4.00	3.00	22.00	12.00	0.00	5.00	0.00	13.00	1.00	0.00	4.00	11.00	29.00	19.00	14.00	**10.10**
Division Process	10.00	38.00	12.00	9.00	13.00	26.00	22.00	15.00	16.00	18.00	39.00	26.00	13.00	0.00	2.00	0.00	42.00	19.00	6.00	20.00	**17.30**
Recycling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.00**
Service Correction																					
Correction Serv1	124	124	123	119	121	122	123	126	125	124	125	124	125	124	121	124	126	123	116	125	**123.20**
Correction Serv2	38	36	37	38	37	36	38	38	38	38	36	38	38	37	38	37	38	37	38	35	**37.30**
Correction Serv3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0.00**

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"Throughput Vector" (ton/h, nm³/h, m³/h, MW/h)

Product	From	To	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean
Coal	-	Coal Processing	1262.533	1255.883	1260.245	1253.048	1242.856	1266.961	1261.528	1258.174	1256.370	1270.409	1258.711	1256.578	1253.970	1268.084	1265.951	1256.972	1265.983	1262.979	1245.839	1255.310	**1258.919**
Coal (Coarse)	Coal Processing	Gas Production	852.210	847.721	850.665	845.807	838.928	855.199	851.532	849.268	848.049	857.526	849.630	848.190	846.430	855.957	854.517	848.456	854.538	852.511	840.941	847.335	**849.770**
Coal (Fine)	Coal Processing	Steam	374.542	373.475	374.109	372.539	370.782	375.382	373.534	373.101	373.284	376.459	374.047	373.541	373.089	375.666	375.514	373.046	375.298	374.854	371.279	373.322	**373.843**
Coal (Fine)	Coal Processing	Slimesdam	35.781	34.687	35.471	34.701	33.146	36.380	36.463	35.806	35.036	36.424	35.035	34.847	34.451	36.461	35.920	35.470	36.146	35.614	33.618	34.654	**35.306**
Water	-	Water Treatment	1858.896	1851.903	1856.059	1845.773	1834.263	1864.400	1852.291	1849.453	1850.652	1871.456	1855.651	1852.336	1849.376	1866.260	1865.266	1849.095	1863.849	1860.941	1837.519	1850.900	**1854.317**
Water	Water Treatment	Steam	2453.896	2446.903	2451.059	2440.773	2429.263	2459.400	2447.291	2444.453	2445.652	2466.456	2450.651	2447.336	2444.376	2461.260	2460.266	2444.095	2458.849	2455.941	2432.519	2445.900	**2449.317**
Steam	Steam	Gas Production	867.279	862.710	865.707	860.763	853.762	870.320	866.588	864.284	863.045	872.689	864.653	863.188	861.396	871.092	869.626	863.459	869.648	867.585	855.810	862.317	**864.796**
Steam	Steam	Oxygen-A	559.444	556.497	558.430	555.241	550.725	561.406	558.999	557.513	556.713	562.934	557.751	556.805	555.650	561.904	560.958	556.980	560.973	559.642	552.047	556.244	**557.843**
Steam	Steam	Oxygen-C	186.481	185.499	186.143	185.080	183.575	187.135	186.333	185.838	185.571	187.645	185.917	185.602	185.217	187.301	186.986	185.660	186.991	186.547	184.016	185.415	**185.948**
Steam	Steam	Electricity Gntn	711.540	713.412	711.776	711.228	713.345	711.096	706.566	708.163	711.605	713.375	713.348	712.933	713.462	711.424	713.208	709.360	711.824	712.907	712.619	713.193	**711.819**
Raw gas	Gas Production	Temperature Rgln	1336077.8	1329040.0	1333656.3	1326039.6	1315254.9	1340763.6	1335014.5	1331465.1	1329555.1	1344412.3	1332033.3	1329776.0	1327015.8	1341951.9	1339694.3	1330193.1	1339728.2	1336550.0	1318410.6	1328434.3	**1332253.3**
Raw gas	Temperature Rgln	Plant(I)	1336077.8	1329040.0	1333656.3	1326039.6	1315254.9	1340763.6	1335014.5	1331465.1	1329555.1	1344412.3	1332033.3	1329776.0	1327015.8	1341951.9	1339694.3	1330193.1	1339728.2	1336550.0	1318410.6	1328434.3	**1332253.3**
Gas-water	Temperature Rgln	Plant(IV)-A	855.090	850.586	853.540	848.665	841.763	858.089	854.409	852.138	850.915	860.424	852.501	851.057	849.290	858.849	857.404	851.324	857.426	855.392	843.783	850.198	**852.642**
Air	Oxygen-A	Oxygen-B	1435907.4	1428343.8	1433305.0	1425119.2	1413528.7	1440943.4	1434764.6	1430950.1	1428897.4	1444864.6	1431560.7	1429134.7	1426168.3	1442220.4	1439794.1	1429583.1	1439830.6	1436414.9	1416920.2	1427692.8	**1431797.2**
Oxygen	Oxygen-B	Oxygen-C	249885.2	248568.9	249432.3	248007.7	245990.7	250761.5	249686.3	249022.5	248665.2	251444.0	249128.7	248706.5	248190.3	250983.8	250561.6	248784.6	250567.9	249973.5	246580.9	248455.6	**249169.9**
Oxygen	Oxygen-C	Gas Production	185175.7	184200.3	184840.1	183784.4	182289.7	185825.1	185028.3	184536.4	184271.7	186330.8	184615.1	184302.3	183919.7	185989.8	185676.9	184360.1	185681.6	185241.1	182727.1	184116.3	**184645.6**
Oxygen	Oxygen-C	Recycling	64709.5	64368.6	64592.2	64223.3	63701.0	64936.4	64658.0	64486.1	64393.6	65113.2	64513.6	64404.3	64270.6	64994.0	64884.7	64424.5	64886.3	64732.4	63853.8	64339.3	**64524.3**
Electricity	Electricity Gntn	-	167.421	167.862	167.477	167.348	167.846	167.317	166.251	166.627	167.436	167.853	167.847	167.749	167.873	167.394	167.814	166.908	167.488	167.743	167.675	167.810	**167.487**
Pure gas	Plant(I)	Plant(II)-A	935254.5	930328.0	933559.4	928227.7	920678.4	938534.5	934510.1	932025.6	930688.6	941088.6	932423.3	930843.2	928911.1	939366.3	937786.0	931135.2	937809.8	935585.0	922887.4	929904.0	**932577.3**
Residue gas	Plant(II)-A	Plant(II)-B	471840.1	469354.7	470984.9	468295.1	464486.4	473494.9	471464.6	470211.1	469536.6	474783.4	470411.8	469614.6	468639.8	473914.5	473117.3	469761.9	473129.2	472006.0	465600.9	469140.8	**470489.5**
Chemical prdt	Plant(II)-A	Sub(I)	475.645	473.140	474.783	472.072	468.232	477.313	475.267	474.003	473.323	478.612	474.205	473.402	472.419	477.736	476.933	473.550	476.945	475.813	469.356	472.924	**474.284**
Residue gas	Plant(II)-B	Plant(III)	471840.1	469354.7	470984.9	468295.1	464486.4	473494.9	471464.6	470211.1	469536.6	474783.4	470411.8	469614.6	468639.8	473914.5	473117.3	469761.9	473129.2	472006.0	465600.9	469140.8	**470489.5**
Down gas	Plant(III)	Division Process	406962.1	404818.4	406224.5	403904.5	400619.5	408389.3	406638.2	405557.1	404975.3	409500.7	405730.1	405042.6	404201.8	408751.3	408063.6	405169.6	408074.0	407105.9	401580.7	404633.9	**405797.2**
H2	Division Process	Plant(II)-A	165144.0	164274.1	164844.7	163903.2	162570.2	165723.2	165012.5	164573.8	164337.7	166174.1	164644.1	164365.0	164023.9	165870.0	165591.0	164416.6	165595.2	165202.3	162960.2	164199.2	**164671.3**
CH4	Division Process	Recycling	141552.0	140806.4	141295.4	140488.5	139345.9	142048.4	141439.3	141063.9	140860.9	142435.0	141123.5	140884.3	140591.9	142174.3	141935.1	140928.5	141938.7	141602.0	139680.2	140742.2	**141146.8**
C2	Division Process	Sub(V)	12385.8	12320.6	12363.3	12292.7	12192.8	12429.2	12375.9	12343.0	12325.3	12463.1	12348.3	12327.4	12301.8	12440.3	12419.3	12331.2	12419.6	12390.2	12222.0	12314.9	**12350.3**
C2	Division Process	Sub(VI)	6487.8	6453.6	6476.0	6439.1	6386.7	6510.6	6482.6	6465.4	6456.1	6528.3	6468.2	6457.2	6443.8	6516.3	6505.4	6459.3	6505.5	6490.1	6402.0	6450.7	**6469.2**
Condensate	Division Process	Plant(V)	129.756	129.072	129.521	128.781	127.734	130.211	129.653	129.308	129.123	130.565	129.363	129.144	128.876	130.326	130.107	129.184	130.110	129.802	128.040	129.014	**129.385**
Recycled gas	Recycling	Plant(II)-A	374101.8	372131.2	373423.8	371291.1	368271.4	375413.8	373804.1	372810.2	372275.4	376435.4	372969.3	372337.3	371564.4	375746.5	375114.4	372454.1	375123.9	374234.0	369155.0	371961.6	**373030.9**
NH3	Plant(IV)-A	Plant(IV)-B	20.763	20.658	20.730	20.607	20.444	20.836	20.747	20.696	20.666	20.894	20.705	20.602	20.621	20.859	20.652	20.671	20.816	20.655	20.489	20.649	**20.688**
Tar acid	Plant(IV)-A	-	3.664	3.646	3.658	3.636	3.608	3.677	3.661	3.652	3.647	3.687	3.654	3.636	3.639	3.681	3.644	3.648	3.673	3.645	3.616	3.644	**3.651**
NH3	Plant(IV)-B	Plant(IV)-C	20.763	20.658	20.730	20.607	20.444	20.836	20.747	20.696	20.666	20.894	20.705	20.602	20.621	20.859	20.652	20.671	20.816	20.655	20.489	20.649	**20.688**
NH3	Plant(IV)-C	-	20.763	20.658	20.730	20.607	20.444	20.836	20.747	20.696	20.666	20.894	20.705	20.602	20.621	20.859	20.652	20.671	20.816	20.655	20.489	20.649	**20.688**
Alcohol	Sub(I)	Sub(II)	17.837	17.743	17.804	17.703	17.559	17.899	17.823	17.775	17.750	17.948	17.783	17.753	17.716	17.915	17.885	17.758	17.885	17.843	17.601	17.735	**17.786**
Carbonyl	Sub(I)	Sub(III)	11.891	11.828	11.870	11.802	11.706	11.933	11.882	11.850	11.833	11.965	11.855	11.835	11.810	11.943	11.923	11.839	11.924	11.895	11.734	11.823	**11.857**
Ethanol	Sub(II)	-	12.486	12.420	12.463	12.392	12.291	12.529	12.476	12.443	12.425	12.564	12.448	12.427	12.401	12.541	12.519	12.431	12.520	12.490	12.321	12.414	**12.450**
Propanol	Sub(II)	-	5.351	5.323	5.341	5.311	5.268	5.370	5.347	5.333	5.325	5.384	5.335	5.326	5.315	5.375	5.365	5.327	5.366	5.353	5.280	5.320	**5.336**
Acetone	Sub(III)	-	5.663	5.633	5.652	5.620	5.574	5.682	5.658	5.643	5.635	5.698	5.645	5.636	5.624	5.687	5.678	5.638	5.678	5.665	5.588	5.630	**5.646**
MEK	Sub(III)	-	3.397	3.379	3.391	3.372	3.344	3.409	3.395	3.386	3.381	3.418	3.387	3.381	3.374	3.412	3.406	3.382	3.407	3.398	3.352	3.378	**3.388**
Aldehyde	Sub(III)	Sub(IV)	2.265	2.253	2.261	2.248	2.230	2.273	2.263	2.257	2.254	2.279	2.258	2.255	2.250	2.275	2.271	2.255	2.271	2.266	2.235	2.252	**2.259**
Methanol	Sub(III)	-	0.553	0.550	0.552	0.549	0.544	0.555	0.552	0.551	0.550	0.556	0.551	0.550	0.549	0.555	0.554	0.551	0.554	0.553	0.546	0.550	**0.551**
Heavy aldehyde	Sub(IV)	-	1.133	1.127	1.131	1.124	1.115	1.137	1.132	1.129	1.127	1.140	1.129	1.127	1.125	1.138	1.136	1.128	1.136	1.133	1.118	1.126	**1.129**
N-Butanol	Sub(IV)	-	0.838	0.834	0.837	0.832	0.825	0.841	0.837	0.835	0.834	0.843	0.836	0.834	0.832	0.842	0.840	0.834	0.840	0.838	0.827	0.833	**0.836**

Product	From	To	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean
Ethane	Sub(V)	-	4954.3	4928.2	4945.3	4917.1	4877.1	4971.7	4950.4	4937.2	4930.1	4985.2	4939.3	4931.0	4920.7	4976.1	4967.7	4932.5	4967.9	4956.1	4888.8	4926.0	**4940.1**
Ethylene	Sub(V)	-	9.413	9.364	9.396	9.342	9.267	9.446	9.406	9.381	9.367	9.472	9.385	9.369	9.349	9.455	9.439	9.372	9.439	9.417	9.289	9.359	**9.386**
Ethane	Sub(VI)	-	2595.1	2581.4	2590.4	2575.6	2554.7	2604.2	2593.1	2586.2	2582.5	2611.3	2587.3	2582.9	2577.5	2606.5	2602.1	2583.7	2602.2	2596.0	2560.8	2580.3	**2587.7**
Petrol	Sub(VI)	-	3.893	3.872	3.886	3.863	3.832	3.906	3.890	3.879	3.874	3.917	3.881	3.874	3.866	3.910	3.903	3.876	3.903	3.894	3.841	3.870	**3.882**
Butene	Sub(VI)	-	2.595	2.581	2.590	2.576	2.555	2.604	2.593	2.586	2.582	2.611	2.587	2.583	2.578	2.607	2.602	2.584	2.602	2.596	2.561	2.580	**2.588**
C5C6	Plant(V)	-	38.290	38.343	38.364	38.557	37.875	37.774	38.046	38.592	38.708	38.436	38.636	37.488	38.501	38.032	38.071	36.665	38.644	38.768	37.934	38.644	**38.218**
Petrol	Plant(V)	-	39.822	39.877	39.899	40.100	39.390	39.285	39.568	40.136	40.257	39.974	40.182	38.987	40.041	39.553	39.594	38.131	40.189	40.319	39.451	40.190	**39.747**
Diesel	Plant(V)	-	39.822	39.877	39.899	40.100	39.390	39.285	39.568	40.136	40.257	39.974	40.182	38.987	40.041	39.553	39.594	38.131	40.189	40.319	39.451	40.190	**39.747**
C3	Plant(V)	-	5.105	5.112	5.115	5.141	5.050	5.037	5.073	5.146	5.161	5.125	5.151	4.998	5.133	5.071	5.076	4.889	5.152	5.169	5.058	5.153	**5.096**
Heavy polymer	Plant(V)	-	5.105	5.112	5.115	5.141	5.050	5.037	5.073	5.146	5.161	5.125	5.151	4.998	5.133	5.071	5.076	4.889	5.152	5.169	5.058	5.153	**5.096**
C4	Plant(V)	-	7.658	7.669	7.673	7.711	7.575	7.555	7.609	7.718	7.742	7.687	7.727	7.498	7.700	7.606	7.614	7.333	7.729	7.754	7.587	7.729	**7.644**
Electricity	-	Oxygen Extra-A	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
(Air)	Oxygen Extra-A	Oxygen Extra-B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
(Oxygen)	Oxygen Extra-B	Oxygen Extra-C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
(Oxygen)	Oxygen Extra-C	Gas Prod/Recyc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Electricity	-	Oxygen Extra-C	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	**0.000**
Steam (Total)	Steam	Gas/Oxy-A, -C/Ele	2324.744	2318.118	2322.056	2312.311	2301.407	2329.958	2318.487	2315.797	2316.933	2336.643	2321.669	2318.529	2315.725	2331.720	2330.778	2315.459	2329.436	2326.681	2304.492	2317.168	**2320.406**
Oxygen (Total)	Oxygen-C	Gas Prod/Recyc	249885.2	248568.9	249432.3	248007.7	245990.7	250761.5	249686.3	249022.5	248665.2	251444.0	249128.7	248706.5	248190.3	250983.8	250561.6	248784.6	250567.9	249973.5	246580.9	248455.6	**249169.9**

* * *

Resource Utilisation (%)

Simulation Object	Run 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	-95%	Average	95%
Coal Processing Service	47.0313	47.0660	46.9629	47.0275	47.0339	47.0762	46.8887	47.0646	47.0930	47.0054	46.9758	47.0306	46.7753	46.7925	47.0635	47.0661	46.9035	47.0470	46.9863	46.9974	46.9522	46.9944	47.0365
Coal Processing Repair	33.8188	32.9086	35.5595	33.5223	34.4666	31.9782	36.6712	31.2682	35.4113	33.9351	34.6030	30.7446	35.3097	34.8707	35.3326	31.5291	33.5261	33.0604	33.3188	34.6186	33.0833	33.8227	34.5621
Steam Service	20.0689	21.2076	20.8559	19.9945	20.5791	20.3747	19.8600	20.8559	20.6156	20.8559	21.2364	20.4624	21.2494	21.2494	20.9212	19.2546	20.8559	20.1675	19.8292	20.8559	20.3070	20.5675	20.8280
Steam Repair	24.1495	37.3136	27.3959	32.1866	31.3513	36.8966	31.4685	23.8041	27.2478	26.2713	35.4407	27.9394	25.8780	31.0686	37.1455	31.0843	29.1926	26.2839	33.4524	22.8820	27.7973	29.9226	32.0480
Gas Production Repair	63.9469	58.5595	58.3266	54.1892	63.8738	59.5347	59.7077	56.6114	59.3060	61.9321	62.0220	59.3036	61.8933	64.4380	61.2601	55.6967	56.7088	57.8569	55.9956	58.9839	58.1457	59.5073	60.8690
Temperature Regulation Service	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222
Temperature Regulation Repair	0.4574	0.2807	0.5474	0.6992	0.8352	0.4972	0.4377	0.7550	0.4256	0.6612	0.5501	0.8140	0.8434	0.6880	0.4521	0.6255	0.3881	0.5865	0.4187	0.5096	0.4981	0.5736	0.6492
Oxygen A Service	9.9996	9.9996	9.9996	9.9889	9.9996	9.9996	9.9996	9.9996	9.9996	9.9813	9.9850	9.9996	9.9996	9.9996	9.9996	9.9996	9.9996	9.9996	9.9996	9.9983	9.9948	9.9973	9.9999
Oxygen A Repair	2.8984	2.4945	2.2767	2.6841	2.2461	3.3361	2.1789	1.9836	1.6173	2.2494	3.0810	2.2219	2.6014	1.9790	2.6246	2.2901	2.1917	2.3540	2.3248	1.8931	2.1848	2.3763	2.5679
Oxygen B Service	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Oxygen B Repair	1.4927	1.7139	2.4563	1.2673	1.0926	1.6099	1.3912	2.1174	1.6543	1.5782	1.8717	1.3365	0.5372	1.4888	0.8823	0.9591	1.2981	2.1856	2.5203	1.8989	1.3275	1.5676	1.8077
Oxygen C Service	11.6662	11.6555	11.6662	11.6639	11.6662	11.6567	11.6662	11.6662	11.6662	11.6662	11.6662	11.6662	11.6237	11.6662	11.6662	11.6662	11.6662	11.6662	11.6662	11.6584	11.6629	11.6675	
Oxygen C Repair	3.2239	3.3609	2.2396	2.5705	2.4090	2.7193	3.1420	2.6193	2.8389	3.2106	2.5611	3.2183	2.5197	2.5691	2.0778	3.0661	2.2995	2.3006	3.2912	2.7749	2.5650	2.7506	2.9363
Plant(I) Service	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222	4.7222
Plant(I) Repair	0.5390	0.5637	0.5281	0.4443	0.3881	0.8567	0.5901	0.5465	0.6137	0.2985	0.4843	0.4623	0.1027	0.1697	0.1466	0.2523	0.5833	0.3294	1.2220	0.5645	0.3655	0.4843	0.6031
Plant(II) A Service	67.6038	68.3776	68.8879	68.6102	67.7769	67.2213	68.8879	68.8879	68.6102	68.8879	68.8820	68.5777	68.8346	68.3324	68.8879	67.2702	68.6102	68.8879	68.6102	68.6102	68.2060	68.4627	68.7195
Plant(II) A Repair	7.7778	7.7778	5.8333	14.0741	17.5000	5.8333	5.8333	7.7778	9.7222	1.9444	8.2138	13.6111	17.5000	7.7778	9.7222	11.6667	3.8889	18.5098	9.7222	7.2136	9.4288	11.6439	
Plant(II) B Service	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667	4.1667
Plant(II) B Repair	0.0564	0.0000	0.0922	0.0570	0.0000	0.0389	0.0236	0.0000	0.1032	0.0000	0.0463	0.0407	0.0000	0.0372	0.0227	0.0000	0.0658	0.0000	0.0854	0.0535	0.0203	0.0361	0.0520
Plant(III) Repair	0.1037	0.8350	0.5091	0.1752	0.2635	0.1158	0.3367	0.4047	0.2209	0.0000	0.1290	0.0000	0.3182	0.1122	0.0000	0.1434	0.1668	0.7349	0.5783	0.3881	0.1653	0.2768	0.3883
Division Process Repair	0.4167	1.0588	0.3333	0.2190	0.3627	0.5409	0.5414	0.6176	0.4860	0.3872	0.6281	0.2455	0.3874	0.0000	0.2063	0.0000	0.6395	0.5557	0.3812	0.7266	0.3209	0.4367	0.5525
Recycling Service	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998	39.9998
Electricity Generation Service	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Electricity Generation Repair	0.4157	0.3295	0.3525	0.4115	0.3669	0.3126	0.4686	0.5373	0.5070	0.3500	0.3651	0.2179	0.3014	0.4879	0.2605	0.2831	0.3874	0.2148	0.3460	0.4503	0.3255	0.3683	0.4111
Plant(IV) A Repair	0.0000	0.0000	0.0219	0.0591	0.0000	0.0000	0.0000	0.0000	0.0000	0.0406	0.0276	0.0000	0.0000	0.0000	0.0201	0.0124	0.0341	0.0196	0.0000	0.0357	0.0052	0.0136	0.0219
Plant(IV) B Repair	0.1350	0.0000	0.0000	0.1078	0.0000	0.0695	0.1315	0.0000	0.0000	0.0990	0.0281	0.0671	0.1357	0.0000	0.0000	0.1741	0.1081	0.0648	0.1210	0.0000	0.0338	0.0621	0.0903
Plant(IV) C Repair	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2982	0.0000	0.0000	0.8184	0.0000	0.0000	0.6163	0.0000	0.0867	0.1934	
Plant(V) Repair	51.4703	50.8296	28.0392	24.7547	48.8149	52.4755	65.9336	33.2966	28.0813	63.2561	41.0978	54.7524	43.8369	31.4699	45.8983	64.9902	52.5670	34.3122	46.8198	39.8130	39.3086	45.1255	50.9423
Oxygen Extra A Service	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889
Oxygen Extra B Service	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889
Oxygen Extra C Service	3.8889	3.8889	3.7727	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8889	3.8709	3.8831	3.8952
Oxygen Extra C Repair	1.1199	1.4297	0.8057	0.7596	0.9155	0.5278	1.8676	1.3548	1.0694	0.6242	1.7275	0.7334	0.6900	0.8002	1.1664	2.0083	1.3259	0.4835	0.4703	0.6031	0.8060	1.0241	1.2423

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Comparison

8640 Simulation time

Service (Compare ((number of services completed*service time)/simulation time) with (resource utilisation))

Plant	Service	Service Time	Hours	H/Time	Util	% Delta
Coalp	356.45	1	356.45			
	54.65	2	109.3			
	10.00	336	3360			
		Total	3825.75	0.4428	0.4699	-2.7149
Steam	52.55	34	1786.7	0.2068	0.2057	0.1119
Tempr	2.00	408	816	0.0944	0.0944	0.0000
OxygA	36.00	24	864	0.1000	0.1000	0.0027
OxygB	0.00	336	0	0.0000	0.0000	0.0000
OxygC	42.00	24	1008	0.1167	0.1166	0.0037
Elecg	0.00	720	0	0.0000	0.0000	0.0000
Plan1	2.00	408	816	0.0944	0.0944	0.0000
Pla2A	47.25	24	1134			
	16.05	120	1926			
	8.00	360	2880			
		Total	5940	0.6875	0.6846	0.2873
Pla2B	1.00	360	360	0.0417	0.0417	0.0000
Recyc	16.00	216	3456	0.4000	0.4000	0.0002
OxyeA	1.00	336	336	0.0389	0.0389	0.0000
OxyeB	1.00	336	336	0.0389	0.0389	0.0000
OxyeC	1.00	336	336	0.0389	0.0388	0.0058

Failure (Compare ((number of failures repaired*repair time)/simulation time) with (resource utilisation))

Plant	Failure	Repair Time	Hour	H/Time	Util	% Delta
Coalp	337.30	8	2698.4	0.3123	0.3382	-2.5912
Steam	24.90	120	2988	0.3458	0.2992	4.6607
Gaspr	352.30	16	5636.8	0.6524	0.5951	5.7334
Tempr	11.35	3	34.05	0.0039	0.0057	-0.1795
OxygA	46.25	2	92.5	0.0107	0.0238	-1.3057
OxygB	5.80	24	139.2	0.0161	0.0157	0.0435
OxygC	72.05	1	72.05	0.0083	0.0275	-1.9167
Elecg	22.80	1	22.8	0.0026	0.0037	-0.1044
Plan1	3.95	6	23.7	0.0027	0.0048	-0.2100
Pla2A	4.80	168	806.4	0.0933	0.0943	-0.0954
Pla2B	1.25	1	1.25	0.0001	0.0004	-0.0217
Plan3	1.95	8	15.6	0.0018	0.0028	-0.0962
Divip	1.80	18	32.4	0.0038	0.0044	-0.0617
Pla4A	0.90	0.5	0.45	0.0001	0.0001	-0.0083
Pla4B	1.15	3	3.45	0.0004	0.0006	-0.0221
Pla4C	0.30	24	7.2	0.0008	0.0009	-0.0033
Plan5	11.05	336	3712.8	0.4297	0.4513	-2.1532
OxyeC	7.40	12	88.8	0.0103	0.0102	0.0036

Evaluations

			Number	(Removed Histogram)	
Completed	3259.55		1	1432.80	1432.80
			2	41.45	82.90
Mod Extra	1551.00	Modules returned that removed no modules	3	6.05	18.15
Mod Rem	3.25	Modules returned that removed modules	4	3.85	15.40
Eva Extra	223.40	Evaluators that removed no modules	5	0.00	0.00
Eva Rem	1481.90	Evaluators that removed modules	6	0.00	0.00
Total	3259.55		7	0.00	0.00
			8	0.00	0.00
Removed	1559.20		9	0.05	0.45
Returned	1554.25		10	0.95	9.50
Multiple	49.75		10+	0.00	
Destroyed	1555.25		**Total**	1559.20	

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