REFERENCE

A Study on Model Design in the Simulation of Manufacturing Systems

Benjamin Spencer Tye

A thesis submitted in partial fulfilment of the requirements of Sheffield Hallam University for the degree of Doctor of Philosophy

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Collaborating Organisations

Engineering and Physical Sciences Research Council

Special Melted Products Ltd.

The CIMulation centre Ltd.

Abstract

A Study on Model Design in the Simulation of Manufacturing Systems

By

Benjamin Spencer Tye

Global competition in industry demands that organisations take steps to improve or even re-design their manufacturing systems in order to remain competitive. Such improvements invariably require considerable investment and risk. The use of computer simulation allows managers to understand the underlying dynamics of complex manufacturing systems in order to identify problem areas. The models can also be used to evaluate re-design strategies and options for improvement, thereby reducing the potential risk and increasing the likelihood of a positive return on investment. However, developing a valid simulation model that represents the system to a sufficient scope and level of detail to allow confident decision making is a difficult task.

The research explores the application of a novel methodology consisting of a questionnaire survey, case studies with expert model builders and action research with a steel manufacturing company. Using these research techniques, this study focuses on the crucial early phases of the simulation model development process.

The research demonstrates that the combination and application of the research techniques has proved to be a powerful methodology to explore the dynamic interactions of the early stages of the simulation life cycle.

The findings conclude that the simulation life cycle is highly iterative process where it is difficult to identify clear steps between the different stages of a simulation project. The model builders engage in a number of cyclic activities where there is significant interaction with the client stakeholders to ensure that the model is a valid representation of the problem. The increased use of Visual Interactive Simulation Software (VISS) has had a major impact on the life cycle by allowing dynamic models to be created at a very early stage which facilitates the interaction between model builder and client.

Preface

This thesis is submitted to the School of Engineering of Sheffield Hallam University for the degree of Doctor of Philosophy.

I would like to express my deepest gratitude and appreciation to my supervisor **Dr. D.T.S. Perera** (School of Engineering) for his guidance and constructive criticism during the course of this study. I would like to thank my family and friends, in particular my wife Nicola Sands-Tye for her patience and supprt. I would also like to thank my colleagues and administrative staff within the School of Engineering, and the Research Office for their help and support. Finally, I would like to thank those individuals who participated as case study subjects in this study.

The results obtained during the course of this research are to the best of my knowledge original, except where reference is made to the work of others.

B. Tye

April 1999

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1. Introduction

1.1 Background to the research

"Computer simulation is a process of designing a mathematical logical model of a real system and conducting experiments with this model. These experiments are for the purpose of understanding the behaviour of the system and/or evaluating various strategies" - Shannon (1975).

Global competition amongst manufacturing companies has increased the need for companies to become more competitive. Becoming more competitive requires quality, cost effectiveness and innovation both in products and in production.

Because of this situation, manufacturers have to invest in new capital, new working practises, new products and also evaluate and improve existing capital, working practises and products. However, new investment and change to existing manufacturing systems involves considerable expense, risk and much uncertainty.

Computer simulation is an attractive tool because it allows manufacturing companies to :

- Evaluate and predict the performance of investments *prior* to purchase and implementation. Reducing both risk and waste.
- Enables "what-if" analysis of proposed changes to existing systems prior to implementation.
- Provides the capability to understand the complex dynamic interactions of processes and the capability to vary multiple factors.

1.2 Justification for the research

It has been estimated (Simulation Study Group 1991) that UK manufacturing industry could save a potential £ 64M per annum through the wider deployment of simulation.

However, the study conducted by the Simulation Study Group (1991) discovered that simulation had only been deployed by 9% of the manufacturing companies surveyed. This figure is far lower than other technologies such as MRPII, which had been employed by more than 50%.

The study concludes that a low awareness of the technique and lack of knowledge concerning how simulation can be applied present obstacles to the wider use of simulation. These obstacles where further compounded by a lack of training, a lack of appropriate skills, difficulties in obtaining data, the speed of model development and the high cost of simulation software.

Studies conducted by Cochran et al. (1995) led them to propose that the success of a simulation project is more dependent on methodology than on the software tools employed. This view is supported by Law and McComas (1989) who argue that simulation projects are far more than an exercise in computer programming and that the literature of modelling and simulation places too much emphasis on software selection and model coding. They estimate that model coding represents only %30 to %40 of the total effort input by the modeller. Regarding modelling they list a number of pitfalls that can occur.

- Failure to have a well defined set of objectives
- Inappropriate level of model detail
- Failure to interact with management on a regular basis
- Insufficient simulation and statistics training

Finally, Townsend, Lamb and Seth (1988) lament the "paucity of literature" on the subject of model creation, Paul and Lehany (1996) state that simulation texts give no real guidance on how the process should be undertaken.

1.3 The focus of the research

It is clear that the success of a simulation project is very much dependent upon the methodology employed by a model builder to develop a valid simulation model. However, there is little guidance available to help those with limited experience in this area. In addition, much of the theory that is available was written prior to the increase in the use of Visual Interactive Simulation Software (VISS) and does not address how the use of this software influences the activities of model builders.

Chapter 2 explores this subject in more detail and concludes with the proposal of three questions, which form the basis of this research.

- **Research Question 1 - "What do modellers do prior to experimentation?"**
- **Research Question 2 - "What impact has the increase in use of VISS had on**

the life cycle of simulation projects and the activities of modellers and clients?"

- **Research Question 3 "What is the role of model representation techniques in projects using Visual Interactive Simulation Software?"**

Collectively they form a topic of research of which the primary focus is:

Understanding the methodology of simulation modelling in the light of Visual Interactive Simulation Software.

By answering the research questions, the study addresses a number of the problems outlined in section 1.2. Inexperienced model builders will benefit from the application of the findings in the following ways:

- An understanding of how model builders should interact with their clients.
- How the development of project objectives drive the modelling process.
- Developing a model with the most appropriate scope and level of detail to solve the problems identified.
- How to use VISS to enable the development of a valid model.

1.4 The Research Methodology

The research questions outlined in section 1.2 are of an exploratory nature. Their motive is to understand the way in which models are developed and primarily why they are developed in a particular way. Such questions lend themselves to a qualitative approach as opposed to a quantitative, experimental procedure.

The rationale for the methodology was motivated by 2 main factors.

- The lack of published information concerning the procedure of expert model developers.
- The need to elicit knowledge, techniques and tools employed by the expert model builders to answer the research questions.

The methodology was composed of three different research techniques, a questionnaire survey, case studies with model builders and action research conducted with a collaborating manufacturing organisation

1.5 Outline of this thesis

The thesis is composed of five chapters, each describing a fundamental component of the research programme.

Each chapter is written so it can be read as a separate piece of work. The intention is to enable the reader to locate and identify any aspect of this study quickly and easily.

1.5.1 Chapter 1 - Introduction

An overview of the entire thesis, containing a summary of each of the subsequent chapters.

1.5.2 Chapter 2 - Literature Review

This chapter reviews the literature of the subject area and discusses the strengths and weaknesses of the referenced material. From this analysis, a number of questions arise. These questions are summarised and form the 3 main research questions of the study.

1.5.3 Chapter 3 - Research Methodology

Opening with a discussion of the nature of research and the process of learning, this chapter then examines the nature of the research questions themselves. This analysis enables the positioning of the questions against a continuum of management research techniques and therefore the selection of the most appropriate methods to provide the answers. This is followed by a discussion of the strengths and weaknesses of the selected methods and a review of how they were applied in practise during the course of the study.

1.5.4 Chapter 4 - Results

This chapter presents an overview of the data collected by the research methods.

1.5.5 Chapter 5 - Analysis

The data collected is analysed against each research question of the study.

1.5.6 Chapter 6 - Conclusions

The final and most important chapter of the study brings together the previous three in a discussion of the results against the literature in the light of the application of the research methods employed for the three research questions.

It also presents a discussion on the implications for both industry and academia and proposes further areas for research in this area.

1.6 Delimitation's of scope and key assumptions

The scope of the study is defined in two ways.

1. The case study and action research sources were restricted to discrete-part manufacturing industry.
2. The stages of statistical model verification and experimentation were not examined.

This thesis assumes that the reader is familiar with the basic technical aspects of simulation modelling. However, to aid the reader, a glossary of terms can be found in following Chapter 6.

The type of simulation models developed for most of the applications in these systems are discrete, dynamic and stochastic and are called discrete-event simulation models. Unless indicated otherwise, any model referred to in this study is a discrete event simulation model.

2. Literature Review

2.1 Introduction

This chapter presents a background and history of the technology followed by a review of the literature reporting problems and obstacles regarding the use of computer simulation in industry. This section is followed by a review of documented approaches to developing simulation models, the similarities and differences between them and an evaluation of their shortcomings. The chapter concludes by describing the focus of this study and the resulting questions answered by the subsequent chapters of this thesis.

2.2 What is Computer Simulation?

Computer simulation is a tool that allows a model of system to be executed on a digital computer to enable experiments to be conducted with the aim of observing the impact of changes to the variables affecting the system. As computers can model the behaviour of a system over say a few months in a relatively short space of time, a few minutes or even seconds, the attraction of computer simulation as a decision support tool becomes obvious. The impact of a change in system variables can be observed quickly and easily, enabling managers to explore a range of options without impact on the system itself.

This concept is best illustrated by means of an example:

A steel bar manufacturer wishes to increase the throughput of the forge workshop at one of their factories. In simple terms, the forge workshop consists of three furnaces to pre-heat a variety of bars before they are loaded by crane into the forge where they are reduced in diameter. Once the desired diameter has been reached, the bars are unloaded and then cut to length before despatch to the customer in one of two loading bays.

There are a number of options available to the management to increase the throughput of this workshop.

1 - Purchase an additional furnace to increase the available pre-heater capacity.

2 - Increase the number of manned shifts per week on the forge.

3 - Alter the operational characteristics of the workshop e.g. decrease tool change times on the forge, decrease transit and loading times on the crane etc.

4 - Increase the number of loading bays to reduce queuing for despatch.

It would be possible of course to investigate the impact of these changes by introducing the changes in the workshop itself. However the degree of investment and the time required to implement such change without any indication of whether it would be a success or not is clearly impractical. Hence the need for some analysis prior to any decision being made concerning the most suitable means of improving the throughput.

Any analysis requires the development of some kind of model, an abstraction of the system upon which the effects of change can be observed without impact on the system itself. However, to model the system to any degree of accuracy requires a complex model. Hence the need for a computer to manage this complex model.

In the example above, a series of experiments could be conducted where the variables in the model are changed to reflect the intended changes to the system. For example, increasing the number of pre-heat furnaces would be reflected in an increase in the variable 'pre-heat capacity'. The model could then be run to observe the effect of this change on the overall throughput of the system.

In this way, all of the options for improvement listed above can be explored to find the most acceptable method without any additional capital investment and change to system operations. Hence the attraction of computer simulation as a decision support tool.

2.2.1 An explanation of the modelling paradigm.

A system, as proposed by Schmidt and Taylor (1970) is defined as a collection of entities e.g., people or machines that interact together toward the accomplishment of some logical end. Law and Kelton (1996) indicate that in practise, the system in questions depends very much on the objectives of the simulation study. For example, the system described above, the forge workshop, is a subset of the overall manufacturing system at the steelworks.

The state of a system is essentially a snapshot at a point in time. Law and Kelton (1996) define system state as being a collection of variables necessary to describe a system at a particular time. Again to refer to the example above, the state of the system could be described in terms of the number of bars in process, whether the machines were active or idle or the number of bars waiting in the despatch queue.

It is possible to draw a distinction between two types of systems, discrete and continuous. A discrete system is characterised by abrupt changes to the state of a system at distinct points in time such as the example above where discrete change occurs to the state of the forge, as when a bar is loaded into the forge, the state changes from idle to busy. In contrast, the state of a continuous system changes continuously over time, the furnace heating the bar is a good example of a continuous system as the temperature, and flow rate of gas are subject to constant change. Many other systems consist of both discrete and continuous systems and it therefore depends on the objectives of study as to the manner in which it is to be categorised.

When a system is under study, for exploratory purposes or to analyse the effect of changes to particular conditions, there are two options available. The first is to study the system itself, to change the physical characteristics and then observe the effects. The second option is to develop a model that allows experiments to be conducted without altering the system itself.

The first option is rarely achievable or even feasible, introducing changes to many systems is either too costly, too disruptive or even impossible, for example when designing a new factory. In many situations, it is therefore desirable to construct some kind of model to represent the system in question.

2.2.2 Different Types Of Model

According to Pidd (1984), there are two types of models, physical and mathematical. Physical models consist of plastic car mock-ups in wind tunnels, scale models of architectural designs, and scale boat hull designs. These models are typically employed in design or analysis situations where the primary consideration is that of physical or functional characteristics.

Mathematical models, such as queuing networks, cash flow forecasts and mechanical equations are concerned with logical and quantitative characteristics of systems. One of the most simple mathematical models is the equation v=d/t. This equation allows us to predict the velocity of an object if we know how far it has travelled and how long it has taken. This mathematical model is also analytical. By employing algebra we can re-arrange the equation to determine a value for any of the three variables if we know the value of the other two.

The problem with many real world systems is that the degree of complexity inherent in their logic means that it is impossible to derive an analytic mathematical solution. In these instances, it is necessary to employ simulation.

2.2.3 Simulation Models.

Three dimensions can describe simulation models.

Static / Dynamic

Static simulations either represent a system at a single point in time or a system in which time has no role.

Deterministic / Stochastic

Deterministic simulation models contain no random characteristics. On the other hand stochastic models contain elements of probabilistic behaviour. Queuing systems are generally modelled with some stochastic behaviour.

Continuous / Discrete

The definition of a continuous or discrete model is the same as the respective system descriptions given above. However, many continuous systems can be simulated by discrete models and vice-versa. The choice between one method and the other is motivated by the objective of the study. Law and Kelton (1996) refer to the example of a model of traffic flow along a road. If the objective were to observe the behaviour of single vehicle, then a discrete model would be the only viable technique. However, if the objectives considered the vehicles as an aggregate and were interested in observing flow rates under different conditions, then the system would be best described as a continuous model of differential equations.

The focus of this study is on the use of simulation in the analysis of discrete part manufacturing systems. The type of simulation models developed for most of the applications in these systems are discrete, dynamic and stochastic and are called discrete-event simulation models. Unless indicated otherwise, any model referred to in this study is a discrete event simulation model.

2.2.4 The Benefits of Using Simulation in Industry

Simulation is one of the US industry's most used operational research techniques (Lane, Mansour, Harper 1993). A survey of UK manufacturing industry (Simulation Study Group 1991) summarised the key benefits gained by the deployment of simulation.

1. **Risk reduction**
2. **Greater understanding**
3. **Operating cost reduction**
4. **Lead time reduction**
5. **Faster plant changes**
6. **Capital cost reduction**

These benefits were realised by the deployment of the technique to support the following applications.

Base = 65 Current/Past Users	%
Plant Layout and Utilisation	77
Analysing Material Control Rules	66
Analysing Required Manning Levels	65
Short Term Scheduling and Loading	60
Capital Equipment Analysis	52
Line Balancing	51
Inventory Evaluation and Control	49
Information Flow Analysis	40
Process Definition and Analysis	35

Table 2.1 - Deployment of simulation in industrial applications

In the US, the most common application for simulation is design (facility design, system developments and design), closely followed by research (product development, industry modelling) and then scheduling (shop floor workflow analysis, prioritising) (Cochran et. al. 1995).

A significant proportion of each annual Winter Simulation Conference is devoted to the successful deployment of simulation in manufacturing industry. Many papers and books have been published describing the use of simulation in many different industrial applications (Table 2.2).

Focus of publication	Authors
Operational Control and Planning of Press Shops	Battacharyya and Roy (1988)
Design and planning of Flexible Manufacturing Systems	Carrie (1988)
	Goodhead and Mahoney (1985)
Planning for JIT production	Chararbaghi, Davis and Minett (1989)
Simulation for control of advanced manufacturing facilities	Chrystall, C.N. Nurse and Kaye(1990)
	Law (1986)
Simulation for evaluating manufacturing planning and control strategies	Dunham and Kochar (1981)
Simulation based scheduling	Feuer, Givon and Dar-El (1989)
	Grant (1986)
	Jain (1975)
Visual Simulation for Industrial Management	Hurrion (1980)
Simulation in low technology industry	Townsend. Lamb and Seth (1988)

Table 2.2 – Documented Simulation Applications in Manufacturing Industry

The survey (Simulation Study Group 1991) concluded that UK manufacturing industry could save a potential £ 64M per annum through the wider deployment of simulation.

2.2.5 Obstacles and Problems encountered in the use of computer simulation.

Despite the many benefits of using simulation outlined in the previous section, the use of the technique in the UK when compared with other enabling technologies has been low. The recent survey on the use of simulation in UK manufacturing (Simulation Study Group 1991) discovered that simulation has only been deployed by 9% of the manufacturing companies in the survey. This figure is far lower than other technologies such as MRPII, which had been employed by more than 50%.

In the US, despite a wider deployment of the technique, stories concerning disasters and unsuccessful projects are as common as those detailing success (Cochran et al. 1995).

The reasons for the lack of success in simulation projects are many. Among the major obstacles to the wider use of simulation are a low awareness of the technique and lack of knowledge concerning how simulation can be applied (Simulation Study Group 1991). These obstacles where further compounded by a lack of training, a lack of appropriate skills,

difficulties in obtaining data, the speed of model development and the high cost of simulation software. These findings are supported by the work of Cochran et al. (1995) who report that the lack of a technical background, the need for dedicated personnel, and a lack of training were the main factors contributing to the lack of success. Townsend, Lamb and Seth (1988) lament the "paucity of literature on the subject (model creation)"
This conclusion is supported by the Simulation Study Group (1991) who add that for a project to succeed, a simulation model builder must be able to define:

- The problem to be solved.
- The control parameters.
- The process logic.
- The control logic
- The performance measures

The studies conducted by Cochran et al. (1995) led them to propose that the success of a project is more dependent on methodology than on the software tools employed. This view is supported by Law and McComas (1989) who argue that simulation projects are far more than an exercise in computer programming and that the literature places too much emphasis on software selection and model coding. They estimate that model coding represents only %30 to %40 of the total effort input by the modeller. Regarding modelling they list a number of pitfalls that can occur.

- Failure to have a well defined set of objectives
- Inappropriate level of model detail
- Failure to interact with management on a regular basis
- Insufficient simulation and statistics training

These conclusions suggest that manner in which a project is carried out is a significant factor in the success of a project. The following section details a number of documented approaches for conducting a simulation project.

2.3 Procedures for Conducting a Simulation Project

The process of conducting a simulation project has been documented by a number of practitioners since the early days of the technology. This section details a number of these documented approaches to conducting projects. Whilst modellers do not always use the same terminology, Banks (1986) and Robinson (1994) amongst many others have noted that there are certain concepts that are common among the different descriptions. These similarities and the differences between the procedures are discussed, followed by an analysis of their shortcomings with respect to the reasons for the failure of projects outlined in the previous section.

2.3.1 Law and Kelton's Procedure

One of the most cited texts concerning simulation is by Law and Kelton (1991). In their book, they propose a series of twelve steps that compose a typical simulation study (Fig 2.1). They state that a simulation study is not a sequential process, but as a project progresses, it may be necessary to return to earlier steps as a greater understanding of the system is gained. They give an example where the problem in question is re-formulated in the light of new insights into the system.

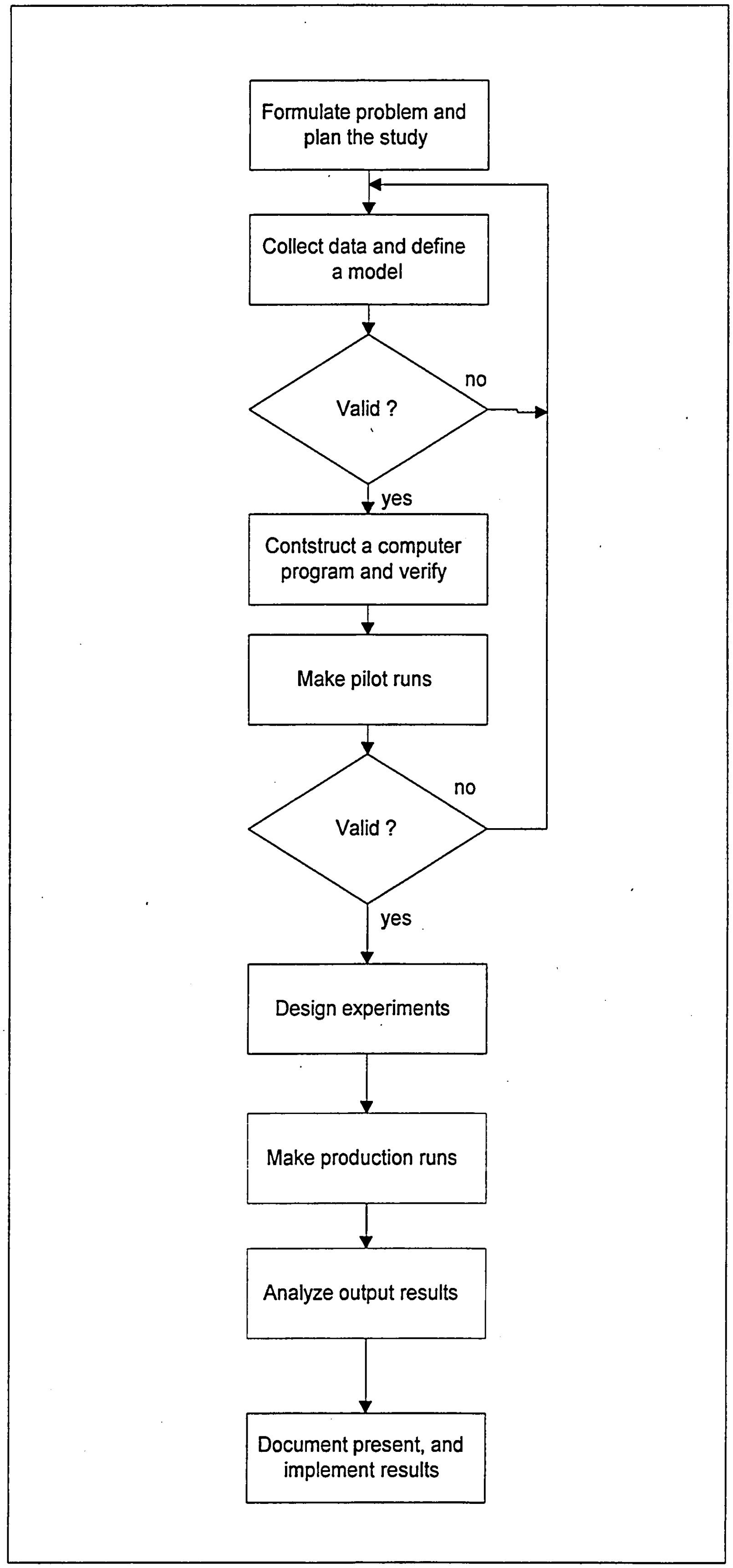


Figure 2.1 - Steps in a Simulation Study (Law and Kelton)

Steps of a study

1. *Formulate the problem and plan the study.* This step involves stating the objectives of the study and the development of a plan, which states the required number of people, the cost of the study and the time required for each aspect of the study.

2. *Collect Data and Define a model.* If the system exists, the function of this step is to collect data used to specify operating procedures and probability distributions for random variables used in the model. They state that the construction of a model is *as much of an art as it is a science* (pp 106-107), and follow by suggesting that it is good practise to begin with a moderately detailed model to avoid excessive costs involved in the programming and execution of a model with excessive detail.

3. *Valid ?* - Although the authors believe that validation is something that should be carried out throughout the entire study, they propose that there are a number points during a study where validation is particularly appropriate. Attention is drawn to the concepts of the actual validity of the model itself and of the model credibility to the decision maker. To achieve validity and credibility, it is important for the modellers and analysts to involve the decision makers and models users on a regular basis.

4. *Construct a computer program and verify.* The modeller is faced with the choice between programming a model in a general purpose language or a simulation language.

5. *Make pilot runs.* Pilot runs allow the modeller to conduct a process of sensitivity analysis of input data to determine the accuracy of input data and to compare output data to values from the real system.

6. *Design experiments.* To evaluate different system designs, it is necessary to design experiments to test the system. The authors note that often, a complete decision regarding the number and type of experiments to be conducted at this stage, but data from experiments will generate additional experimental requirements.

7. *Make production runs.* The model is run to generate performance data for each experiment.

8. *Analyse output data.* The data produced in the previous step is analysed using statistical techniques. Confidence intervals can be constructed and data from different systems can be compared.

9. *Document. present, and implements results.* The assumptions that go into models and the computer program itself should be documented so that simulation models can be re-used. If results are not implemented if the study is not be a failure.

2.3.2 Pidd's Procedure

In a number of publications (Pidd 1984,1992, 1996), Pidd presents three key phases in computer simulation.

1. **Modelling**
2. **Computing**
3. **Experimentation**

Believing simulation to be an experimental approach, he (Pidd 1989) considers modelling and programming as preliminaries to *the real business of simulation*, that of experimentation. However, despite this fact, he acknowledges that the three phases may be difficult to separate in practise and suggests that it would be foolish to ignore the implications of programming a particular type of model. His experience suggests that experimentation often leads to changes in the model and in the computer program, and concludes that the three phases are *intimately linked*.

1. Modelling

The discussion of modelling focuses on validity, comparing the two methods of black box and white box validation. The former being the ability of the model to produce output data that accurately reflects the that of the system being modelled. One of the problems with this method is that the model may be carried out because something is going wrong with the system, or in an even worse situation, where the real system does not exist and there us nothing to which the results of the model may be compared against.

The second method is that of white box validation, which according to the author, is a method of determining whether the components of the model exhibit known behaviour or any valid theory which exists such as typical patterns for queues.

This section finishes with a sentence stating that the modeller/analyst should know the system well enough to conduct "face validation", otherwise no amount of sophisticated programming or statistical wizardry will prevent disaster.

2. Computing

The author describes two different approaches to the development of a computer model using different software. The first, a data driven approach is described using an example of HOCUS and Xcell+, two simulation software packages. This approach is considered suitable for simulating simple systems and where the modeller/analyst has limited computer programming ability. The second approach is required to model more complex systems and requires the use of a bespoke program written in one of the simulation languages (SIMSCRIPT, SIMULA, ECSL, or SIMAN) or a general purpose language such as C, Pascal or FORTRAN.

3. Experimentation

Experiments must be planned so that the factors which may influence the results may be identified. It requires that the analyst be familiar with a number statistical methods for analysing simulation models. The author describes how Visual Interactive Simulation Software (VISS) can be used to conduct interactive experiments where the simulation model can be halted, some parameters changes and then continued, so observe the effects of these changes.

2.3.3 Gass's Procedure

Although Gass's work was concentrated in the public sector for research on public policy decision problems, his work carries over into the private sector. He believes that a life-cycle view should be imposed on any modelling project and proposes the following thirteen steps.

1. Embryonic (initiation)
2. Feasibility
3. Formulation
4. Data
5. Design
6. Software development
7. Validation
8. Training and education
9. Installation
10. Implementation
11. Maintenance and update
12. Evaluation and review
13. Documentation and dissemination

He then goes on to draw parallels between the cycle of model development and that of software development. Drawing analogies between modelling and the program development cycle and the waterfall model of the software Life-Cycle and suggests that modelling projects should have the same degree of rigour.

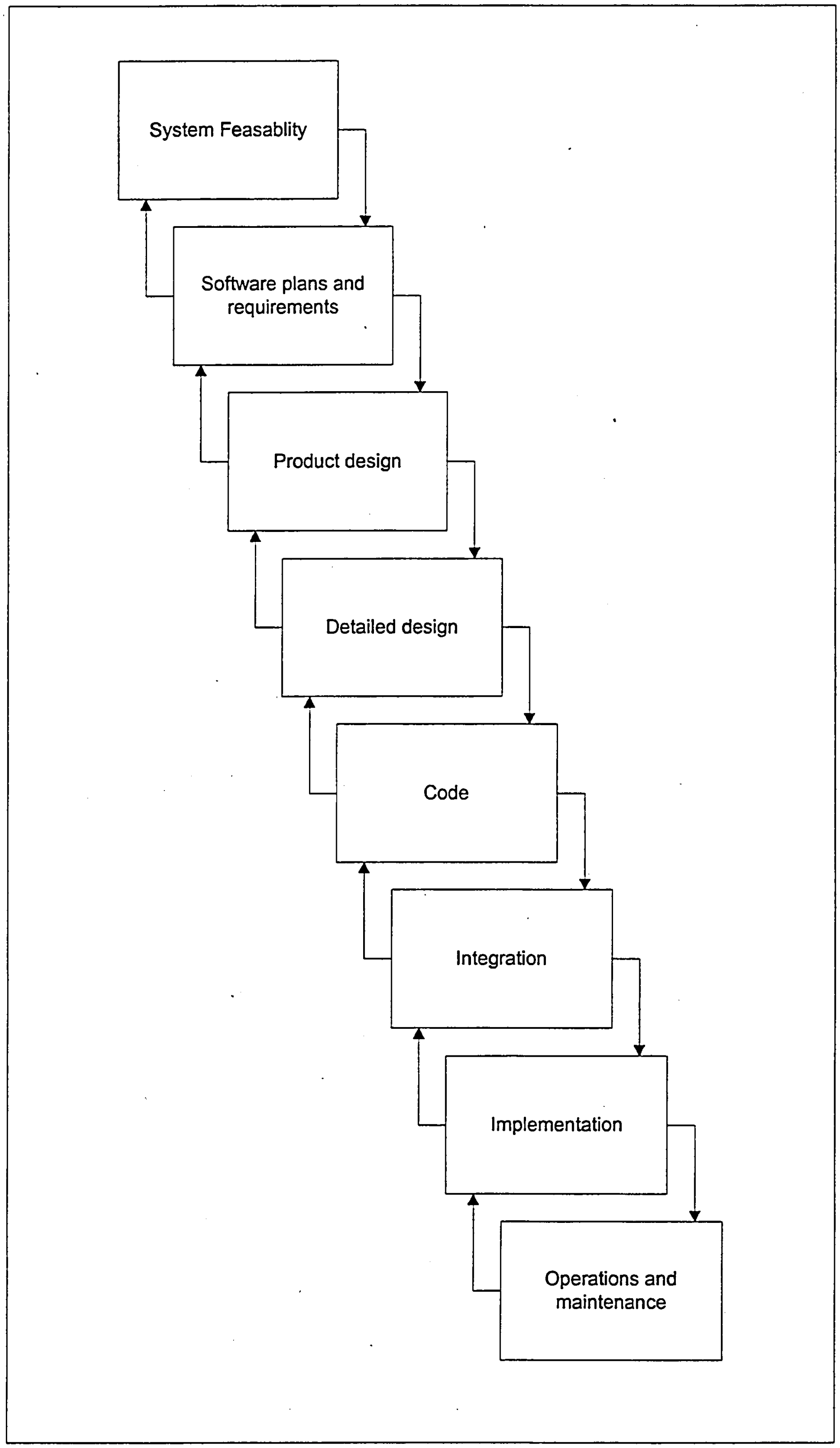


Fig 2.2 - The waterfall model of software development (Boehm 1981)

2.3.4 Banks' Procedure

The majority of Banks work has concentrated on the verification and validation of simulation models. However, in order to illustrate where they should be carried out he describes a five step process to simulation modelling derived from what he believes to be the common threads of other descriptions.

Step	Title	Process
1	Initialisation	Where the problem is defined and the necessity and feasibility of the simulation are determined.
2	Plan	A means of attacking the problem.
3	Detailed Design	This design consists of the computer code that is implemented during the simulation.
4	Testing	Test the simulation
5	Operation and Maintenance	The tested model can be delivered to the client for use

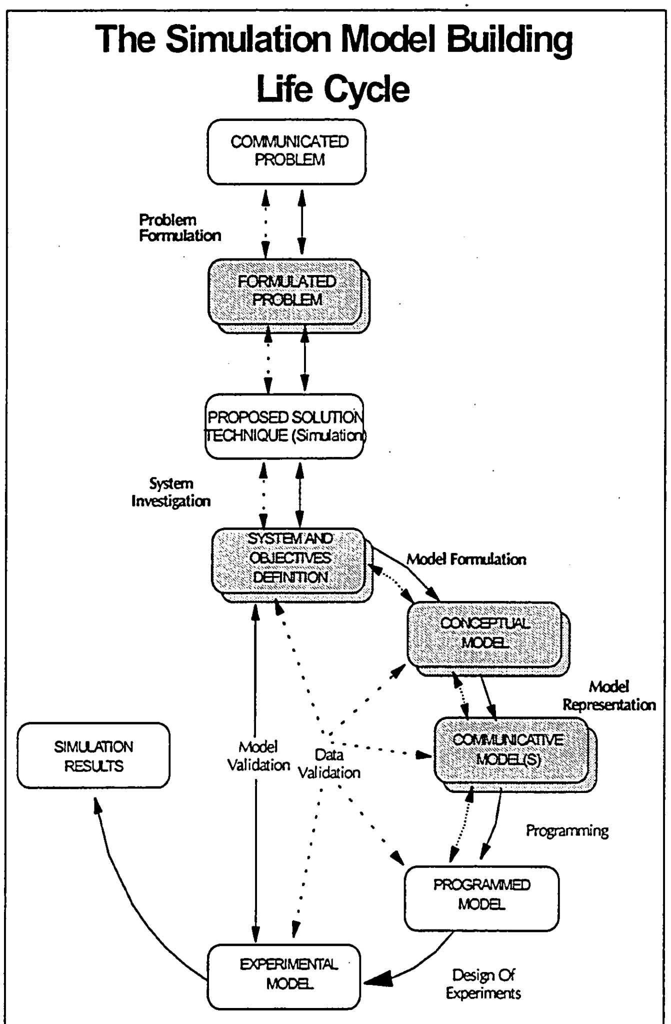
Table 2.3 – Banks' Procedure for Simulation Modelling

Banks notes that the above steps give the impression that the model is only evaluated only during the testing phase. He goes on to state that validation and verification should take place at a series of stages throughout the life cycle of a project to ensure that the model is simulating the real world problem and that the computer code to implement the simulation is correct.

A model of the simulation life cycle that Banks considers to be an excellent learning tool and which thoroughly describes a proposed modelling process is that of Balci and Nance (1985). This is described below

2.3.5 Balci and Nance's Procedure

In recent years, the work of Balci and Nance (1990) concerning the validation and verification of simulation models has gained widespread popularity and is cited in many texts and periodicals. Their description of the simulation life cycle can be seen in figure 2.3. It consists of ten phases, each phase representing an outcome one of ten processes, indicated by the arrows connecting each phase. A brief description of each process is given and it is argued that the overall life cycle is not a sequential process, but that reverse steps may taken when errors occur. Much of their subsequent work has dealt with issues of validation and verification at various stages in the life cycle, in particular identifying which verification and validation techniques are appropriate during the different phases.



Based On: The Life Cycle of a Simulation Study. Balci [1990]

Figure 2.3 – Balci and Nance's Procedure

2.3.6 Sargent's Procedure

Sargent (1984) developed a concept, which he calls "A simplified version of the Modelling Process" as shown in Figure 2.3 below. This describes the modelling process as a circular activity with the main emphasis on verification and validation at various stages throughout the cycle.

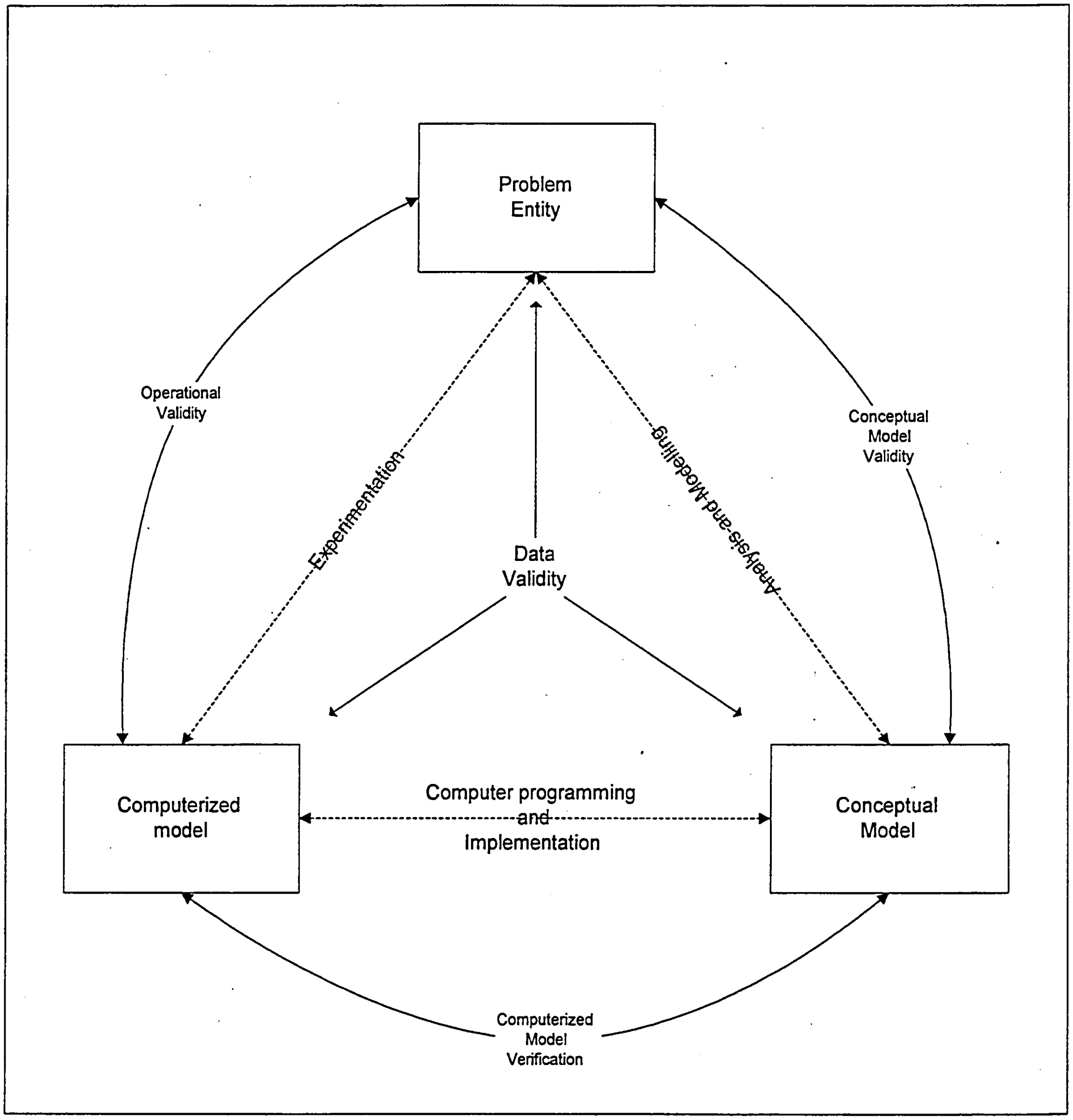


Fig 2.4 - A simplified version of the modelling process (Sargent 1994)

According to Sargent validation of a conceptual model is achieved by conducting statistical analysis on the assumptions underlying the model to ensure that they are correct. The primary technique for performing this should be face validation.

He believes that the validity of data is of high importance in achieving a successful simulation model, however, he does not believe that there is much that can be done to ensure this fact beyond developing good data collection procedures, screening for outliners and to develop good procedures for maintaining the collected data.

To ensure computerised model validity, he suggests that the tests developed for software engineering such as top-down design and structured programming should be employed.

He finishes with recommendation that the following five steps are taken as a minimum requirement to ensure model validation.

1. An agreement should be made between the modelling team, the sponsors and the model users on the basic validation techniques to be used prior to developing the model.
2. The assumptions and theories underlying the model should be tested, when possible.
3. In each model iteration, at least face validity be performed on the conceptual model.
4. In each model iteration, explorations of the models behaviour be made using the computerised model.
5. In at least the last model iteration, comparisons are made between the model and the system behaviour (output) data for at least two sets of experimental conditions when possible.

Validation is discussed in the model documentation.

2.3.7 Robinson's Procedure

Robinson (1994) presents a simple four phase representation of a simulation project. Figure 2.4 shows how these phases fit together in terms of the non-sequential nature of a simulation project. He proposes that a successful study must always begin with a definition of the problem and finish with the implementation of the project findings. However, he stresses that the movement between phases is not always downward and that upward movement will occur as both the simulation model and the system being modelled is understood further.

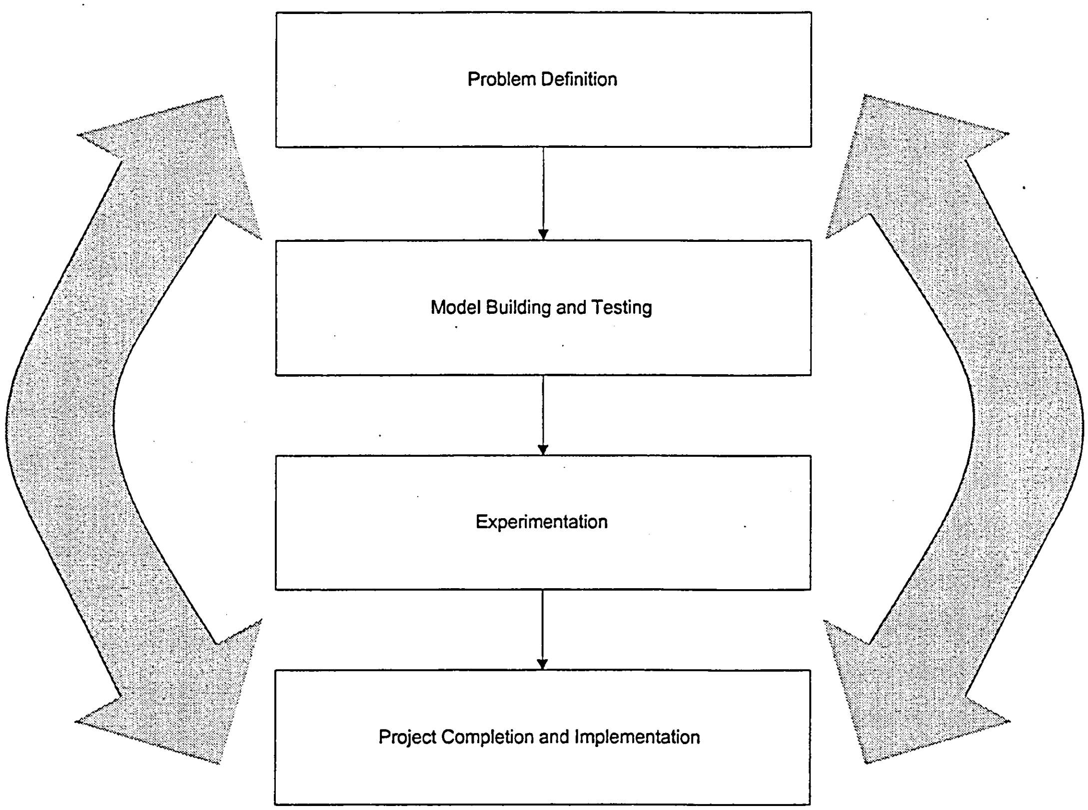


Figure 2.5 - An overview of a simulation project [Robinson 1994]

This section is not exhaustive, as it would be a significant task to summarise all the documented approaches to simulation. A number of the major authorities have been cited here, however, many other authors have described the process of conducting a simulation project, among them are Askin and Standridge, C. (1993), Shannon (1975, 1981), Bakalem and Habchi (1994), Wadsack and Tobias (1994).

2.4 A Comparison and Evaluation of the Documented Procedures

2.4.1 Evaluation of procedures

In section 2.2.4 above, a number of factors were listed that have been identified as reasons for the failure of simulation projects.

- Failure to have a well defined set of objectives
- Inappropriate level of model detail
- Failure to interact with management on a regular basis
- Insufficient simulation and statistics training
- Difficulties in obtaining data
- The speed of model development

Another factor is that the modeller must be able to define the following:

- The problem to be solved.
- The control parameters
- The process logic
- The control logic
- The performance measures

It is possible to group some of these factors together into a set of issues, which have an impact on the success of a project.

- Defining the problem to be solved and defining objectives
- Defining the logic of the model
- Collecting data
- Timely model development
- Interaction with management

Despite their strengths where model programming and statistical validation and verification are concerned. All the approaches documented above provide little guidance on how to:

- Develop an understanding of the problem(s) to be addressed.
- Formulate objectives.
- Determine the most appropriate viewpoint for developing the model.
- Decide which elements of the system to include in the model.

Robinson (1994) does provide a Case Study with Natland Bank which provides some specific examples of how to address some of the issues listed above. In order to understand the problem, a series of interviews was carried out with a cross section of staff and managers. The problem was then agreed by the team as well as a set of objectives which included performance measures related to the problem. These performance measures enabled the modeller to identify what data should be collected.

In summary, most of the currently documented procedures identify the practical issues facing a modeller interacting with a client and developing a simulation model, but do not provide sufficient guidance on how to successfully overcome these potential pitfalls.

Research Question 1 - "What do modellers do prior to experimentation ?"

2.4.2 Developments in Simulation Software

A number of the documented approaches were developed prior to the increase in desktop computing power in the mid to late 1980's. This increase in computing power was mirrored by development in Visual Interactive Simulation Software (VISS). The main driver behind the development of VISS was stated by Hurrion (1978) as :

"by watching a simulation model progress through time and having e ability to interact with it, the user can improve his analysis and understanding of the original problem situation.. the decision maker can watch the progress of the model and can himself contribute to the validation of the model"

The study conducted by the simulation study group (1991) discovered that much of the software employed by modellers today has the ability to produce animation's of the models during execution and many packages use a graphical interface for model development, in some cases, the animation and the model are combined in a fully interactive environment. Bell and O'Keefe (1994) conducted a study on VISS from a methodological perspective and conclude that visual interactive simulation is an approach to problem solving that suggests a very different approach for simulation projects than traditional simulation modelling. They go on to suggest that it is a more "exposed" approach to model development, just as a prototyping approach to systems development is riskier than formal systems development methods. However, in the same way that a formal method can produce a well crafted system that solves the wrong problem, traditional simulation approaches can produce models of the wrong problem.

They suggest that VISS encourages and perhaps even forces intense end-user involvement in the design and development of simulation models. It increases the probability of modelling the real problem at the correct level of detail with all the assumptions understood and validated by the end-user resulting in the initiation of meaningful decisions.

The development of simulation models using VISS is an area that is under researched in comparison with other areas of simulation. Very little is understood about how people develop simulation models and how modellers interact with decision makers and few simulation researchers have yet considered most of what goes on prior to the formal analysis of a valid simulation model.

Given that the procedures for model development discussed in the previous section were developed prior to the increase in the use of VISS, a question must be raised asking whether they reflect the current approaches to the development of simulation models when the majority of simulation models are developed using a VISS.

Research Question 2 "What impact has the increase in use of VISS had on the life cycle of simulation projects and the activities of modelers and clients ?"

2.4.3 Model Representation

In most of the model development procedures explored in section 2.6 above, a conceptual model is typically represented in some way prior to being coded. A conceptual model can be represented in a number of different ways.

Ceric and Paul (1994) identified a number of reasons for graphical model representation and also classified different approaches and methods that have been employed for this task. Their reasons are listed below.

- Conceptually connected objects can be represented by physical proximity;
- Interactions between objects can be shown in two dimensions (compared with the sequential nature of procedural statements);
- The parallelism of the human visual system enables the easier comprehension of the model;
- The syntax and semantics of these methods are mostly rather simple;
- Hierarchical descriptions of the model are often enabled;
- Manual simulation using diagrammatic models is usually possible (which is helpful for model validation).

They propose four different groups of graphical representation methods.

1. *Simulation strategy neutral methods*

According to the authors, these methods do not belong to any of the simulation strategies or to any simulation languages. Their neutrality enables their use with any simulation language. This group includes Petri Nets and Activity Cycle Diagrams.

2. *Simulation strategy oriented methods*

These methods inherit characteristics belonging to a particular strategy, but are not language specific. Event graphs are a good example of this kind of method.

3. *Simulation language oriented methods*

The most common methods in this group are GPSS block diagrams and SLAM networks. Each symbol in such approaches corresponds to a statement in a simulation language.

4. *Methods borrowed from other computer modelling areas.*

Entity relationship modelling is one such method that has been used for simulation model representation.

Although the traditional approach to simulation model development is still being used for large scale projects, many projects today are carried out using a VISS tool. Given that one of the functions of these tools is to enable interactive model development, it raises a question of the role of model representation when using VISS.

Research Question 3 "What is the role of model representation techniques in projects using Visual Interactive Simulation Software ?"

2.5 Summary of Research Questions

A review of the literature concerning the life cycle of simulation modelling has highlighted a need to understand and document the methodology employed by simulation modellers during the design and development of their models.

- **Research Question 1 - "What do modellers do prior to experimentation?"**

Further findings suggest that the model development methodology has been influenced by the increased use of Visual Interactive Simulation Software (VISS). The literature suggests that it has enabled a prototyping approach with more end-user involvement in model design and development.

- **Research Question 2 - "What impact has the increase in use of VISS had on the life cycle of simulation projects and the activities of modellers and clients?"**

In traditional simulation model development, a number of model representation techniques were employed to validate the model logic before the development of code. Given that VISS allows a modeller to develop the model logic and code simultaneously, what is the role of the model representation techniques?.

- **Research Question 3 "What is the role of model representation techniques in projects using Visual Interactive Simulation Software ?"**

Collectively they form a "topic" of research of which the primary focus is:

Understanding the methodology of simulation modelling in the light of Visual Interactive Simulation Software.

3. Methodology

This chapter describes and defends the methodology employed to answer the research questions developed in the previous chapter and places the work in the context of research methodologies developed and employed by other researchers. It outlines the spectrum of scientific research methods available to researchers and details and defends the rationale behind the selection of the methods employed in this study, in particular the concepts of multiple research methods and theory generation from a small number of case studies. Finally it reviews the development of the methods within the context of the research area, the evolution of and evaluation both theoretical and practical, of the research methods employed during the study.

3.1 Chapter Summary

Research methodologies employed

This section briefly summarises the rationale behind the selection of and the employment of case studies, questionnaire and action research. It is intended as an overview of this chapter.

The process of research

A review of the literature concerning the process of research, in particular the impacts of a deductive or inductive approach to solving a research question.

Justification for the paradigm and methodologies employed

With respect to the research questions developed in Chapter 2. This section details the rationale behind the selection of the research techniques employed.

The conduct and procedure of the research methodologies

A chronological overview of the development, application and evolution of the case studies, questionnaire survey and action research.

Strengths, limitations and post - study appraisal of the research methods employed

This section presents a practical appraisal of the methods employed

3.2 Introduction

With a bewildering array of data collection techniques, analysis tools and results reporting available to researchers, the initial stages of this study were devoted to the development of an effective research methodology. The rationale for the methodology was motivated by 2 main factors.

- The lack of published information concerning the procedure of expert model developers.
- The need to elicit knowledge, techniques and tools employed by the expert model builders to answer the research questions.

3.3 The research methodology employed

The methodology was composed of three different research techniques, a questionnaire survey, case studies with model builders and analysts and action research conducted with a collaborating manufacturing organisation. The rationale behind the selection of these techniques was determined by the nature of the research questions being of an exploratory nature. That is they were developed to seek an understanding and generate theory by inductive means. Three different methods were chosen in order to adhere to the principles outlined by (Eisenhardt, 1989), (Payne, 1964), (Yin, 1994) and many others . They suggest that deploying multiple data collection techniques not only maximises and strengthens the data collected, but provide a means of validating emerging theory and hypotheses.

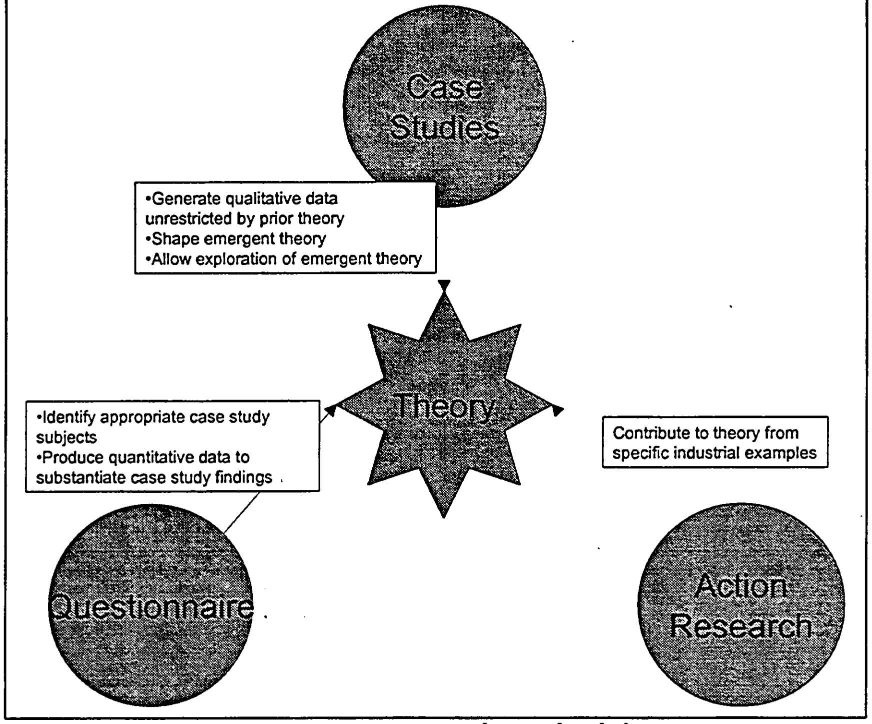


FIG 3.0 : Research Methodology

3.4 The Research Process

The process of research has a starting point in one of two forms. Deduction, where a theory is applied or tested against the processes it attempts to describe (Fig 3.1) and Induction where theory is generated from observation of a process (Fig 3.2).

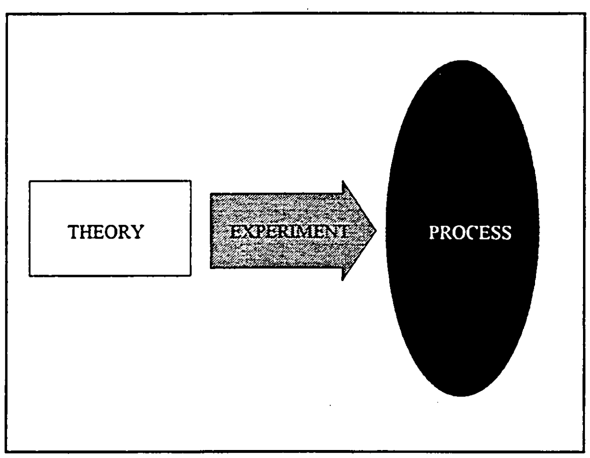


FIG 3.1: Deduction

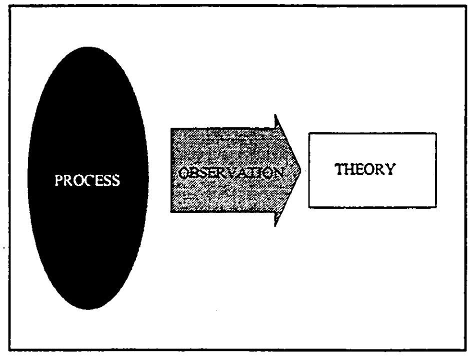


Figure 3.2: Induction

Gilbert (1979) defines induction as a means of generating theory and deduction as a technique for the application of theory. Despite methods being distinct, he adds that both are employed during research. Kolb et al (1979) propose a cycle of Experimental Learning (Fig 3.3) during which both methods are employed to make sense of the world about us.

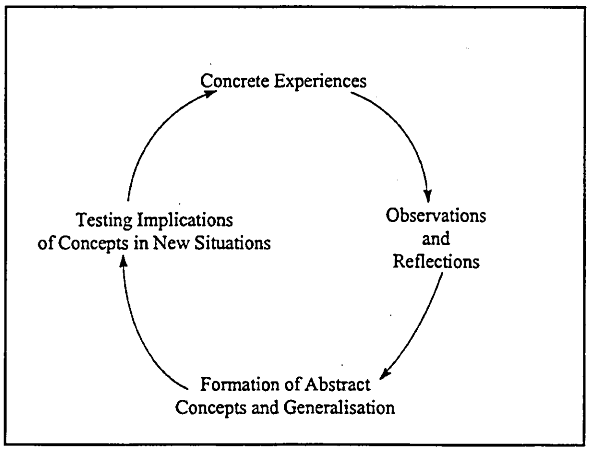


Figure 3.3 : Kolb's Experimental Learning Cycle

According to Kolb (1979), learning starts at one of two points. Either the individual starts with an experience of an event and then reflects upon that experience leading to the generation of explanations which can then be used to form an abstract rule or principle. These rules and principles can be generalised and applied to similar events. Or the individual starts with a rule received from others and is subsequently applied and tested out. In both cases, the testing of the rule in new situations creates new experiences which in turn enable observation and reflection and resulting in revisions to existing rules and the generation of new explanations and hence new rules.

Gill and Johnson (1991) describe the deductive research method as being the development of a conceptual and theoretical framework prior to its testing through empirical observation. In this sense, deduction corresponds to the left hand side of Kolb's (1979) experimental learning cycle (see Fig 3.3). The outcome of deduction is the generation of new experiences and observations. They then add that induction is the reverse of deduction as it involves movement from observation of the empirical world to the construction of explanation and theories about what has been observed. This process corresponds to the right hand side of Kolb's (1979) cycle. In contrast to deduction, the outcome of induction is theory.

Baker (1988) proposes that a scientific model is incomplete without both procedures and that it is difficult to separate the two in practise. However, he adds that researchers do not have to complete every stage of the process in a single research programme. It is possible to choose to move from observation to the generation of theory (inductive research) or to start with theory and test it (deductive research). This view is also supported by Eisenhardt (1989) who states that it is impossible to achieve an ideal of a clean theoretical state, but that in conducting inductive research this ideal should be approached as far as possible because pre-defined theory or perspective may bias or limit the findings.

It is possible to develop a continuum of research methods based upon their logical and procedural disposition to deductive or inductive research. Table 3.1 is based upon a more detailed summary by Gill and Johnson (1991 pp 36) and lists the features of deductive and inductive research. Any research method assumes a position on a deductive/inductive continuum depending on its disposition to the characteristics listed in table 3.1 below.

Deductive methods	Inductive methods
1. Explanation via analysis of causal relationships and explanation by covering-laws.	Explanation of subjective meaning systems and explanation by understanding.
2. Generation and use of quantitative data	Generation and use of qualitative data
3. Use of various controls, physical or statistical, so as to allow the testing of hypotheses	Commitment to research in everyday settings, to allow access to, and minimize reactivity among the subjects of the research
4. Highly structured research methodology to ensure replicability of above characteristics.	Minimum structure as to ensure above characteristics.

Laboratory experiments, Quasi experiments, Surveys, Action Research, Case Studies, Ethnography

Table 3.1: Characteristics of Deductive vs. Inductive research (Gill & Johnson 1991).

A detailed explanation of the various research methods is unnecessary. However, an explanation of the rationale behind the selection of the chosen techniques is important.

3.5 Justification For the Inductive Paradigm and Research Methods.

To select the appropriate research methods, a close examination of the research questions was required to develop an understanding of the nature of information required to solve them.
To reiterate, the research questions developed during the literature survey (see Chapter 2) were as follows.

- **Research Question 1 - "What do modellers do prior to experimentation?"**
- **Research Question 2 - "What impact has the increase in use of VISS had on the life cycle of simulation projects and the activities of modellers and clients?"**
- **Research Question 3 "What is the role of model representation techniques in projects using Visual Interactive Simulation Software?"**

The questions all ask "what?" and "why?" According to many sources (Gill and Johnson, 1991), (Glaser and Strauss, 1967), (Yin, 1994), these type of questions are characteristic of inductive or exploratory research and therefore qualitative research methods are the most suitable to be employed in this situation.
Qualitative research involves first hand face to face observation or participation in the environment of the subject of analysis. Taylor et al (1984) refer to qualitative methodology as research that generates descriptive data in the form of peoples written or spoken words and observations. From this data, the researcher forms concepts, insights and understanding, hence qualitative research is inductive by nature.
However, a number of authors argue that inductive research methods produce both Qualitative and Quantitative data. Eisenhardt (1989) Worsley (1977) and Yin (1994) suggest that "triangulating" both types of data, strengthens and validates any emergent theory.

3.5.1 Summary of Research Methods Employed.

As stated above, other researchers have proved the utility of using multiple research methods to strengthen and validate theory.

3.5.2 Questionnaire Survey

In terms of the continuum of research methodologies (outlined in Table 3.1), survey occupies an intermediate position between ethnography and experimental research. This is due to the nature of the survey that is developed which is highly dependent on the objectives and according to Gill and Johnson (1991), the personal disposition of the researcher. Analytic surveys, which aim to test out the validity of causal relationships in a field context have a deductive basis and the development of such surveys share's many characteristics of the design of laboratory experiments. In these situations, the experimental variables such as sample size, data collection procedures, analysis and measurement scales are major concerns. In contrast, descriptive surveys have much in common with case study development, in that the aims are to generate a body of information from which insights and theory can be generated.

3.5.3 Case Study

The case study is a research method that has received considerable attention in recent years. It has been employed as a useful research technique by many authors including Baker (1988), Goode et al (1952), Glaser and Strauss (1967), Eisenhardt (1989), Miles and Huberman (1984) and Yin (1994). However, Eisenhardt (1989) summarised the procedure in the statements below.

- The case study is a research strategy, which focuses on understanding the dynamic present within single settings.
- Case studies can involve either single or multiple cases.

A summary of the process of case study research is given by Eisenhardt (1989) and is outlined in the table below.

Step	Activity	Reason
Getting Started	• Definition of Research Questions • Possible a-priori constructs	• Focuses Efforts • Provides better grounding of construct measures
Selecting Cases	• Specified Population • Theoretical sampling	• Constrains extraneous variation and sharpens external validity • Focuses efforts on theoretically useful cases which extend theory
Crafting instruments and Protocols	• Multiple data collection methods • Qualitative and Quantitative data combined	• Strengthens grounding of emergent theory • Synergistic view of evidence
Entering the field	• Overlap data collection and analysis including field notes • Flexible and opportunistic data collection methods	• Speeds analysis and reveals adjustments to data collection • Allows investigators to take advantage of emergent themes and unique case features
Analysing data	• Within-case analysis • Cross-case pattern search using divergent techniques	• Develops familiarity with data and preliminary theory generation • Forces investigators to look beyond initial impressions and see evidence through multiple lenses
Shaping Hypotheses	• Iterative tabulation of evidence for each construct and question • Replication not sampling, logic across cases • Search evidence for "why" behind relationships	• Sharpens construct definition, validity and measurability • Confirms, extends and sharpens theory • Builds internal validity
Enfolding Literature	• Comparison with conflicting literature • Comparison with similar literature	• Builds internal validity, raises theoretical level and sharpens construct definitions

Table 3.2 The Process of Theory Generation from Case Study Research (Eisenhardt 1989)

A generic description of each stage is unnecessary at this point. However, a detailed explanation of the conduct of each stage in this study is given in section 3.5.2 below.

3.5.4 Action research

Action research defined by Gill and Johnson (1991) as "research projects which are undertaken to solve specific managerial problems and, at the same time, to generalise from the specific and to contribute to theory". The role of the researcher differs from basic case study research in that the researcher is interacting with the organisation in a role similar to that of a consultant. However, in consultancy, the client or organisation presents a set of problems and defines goals inviting the consultant to solve them. Whereas in an action research situation, the definition of problems and their solution is a collaborative effort.

The concept is best illustrated by examples.

- A study of the day-to-day problems experienced at the manufacturing plant of the Glacier Metal Company (Jaques, 1951);
- A research investigation into the factors contributing to the growth of the small business which, at the same time, was designed to help those managing the small business which provided the data (Gill, 1985).

(Source : Gill and Johnson ,1991 : pp 62)

3.6 The development and conduct of the research methods during the study.

The three methods were developed with respect to the aims of the study and the research questions.

3.6.1 Questionnaire development and deployment.

The questionnaire was the first method to be developed and deployed in the study. The aim was to gather information both quantitative and qualitative to provide further insight into the research questions and to generate data upon which to develop the case study protocol.

The objectives of the questionnaire were as follows:

- To gather general information on practising modellers, for example, their professions, where they first encountered simulation, how they learned simulation. – To provide a basis for interpreting the data collected.
- To investigate their opinions on the development of simulation models which stages in terms of difficulty time and effort. – To provide data to answer research question 1 and 2.
- To discover what representation techniques were employed in model design. – To provide data to answer research question 3.
- To discover how often the project objectives changed and the reasons for such. – To provide data to answer research question 1.

These objectives call for a descriptive survey rather than analytic as there is no testing of hypotheses and the objectives have an exploratory orientation.

The questionnaire survey was conducted over three days at the 1994 Winter Simulation Conference. The conference is the largest annual gathering of simulation professionals in the world, attended by leading academics and practitioners from all disciplines in simulation.

3.6.2 Development and Conduct of the Case Study Strategy and Protocol

Employing the strategy developed by Eisenhardt (1989) summarised in Table 3.2 above, and the techniques outlined by Yin (1994) a case study strategy and protocol was developed as described in section 3.6.5.

3.6.3 Getting Started

The aim of the case studies was to provide qualitative data to answer the research questions (chapter 2).

Eisenhardt (1989) discusses the use of "a-priori" constructs as being of assistance in focusing the case studies and to provide triangulating measures upon which to ground emergent theory, but warns that these constructs should only be employed as indicators for exploration and as such, researchers should be aware of the dangers of bias and selectively altering data to fit existing theory. To this end, a combination of the terminology employed by Balci & Nance (1986), Pidd (1984), Fishwick (1995) was used as a basis for the development of the case study protocol.

- **The Problem** - The situation to which simulation is being applied to provide a solution.
- **Conceptual Model** - A mental model of the system.
- **Model Representation** - Any model that exists external to the mind of the modeller and is not an executable computer program.

3.6.4 Selecting Suitable Case Study Subjects

The concept of population is as important in inductive research as in a theory testing or deductive study. This is because the population determines the sample of people or observations from which the research is developed. The selection of an appropriate population is also crucial in defining the limits for generalising the findings of research. In theory testing studies, the sample is a random selection from a pre-defined population. The aim of this sampling is to acquire accurate statistical evidence for the distribution of variables to support generalisation for the population as a whole.

However, when conducting inductive and theory building studies, random sampling is neither necessary nor desirable. Pettigrew (1985) notes given the limited number of cases that can be studied, it is sensible to choose cases in which the objects of study are "transparently observable". This approach, often termed theoretical sampling, is based upon the notion that cases are chosen to fulfil one of the following criteria.

- Replicate previous cases.
- Extend emergent theory.
- Fill theoretical categories.
- Provide examples of polar types.

The intention of theoretical sampling is to therefore select cases that are likely to replicate or extend emergent theory.

With this concept in mind, it was decided that a random sample of cases from industry and academia would probably be a fruitless and time consuming task. Therefore a set of criteria for selecting appropriate case study subjects was developed.

- They must currently be or have been engaged in developing simulation models for business and industrial applications in a commercial capacity, or if an academic, in a collaborative practical role with industrial partners.
- Considerable experience in developing a variety of models in different situations.
- Willing to be interviewed subject to confidentiality agreements.

Locating and identifying suitable candidates was carried out by a number of means.

- Promoting the study via a simulation software vendor gave us a number of willing subjects.
- The comp.simulation newsgroup on the internet.
- A presentation on the study at a simulation software user group.
- Personal contacts in industry.

When a contact was established, a short telephone questionnaire (see section 3.5.2-3 below) was administered to elicit information to determine the suitability of the candidate as a case study subject before a date was set for a face to face interview.

3.6.5 The Case Study Interview Protocol

The discipline of knowledge elicitation for expert systems development provided a source of techniques for data collection. Welbank (1983) developed a matrix of "Types of Knowledge" versus "Knowledge Acquisition Methods" (Figure 3.4) from which one can select suitable techniques.

The knowledge that the case study questions focus on can be described in the following terms.

- Facts
- Rules
- Procedures
- Experts Strategy

Employing Welbank's (1983) matrix (Fig 3.4), the techniques suggested to elicit these knowledge types are:

- Interviews
- Talking through specific examples
- Observing protocols

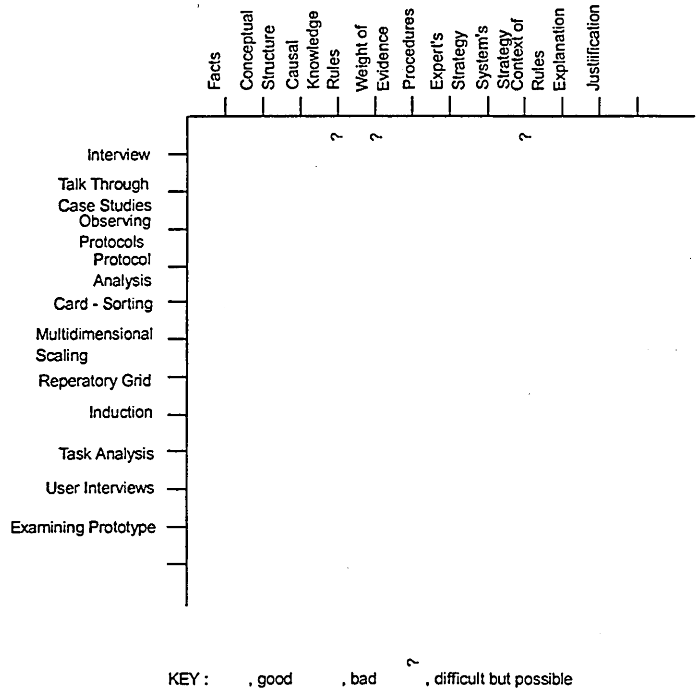


Figure 3.4 - The Knowledge Acquisition Matrix (Welbank 1983).

The literature survey concluded (Chapter 2.4) that the terminology employed modellers differs to a considerable extent. As a result, a set of standard questions to be delivered to each case study subject would be inappropriate for a number of reasons.

- It would incur what ethnographers have termed "translatative bias" where meaning can become distorted when interview subjects are forced to use unfamiliar terminology.
- Any pre-selected terminology would impose a pre-defined structure during the analysis, increasing the possibility of preordained perspectives and propositions biasing and limiting the results.

With these problems in mind, Wood and Ford (1993) describe a technique for structuring interviews to prevent translatative bias. Their approach consists of two stages, the first called descriptive elicitation, is employed to derive the terms and concepts used by the subject. This is then followed up by a second structured expansion stage in which the subjects are interviewed using their own terminology and concepts elicited during the first stage.

With this technique in mind, a three stage interview process was employed to conduct each case study, outlined in table 3.3 below.

Stage	Details
1 - Telephone Questionnaire	To capture details of subject i.e. Consultant, In-House or Academic modeller. Nature of organisation, Modelling Experience etc.
2 - Descriptive Elicitation	General open discussion about personal history of subject with respect to simulation. Intended to elicit terminology and examples of projects to be referred to in the next phase.
3 - Structured Expansion	Questions concerning modelling procedure, techniques employed, tools used and views on difficulty etc. Conducted using the subject's own terminology.

Table 3.3 : The 3 Stage Interview Process.

All the case interviews bar one were conducted at the subject's place of employment. All the interviews bar one were recorded on cassette tape and transcribed verbatim
As this section is concerned with methodological considerations, Chapter 4 summarises the results of the case study interviews. However, as data collection and analysis overlapped, there was a degree of feedback into the interview protocol during analysis. This feedback is best illustrated by selective examination of the field notes taken during and after the case study interviews. The notes pertaining to the conduct of the interviews give an insight into how the protocol evolved throughout the case studies. In particular, the need to conduct a thorough descriptive elicitation phase to generate enough examples of simulation projects to discuss during the expansion phase. Table 3.4 lists a selection of field notes that were made following interviews with the case study subjects.

Case Study	Interview	Selected Field Notes
A	1	• Whiteboard was useful for sketching, although it would be better to be able to take them away to help interpret transcript.
B	2	• Not as good as previous interview, why? Went into this one fairly "cold" (the first interview had been conducted after lunch when much of the first interview phase took place informally). It was difficult to formulate questions without lots of modelling examples to refer to. Therefore, for next interview, need to discuss more examples.
C	1	• Felt a bit "out of my depth" as if my questions were a little naïve.
D	2	• Very good, though subject talked too much, conscious of difficulty of directing interview to address topics without curtailing explanation. • Subject appeared to have difficulty reflecting on abstract concepts.

Table 3.4: Selected Field Notes.

3.6.6 Data Analysis

The transcripts were analysed, with respect to the research questions. The first step was to identify a modelling procedure for each subject and then compare them to determine the similarities and differences. Following the identification of a procedure, the transcripts were re-analysed to search for knowledge, tools and techniques pertaining to the conduct of each stage.

3.6.7 The conduct of the action research with the collaborative organisation.

A local steel manufacturer who had links with the university via undergraduate industrial placements was approached with the aim of collaboration.
The company, which shall be known as Steel Ltd, was keen to improve their manufacturing facilities and felt that simulation was a tool that could assist.
As a simulation practitioner my experience was fairly limited. Two undergraduate projects one theoretical and another with a local business was the extent of my practical modelling experience. Developing models with real industrial and business requirements would be an ideal opportunity to carry out the following tasks.

- To explore the research questions and generate insights into the research area from a practical perspective.
- To consider the results of the case study findings in a real context.
- To consider the requirements of a modelling methodology from a position of novice simulation practitioner.
- To generate practical results for the benefit of the collaborative company during the research programme.

Over the course of the study, two simulation projects were conducted with Steel Ltd. Details of the projects can be found in the chapter 4.5.

3.7 Limitations and post study appraisal of the research methods.

The conduct of this study was not without problems and the researcher, like Morgan (1983) was struck by the notion that the "research was much more problematic than as presented in textbooks and that the results of scientific research must be much less solid than appeared from a reading of scientific reports". These problems were also noted by Becker (1965, pp 602-3) who notes that "the best laid research plans run up against unforeseen contingencies in the collection and analysis of data...No matter how carefully one plans in advance, research is designed in the course of its execution".
However, these problems must be considered in a positive aspect. The unexpected findings and occasional conflicting evidence of the different research methods all serve to inspire new ideas and ways of interpreting the collected data. This chapter has discussed research as a process of scientific learning and as such is subject to the old adage that you learn more from your mistakes than your triumphs. With this in mind, the final section presents the theoretical limitations of the research methods employed with reference to post-study appraisal of the conduct of the research.

3.7.1 Limitations of the research methods.

This section evaluates the strengths and limitations of the results from each research technique with respect to the aims of the study and the theory of research developed in Chapter 3.

3.7.2 Case Study Results

Without doubt, the greatest strength of the Case Study results is their richness. The sheer quantity of data contained provided a rich source of information that was mined for data referring to each of the three research questions of the study. As the transcripts were typed verbatim from the tapes they were free from any translatative bias by the researcher. This was particularly relevant later in the study as hypotheses were being redeveloped in the light of evidence gathered later in the study. They also provide a repository of evidence available to either replicate the results of the study, or for further analysis by other researchers investigating other research questions and hypotheses.

Despite their considerable strengths, the Case Study results have their limitations. The most obvious is the lack of quantitative data from the same sources to back up the qualitative results. To some, this could be interpreted as a lack of rigour. However, as discussed in Chapter 3, the study is on an exploratory nature, which demands the use of qualitative techniques. The use of Quantitative techniques would have skewed the results into the framework upon which such a technique was developed. Chapter 6 proposes further subjects for research. One such subject is to develop a quantitative research programme to test the conclusions of this research in a controlled environment.

In retrospect, the technique is very powerful and produces a considerable quantity of valuable information. However, great care must be taken both during the conduct of the case studies and the analysis of results to ensure that validity is maintained throughout and that the method remains firmly rooted in the contest of scientific process. The technique should not be recommended to those who dislike uncertainty, ambiguity and do not feel comfortable in an interview situation.

3.7.3 Questionnaire Survey

The questionnaire survey provided rich data concerning the current profile of the simulation modelling community. This was particularly useful in determining appropriate case study subjects, and allowed the transcripts of the case study interviews to be framed in the context of a larger community.

The primary limitation of the survey results was the information regarding the stages of the simulation life cycle. The use of a model of the simulation life cycle imposed a rigid framework to which the respondents had to translate their activities. The data from these questions is particularly suspect. However, in retrospect, this shortcoming actually supports the decision for a case study approach and supports the findings of the study as proposed in Chapter 6.

3.7.4 Action Research

The results of the collaborative research were deliberately not included in the findings against research question 1 to avoid biasing the results of the case study findings with those of the researcher/analyst who in no way qualified as an expert simulation modeller. However, rich findings concerning the use of the graphical interface and the impact this had on the project and the use of model representation techniques did emerge.

3.8 Concluding Remarks

This chapter has summarised the development and application of the research techniques employed to answer the questions posed in Chapter 2. The next chapter presents the results of the research techniques

4. Results of the Research Techniques

4.1 Chapter Summary

This chapter presents an overview of the data generated by research methods outlined in the previous chapter.

The objective is to present the collected data in a way that illustrates its internal validity. The details of the questionnaire survey results, descriptions of the case study subjects and summary of the action research projects are presented. The analysis of the data against each research question can be found in Chapter 5 (Analysis of data).

The conclusions of the analysis can be found in the following chapter (Chapter 6 Conclusions).

4.2 Introduction

Employing the research methods developed in the previous chapter a large quantity of data was collected. Survey results, large interview transcripts from the case studies plus observations relevant to the research questions from the action research.

4.3 Details of data sources

This section presents the details of the data sources employed in the study. The basis for choosing such sources is explored in chapter 3.

4.3.1 Questionnaire Survey

The questionnaire survey was conducted over three days at the 1994 Winter Simulation Conference. The conference is the largest annual gathering of simulation professionals in the world, attended by leading academics and practitioners from all disciplines in simulation.

A total of thirty questionnaires were completed and returned. However, a number of questionnaires were returned incomplete, the data from these has been left out of the quantitative results as it was felt that they could invalidate the data in some respects. However, comments of a qualitative nature were noted and collected.

Tables 4.0 to 4.6 present the summary data from questions addressing the background and experience of the respondents. The experience of the respondents totals over 200 years and has been mainly in manufacturing and industrial engineering. Approximately half the respondents learned the technique at university whilst the other half are mainly self taught.

Number of Respondents	Background
2	Business Management
5	Operations Research/Management
3	Systems Analysis
8	Manufacturing/Industrial Engineering
3	Others (Mathematics, Chemistry, Software)
21	(Total)

Table 4.0 - The Background of the Respondents

Number Of Respondents	Current Profession
1	Simulation Teacher
2	Systems Analyst
2	Research Student
2	Operational Researcher
3	Senior Manager
5	Simulation Consultant
6	Industrial Engineer

Table 4.1: Breakdown of sample by profession.

Number Of Respondents	Degree/Professional Qualification
1	Systems Analysis
1	Mechanical Engineering
5	Production/Manufacturing Engineering
7	Software Engineering
7	Operations Research
1	Other (Chemistry)

Table 4.2 - Education of Respondent

Number Of Respondents	1st Encounter
0	Vendor Presentation
1	Course at work
6	Project at work
16	College/University

Table 4.3 - Location of Respondents First Encounter with Simulation.

Number Of Respondents	Location of Learning
0	Short Course
2	Vendor Course
10	Self Taught
11	College/University

Table 4.4 - Where Respondents first learnt simulation.

Number Of Respondents	Length Of Time Building Models
9	Under 5 Years
7	5 to 10 years
1	10 to 15 years
3	15 to 20 years
3	Over 20 Years

Table 4.5: Length of Time Building Models

Number Of Respondents	No. of Models Built
12	<10
4	>10 <20
2	>20 <30
1	>30 <50
2	>50

Table 4.6 - Total Number of Models Built

4.3.2 Case Studies

The case studies were all individuals with considerable experience in the development and application of simulation in manufacturing industry. The individuals themselves were contacted via a number of different sources:

- Industry contacts
- Software vendor contacts
- Academic contacts

A total of 9 potential case study subjects were identified and reduced to a shortlist of 5 due to some not having the appropriate experience or being unable to participate in the study.

Tables 4.7 and 4.8 present the background and experience of the 5 case studies. The sum total of experience exceeds 40 years and includes over 90 commercial projects.

Case Study	Degree	Doctorate	Background	Current Position
A	Y	Y	Production / R&D	IC
B	Y	Y	OR and Simulation	AC
C	Y	N (In Progress)	Industrial Engineering and Simulation	AC/IC
D	Y	Y	Manufacturing	IH
E	Y	N (In Progress)	Manufacturing	AC/IC

Key - AC = Academic Consultant, IC = Independent Consultant, IHC = In House Consultant.

Table 4.7 - Case Study Subjects Background and Current Position.

Case Study	Years Modelling	No. Of Commercial Projects	Software
A	9	>11	Siman, Arena
B	8	>15	SeeWhy, Witness
C	10	>20	SeeWhy, Witness
D	20+	>25	Languages + Witness
E	8	>20	Siman, Arena, Grasp, Witness.

Table 4.8 - Modelling Experience of Case Study Subjects.

4.3.3 Action Research

Section 3.5.3 outlines the rationale behind the conduct of action research for this investigation and lists the aims of the collaborative research. This section presents a summary of the two simulation projects undertaken to provide a basis for the insights generated with respect to the individual research questions.

4.3.3.1 Organisational Summary and Background

The company, which for confidentiality reasons shall be known as Steel Production Products Ltd (S.P.P Ltd) is a subsidiary of a larger corporation. It's annual turnover is in excess of 60M per annum and it employs over 500 full time staff at it's three sites in the South Yorkshire.

It sells high value semi-finished super alloy bar to the aerospace, military, nuclear and offshore industries. Since the mid-eighties, there has been a shift in market characteristics from a narrow variety of product types produced in large batches for a small number of customers to a wide variety of product types produced in very small batches for large number of customers.

The existing production systems were developed during the period of large batches and low product variety. Consequently, the change in market manifested itself in the following characteristics.

- Increases in Work In Progress throughout the organisation.
- Wide variances in lead time for products - hence late deliveries.
- Increases in the number of changeovers and set-ups required.

The management implemented a company wide re-structuring programme to address the problems listed above. It was felt that simulation presented a tool for conducting analysis of change in particular areas.

4.3.3.2 Project 1 - The Finishing Area

The first project that was undertaken was an analysis of the finishing area where bars were machined, inspected and cut to length before despatch to customer.
An initial meeting concluded that there was a general lack of understanding concerning the causes of variation in throughput time in this area. Identification of bottleneck resources was also to be given consideration.
The project team consisted of:

- Production Director
- Production Manager
- Researcher/Analyst
- Senior Production Controller

An approximate project duration of six months was specified with a monthly meeting to monitor progress.

System Description

The finishing area consists of machinery for machining, cutting and inspecting bars before they are despatched to customers.
Resources include:

3 Saws, 3 Lathes
1 CNC Lathe, 2 Grinding Machines
Inspection Area
Aquasonic Testing Rig

A wide variety of part types are processed by the resources, yet all fall under 4 main part types.

1. Low Alloy Steels
2. Alloy Steels
3. Nickle Based Steels
4. Engine Shaft Material

Project Description/Summary

The intention was to produce a model of the finishing area to identify bottlenecks and the causes for the wide variation in the lead time of the main part types. No objectives were stated, as the problems were not clearly understood.

Discussions with the production controller enabled the process routes of the four material types to be determined including exceptions and re-work for inferior quality material.

There was little data available electronically concerning cycle times and production rates for the different material types apart from cutting times on the saws which were logged on the payroll system as the saw operators were paid on a "time spent cutting" basis.

4.3.3.3 Project 2 - The Forge Workshop

The shift in market characteristics outlined above resulted in the forge workshop manifesting itself as a bottleneck.

Plans were proposed to purchase two items. An additional batch furnace to increase the flexibility of the resources feeding the forge and an automatic tool changer which would enable the processing of smaller batches through the forge and it's respective feeding resources.

It was felt that simulating the workshop to assess the impact of these proposed changes would be wise before committing to investment.

The project team consisted of:

- Production Director
- Senior Production Controller from the forge workshop
- Business Development Manager
- Researcher/Analyst

A time scale of 5 months was determined with monthly meetings to validate models and discuss development.

System Description

The forge workshop consists of the following resources

- 3 Furnaces (Pre-Heater, Batch and Rotary) to heat bars for input into the;
- Forge
- 2 Heat Treatment Furnaces (For treatment after forging)
- Hot Saw.

Again, the resources process a wide variety of part types. The material properties and the dimensions determine the routes that the bars take and their respective cycle times. Generally large diameter material has to be pre-heated before heating in the rotary furnace and forging. Bars with special metallurgical properties are generally heated through a cycle in the batch furnace before being forged.

Project Summary

The objectives were to determine the utilisation of the forge and the three feeding furnaces under the operating conditions of the previous six months. Once this had been verified, an additional batch furnace should be modelled with an increase in the material to be processed to observe the utilisation of the resources under the new conditions.
A schedule for the previous six months was available from the shopfloor data collection system. From this schedule, an input file for the model was created as a spreadsheet.

4.4 Concluding Remarks

This chapter has presented a summary of the data collected during the study. The following chapter presents an analysis of the data with respect to the three research questions derived from the literature review in Chapter 2.

5. Analysis of data

5.1 Patterns Of Data Relevant To The Research Questions

This section presents an analysis of the data collected from each of the research methods pertaining to each research question. Conclusions regarding the analysis can be found in section 6.

5.1.1 Research Question 1 - "What do modellers do prior to experimentation?"

5.1.1.1 Questionnaire Survey Results for Research Question 1

As a questionnaire employs pre-defined concepts and terminology, the survey method is not particularly suitable for capturing a respondent's personal approach to designing and developing models. As such, there is little information relevant to this particular question. However, a number of questions were constructed to examine certain characteristics of modelling activities, such as the difficulty and length of time particular activities take.

Modelling Stage	Percentage Of Total Project Time
Definition of Objectives	11
Determination of scope and level of model detail	14
Data Collection	23
Validation of Conceptual Model	15
Model Programming	14
Verification of Programmed Model	25

Table 5.1 - Each Modelling Stage as percentage Of Total Project Time

The respondents were asked to tick a scale of difficulty corresponding to the four following phases.

Stage	Hardest--Easiest (No of ticks)			
Definition of objectives	2	9	8	4
Determination of scope and level of model detail	6	9	6	2
Data Collection.	5	4	5	9
Validation of Conceptual Model.	9	3	4	7

Table 5.2 – Relative difficulty of modelling stages.

5.1.1.2 Case Study Data for Research Question 1

Chapter 3 explains why the case study approach lends itself particularly well to the elicitation of information concerning personal procedure and protocol.
This section presents a modelling procedure elicited from the interview transcripts of each case study subject. This was carried out using the process of within case analysis as described chapter 3. The interviews conducted with each Case Study subject lasted between 4 and 6 hours and were conducted in two sessions over one or two days. The entire transcripts are not reproduced in the text because of the volume of material that was not relevant to the research questions. However, it was necessary to cover other aspects of simulation in order to allow each case study subject to talk freely about their experiences. This enabled the researcher to ask questions using examples provided by each case study subject. For reasons of confidentiality, the names of individuals and organisations referred to by each case study subject have been removed. The case study transcripts were sent to each subject for their approval before analysis took place.

Insights into the reasons and factors that affect the conduct of particular activities and the design and development of models in general are re-produced in their own words. Following the analysis of each case study on an individual basis, a cross case analysis is given, to observe similarities and differences between the individuals procedure.

Case Study A

Case Study A Model Design Approach

1 Define Problem

2 Define Questions and Expected Outcome

3 "Eyeball" Plant

4 Talk Through Plant Operation

5 Write system description & draw flow chart

6 Construct Basic Computer Model

7 Collect Data

8 Develop Model

<steps 6-8 Iterated until satisfactory model is developed>

9 Experiments

Insights pertaining to each stage

Stage 1 - Define Problem

"Generally the problem is not clearly defined or understood, the client will present you with a series of symptoms as being problems"

"It isn't always easy when you are presented with a system that you don't understand and a client seems to have got it quite clear in their own mind what it is they want to do"

Stage 2 - Define Questions and Outcomes

"You have to sit down with them and work out what the questions are that you are trying to address and what the outcome has to be"

"Budgetary constraints require me to make it clear to them what I am actually going to do"

Stage 3 - "Eyeball" plant

"This eyeballing phase is extremely important, I think it makes a big difference. I often try to talk to the shopfloor personnel at the same time".

Stage 4 - Talk Through Plant Operation.

" I sit down with someone and go through the operation of the plant in some detail"

"There is generally one person in the clients company who I identify as my principle contact"

"The principle contact is generally somebody who understands the plant or believes they understand the plant"

" ... they given me a very full description of the operation of the plant and then I say to them 'Can I go down and talk to the people on the shop floor, and see what happens?."

" Almost invariably, I find that the people on the shop floor overcome the problems in the basic system by adapting, thereby camouflaging the defects in the system which are in there.... but the people in charge don't have a clue that these things go on".

Stage 5 - Write system description & draw flow chart

and

Stage 6 - Construct Basic Computer Model

" I will translate the written description to the computer stage by stage"

"When I was writing in FORTRAN ... I used to draw a flow chart. Though now I use Siman I tend to go straight from the words on paper to the graphical image. If I get a particularly difficult problem, I draw a flow chart and then translate to the graphical image".

Stage 7 - Collect Data

"I very frequently get the times for a job for the initial rough cut model from the people on the shop floor, I have to explain things like distributions to them and I often get detailed information from them because the principle contact just doesn't know this sort of information"

"As a proportion of project time, this varies wildly, it can be about ten percent, it can be about half the project"

"Some projects, you're supplied with information that is collected and there it is and it's a well structured process, generally the mechanical processes, there are lots of fixed times and quite well constrained variables. The other sort is where you have a person wandering around doing this and that and the other, they are the ones that take a long time."

"I mean Pegden says it's a third collecting data, a third building the model and a third verification, which is all fine and dandy, but is just doesn't work like that".

Stage 8 - Develop Model

" Well it's a process of iteration, you generally add bits to the model. By the time the iteration process has finished, you have a final model, well not a *final* model, but a more sophisticated model".

"But, the model is changing all the time, you may discover you can simplify it, you may have built in some complexity that you can now discard"

"It <the model> tends to get bigger, but you get areas where initially you thought it was important top include detail, but in fact it isn't. For example, in the plant we modelled the weeks and the weekends and it became very complicated, then it became obvious that we didn't need to model the week at all, but only needed to model the weekend".

"I tend to show the development of the model to the client frequently, firstly to validate my assumptions about the plant and the operation and secondly to keep them informed about what I am doing"

General Insights and Comments Regarding the Entire Process

Regarding change in objectives

"Yes almost every time. Hopefully you try to get it not to change, but one of the things with simulation is that the client begins to learn more and more about their own systems.

Case Study B

Case Study B - Analysis of Model Design Procedure

1 - Analyse Problem

2 - Define Objectives

3 - Define Assumptions

4 - Define Model Content and Logic

5 - Sketch "paper" Model

6 - Develop Model

7 - Data Collection

8 - Validation

<Steps 6-8 Iterate>

Insights pertaining to each stage

Stage 1 - Analyse Problem

"One skill that you have to pick up is how to determine what is relevant information and ignore the irrelevant information"

"So I was dealing with all these different people, going around talking to them separately and having meetings together so there was quite a lot of interaction going on"

"They also had different perceptions of what simulation was and what it could do and whether they liked it or not. I mean part of your job at this stage is essentially a sales job, trying to bring them into the process so they will give you the information you need".

"I think that when you have a plant that is already there you run into more problems because everyone who is a part of the system has different views on what is actually going on. Sometimes, there can be a significant difference in the information you get".

" One problem that you can get is that you get Fred and Joe at the first meeting and then you get Fred, Joe and Harry at the second meeting and Harry suddenly tells you a number of different things. And then at the fourth meeting, Fred and Joe aren't there, Harry and George are, and George has different ideas still. And you can end up never coming to a conclusion as to what is actually going on"

"I usually try to get everyone together at the first meeting. I think that is quite important, then you get a fuller picture of what is happening".

Stage 2 - Define Objectives

"They are the key thing behind everything you are doing, without that, I think that all you are doing is building a model of everything and that is all you'll end up doing because you don't know how to simplify it"

"Because if I want to meet those objectives, I need to this, this and so on. For example, throughput is often an objective so I therefore need to get the model to give accurate throughput results, I therefore need to include this information, but this other information doesn't affect throughput, so I don't need to model it".

Stage 3 - Define Assumptions.

"In order to develop objectives, you have to make a series of assumptions about the system you are modelling. It is important to state these up front in order to consider the any conclusions later on"

Stage 4 - Define Model Content and Logic

"Basically, in terms of scheduling, i.e. getting things in the right place at the right time, you are only worried about the sequencing and not so much the timing of these things, so a lot of these lines you have ten machines in a row connected by a conveyor and parts take five minutes to go through this section and pop out of the other end. So what is the point in modelling all that detail, when I can basically black box each row and then add a few additions for breakdowns. The only sections I modelled in detail was where there were parallel machines".

"The detail occurred where any re-sequencing took place or where it was a scheduling point.... It was based upon the objectives, and the objectives where to look at the sequencing through the line.. so we had to model the bits that were involved with sequencing and the bits that don't affect sequencing we name as simple as possible".

" In a sense, some manufacturing systems are very simple, you have machine-conveyor, machine-conveyor and you know that some machines break down, some require operators and that the parts go through a schedule and each machine cycles for a particular length of time. So in that sense it's a fairly simple thing to grab hold of once you understand the terminology"

Stage 5 - Sketch "Paper" Model

"After interviewing and then I sit down with a piece of paper and scribble out what I believe the model should be and then put it into witness blocks"

"One thing I strongly suggest to people on training courses, is that they get down with a piece of paper and work out what the model should be. OK, at some point you have to convert that into the building blocks of the package that you are using"

"What I am doing here is thinking in terms of Witness building blocks, saying I need a machine here, I need a conveyor here which is all Witness names, you know, buffer etc. So effectively what I was doing was here is a layout that they have given me and then re-drawing that layout in Witness building blocks or black boxes"

"This is where I am developing my conceptual model. I suppose I go through two steps, one was converting the system into a conceptual model and then converting the conceptual model into a Witness paper model"

Stage 6 - Develop Model

"On the computer, all I was doing was I wasn't thinking that much on the computer, I was basically just typing in what I'd worked out what I was going to do. I mean it's not as simple as that, because you get to a bit where you not sure how you are going to handle it and you need to develop it on the computer".

"You can often do this without any data, and I would sometimes take guesses at cycle times. And then at a later stage I would add the distributions. To some extent, it <data> is independent of model logic".

"There are to things to a model, one is the logic and one is the timings and so on that go in the model, that you don't need to put in until later".

"At this stage, I may recognise that I need to include the labour that runs it <a machine> and what the breakdowns are and so on. But I'm not worried at this stage if I don't know what the breakdowns actually are, all I am going to do is put in some dummy data. So in some respects, I am putting in the data, but I'm not worrying about what the real data is at that stage".

"I am building up what actually needs to be included in the model"

"It is quite hard to articulate what it is I actually do, it is really hard. I mean spotting whether you should include something or not, I don't know how I do it"

"Effectively, the decision that has gone on in my mind is 'Is this actually going to affect the results that the model gives me ?' because of the objectives I am trying to achieve. 'If I include this is it going to make any difference ?'".

"Now how you actually do that, I don't know. I think that this is where the art comes in. You learn, over time for example that modelling labour in detail isn't necessary for a particular circumstance. How you actually define the logic you go through to decide that.... I mean the logic is 'I know that if I include that labour, it is not going to affect the accuracy of the model in terms of what the model is going to be used for'. I suppose you can bear that out by modelling that labour and then not modelling that labour and seeing whether it does have an effect. But you learn from experience, that in that sort of system, it's not important".

Stage 7 - Data Collection

"During the whole "interview" process, I filter information. For example, I went to see the chap who drove lorries delivering parts between the two plants. What I wanted was a reasonable estimate of transport times between the two plants. I spent two hours with this bloke discussing all the problems of his job in great detail. My job at the end was to figure out what was relevant. In fact the conclusion at the end of the two hours, was that ' well, we normally do between 18 and 24 deliveries a day'. So all I modelled was 18 to 24 deliveries a day, I didn't model the times, or whether there was ice on the road or whether there had been an accident".

Stage 8 - Validation

"This is an iterative process were going through now. You may do it over the phone, but basically, you show them the model and you go through and explain in some kind of sequence, which will normally be through the direction of flow along a line for example. What is going on, what you have put in and you actually get them to discuss it and you get to points were they say "Hang on, that's not quite right" and you just make notes as you go through, this needs changing etc. And that way you develop and validate the model and depending on the complexity you have to repeat this process."

"You can never actually say, this model is correct. Basically, it is up to the customer to reveal the correct information and you can only do your best to get the correct information out of them."

"You need to use various sorts of validation techniques available. The key one is pointing at the screen and pointing at things and saying 'Does this work like that?'. Another one is doing initial runs with it and so on, however, if you are modelling a new plant, that doesn't work because you are only comparing it to expectation which could be completely wrong. And if it is an existing plant, very often you'll find that you've got data to do comparison. Another way is to scrap all stochastic events and run it so you can predict what you would expect to happen.

"You actually learn an awful lot just by watching the model run, because you may notice something that appears to be blocked all the time and then you can go back and check it against the system."

"Another method is to check what you are getting from the model versus the expectations, and try and work out why there is a difference"

<u>General Insights and Comments Regarding the Entire Process</u>

"I think it is very difficult to come up with, 'this is the best system to use. This is the best way to develop your model'. I think that you can draw up guidelines which help, but I think it is very difficult to come up with a process that says 'you must do A, B and then C'".

"It is relating what you can see to what the actual problems are, and there is some experience factor or art not science involved in being able to pick up on these things or not".

"There is some science in modelling, there are bits were you must do this and that, but I

think a lot of it is an art and a skill which to some extent you either have or you don't".
"I think thirty percent of the work is actually building the model in the simulation package, and the other seventy percent is project management".

Case Study C

Case C - Model Design and Development Procedure

1 - Define broad requirements

2 - Set modelling objectives

3 - "Walkthrough" system

4 - Discuss system boundaries

5 - Discuss level of detail

6 - Black box operations

7 - Draw activity life cycle diagram/flowchart

8 - Develop computer model

9 - Data Collection

10 - Experiment.

Stage 1 - Define Broad Requirements

"The clients said, we basically want to understand the behaviour of this system much better than we do now. Once we understand the behaviour, we want to predict the behaviour of the system. It's all classic stuff. It's like the first five minutes of a simulation lecture, i.e. we don't understand the behaviour, we want a model to represent the behaviour and to predict the behaviour"

"They said, "We've got this problem, do you think simulation can help us?". And I said, well it won't be able to give you a detailed plan of implementation. But, it will be able to help you understand the nature and behaviour of this system. Now, that doesn't produce any savings, as a statement. But you have got them interested because once they can understand how it works, they can start changing things and designing the system properly rather than just stabbing at it."

"you do sometimes find yourself drifting away and thinking about building the model."

Stage 2 - Set modelling objectives

"It's only when you start modelling do you then draw up an idea of how the system works, you can only then home in the real objectives"

"Another thing we find with ALL our projects is that people always say we want lead time reduction, we know our lead time is between ten and twenty weeks, we want it reduced down to five and ten weeks. What we see normally are the problems that generally arise with many companies is that it is not the overall average lead time that needs to be reduced, but the variability."

"OK, setting objectives, the objectives were generally continuous improvement, we didn't have any actual figures to be met, we weren't looking for an output to be met, we weren't looking for a specific lead time reduction."

Stage 3 - "Walkthrough" system

"Normally they say, well we'll give you a walk around the plant so you have an idea."

Stage 4 - Discuss system boundaries

"You sit down and you say, "right, lets discuss the boundary in detail", a classic, what is the boundary? Are we going to look at the supply and despatch of the system or are we going to assume perfect supply of materials."

"So we have got to set the boundaries of the system and this is the same procedure that we apply to all our projects. So it's an approach that we think is best so far. So initially we set objectives IF they are clearly understood. Some other companies those that are very 'up' in terms of understanding how their systems work, objectives setting is very easy, but for somewhere like this where we are feeling out way throughout is difficult."

"Yes, for example we know there are many problems throughout the organisation but we can only realistically hope to attack these one by one, so we isolate them one by one and we assume that everything out there is a perfect black box it perfectly exhorts all the parts that we are despatching and we have a perfect supply from that black box environment. And we assume that to be the best way now in some ways it isn't the best way because it doesn't give you the opportunity to look at completely redesigning the process which feeds and which takes parts 'cos really in reality it might be the case that if you were in some way to change the way that we supply parts and change the way we absorb parts will have a fundamental effect on the model within the boundary. By changing our environment we change our system itself. The only way you can really do that is by simulating everything which is impossible, you can't simulate everything then what do you do?. You try and make a lot of assumptions to make this simulation work easier. The more assumptions you make, the less valid the analysis is going to be. OK so you reach that problem, so what do you do? We say that, in the medium term for this company, they are not going to make any radical changes. Not much capital expenditure. For this purpose, for short and medium term requirements, therefore we can look at this place as being within our boundary. That maybe takes half an hour one to one then you have to leave it for a week and you have a talk with a director or another manager to see if they agree."

"You go away and talk to other people until you come to some sort of agreement that everybody thinks "yes that is the boundary" our problem really lies within that boundary within all these activities."

Stage 5 - Discuss Level Of Detail

"The next thing to discuss is the detail, OK. Within that boundary, what detail are we going to be looking at each activity, for example are we really interested in milliseconds of lead time now if you are making aeroplanes, you are talking about weeks anyway, so milliseconds don't come into it. So, were going to think something which is realistic, something that is going to realistically reflect in accuracy of the model. If you go down to milliseconds, you might have the most accurate model in the world, but the amount of work that goes into measuring things to the nearest millisecond is going have less margin than.."

"So we have got to think in our minds about that diminishing returns curve about where we are going to hit the point where it starts going horizontal. And that's all intuitive because they have their own ideas."

"A big question here would be products, there are families of products and sort of a hierarchy of groups of products say two or three products have the same design but different background, they might be in a bigger group that uses the same size of tile which may belong to a bigger group for example tiles that go on walls rather than floors. So, to what detail do we model each individual tile ? or do we go down to the next group or can you go right down to the next group or can we just assume all tiles to be the same ?. Are the cycle times or processing characteristics similar for those tiles. Again that is another intuitive approach."

"It's both ways, they say "well if you do individual tiles, even though they look differently, the process characteristics are identical. So in order to simulate we will just look at one tile" Because what we are simulating is only requiring process information therefore the process information is the same. Now, If there are any significant operations which need to distinguish between types of tiles and groups of tiles, then we certainly need to segregate those tiles. Yeah, make them different, because the simulation wants to see those differences."

"So, level of detail starts from the very finest detail the information that is needed to do that and what it would it would actually contribute in terms of results. And with every project that's different, and its a different discussion that takes a different length of time. Sometimes there might be the case where we will for example a press shop, at the moment they kind of finish off their press items, OK so you have to hand trim them, hand cut holes in them, hand drill holes. Now we say do we have to simulate that?, and they say "oh no don't bother about that , because in six months we are getting a plasma cutter that will do all that. So we can say, right if that is the case we can ignore all those hand operations and we'll assume a guestimate cycle time."

<u>Stage 6 - Black Box Operations</u>

"we try and black box as much as possible initially to prototype the model."

Stage 7 - Draw Activity Life Cycle Diagram/Flowchart

"during the initial discussion period we are sketching all the time. Erm yes during the initial stages there is a lot of this sketching out."

"we'll draw black boxes with arrows showing ins and outs to explain to me how the system works. And I'll be redrawing it to make these black boxes or to explain things to them. So there is a lot of communication via drawings and flowcharts and things like that. And then what I do privately is that I would draw myself an activity life cycle diagram."

"its like a flow chart that represents what the simulation is going to be doing. So two machines one of which is passing parts to the other would be two squares on a bit of paper with an arrow saying you know 'shaft' with pull or push and you know if there is an empty kanban behind there then fill that."

"So a lot of those sort of conceptual drawings are, I keep to myself and any drawings I do supply as part of the proposal which have been zero to date but a lot drawing initial talks are usually simple flow charts. Very valuable way of doing it because other than me going to visit someone on the shop floor it is very hard to see what is happening. You see a lot of material on the floor and a lot of machines working, but you don't get to see the flow of parts."

"draw down on a piece of paper what I would be generating on the screen, so I draw the actual elements so I draw a machine I draw a dotted line for a conveyor and actually give them the actual names that I would give them in a model. Then because Witness works on input and output and actions then what I would do is write next to the boxes what the input would be, so if condition one is met then pull from this machine or if condition two is met then push to this machine and I would write how long the conveyors would be and what the cycle times for the conveyors would be and I would dot this information around the individual machines as I am writing this down. One cycle diagram wouldn't follow the same format as another cycle diagram, I don't use any formal method, just a scrap of paper. And certain models won't require the same level of detail as other models. SO you could say that these activity diagrams were written by two different people."

Stage 8 - Develop Computer Model

"So, I build according to the information that they give which they've confirmed. I go back and halfway throughout the model building and say " Do you want to see how the model is progressing ?" and if the model is obviously, even though it's using the data correctly, the data is obviously creating certain aspects or activities that are out of sync from what really happens, production management will be called or contacted to find exactly what happens. "Is this right 'cos it doesn't look right" even though it is using data correctly, and logically represented what I've been told in terms of information but it doesn't seem to be working correctly. And they'll come and say "Oh yes I forgot to tell you that one does that" which is fair enough and I don't mind that"

"I've got rough data in there. And the most important thing is that a lot, well the majority, if not all models are driven by data columns so I tried to design the model with as little quadcoded data in there. So things like product structures, product groups, cycle times, set-up times, all those factors that you normally want to change from one experiment to another, I try to leave outside the model. So try and design the model to be as generic as possible."

"I write out all the information that I need, then try and group that information and in a way that could be held together in a file. For example I might want to put the product groups and cycle times in one file so one record might say Part A, machine one ten minutes, machine two, five minutes. Sometimes, I might also put the set-up times in there too. So you try and think in your own mind how much you can group the information. Because grouping the information cuts down the number of files that you have which is great for administration purposes but the files are larger which is not so good when you try to edit files and sift through to change one piece of data. So I try and reach a compromise between the number of files and size of files, but there are certain things you have to keep separate like the calendar file, the product structure file, breakdown file, so they usually fall into two groups."

Stage 9 - Data Collection

"we really start with the objectives and we say that for the objectives to be met, we are going to assume that all these things are going to be perfect. We then later find out that they are not perfect, the data isn't available, we don't know how this works. In which case you have to realise that the objectives are going to have to change, they can't be met with the resources available"

"So you find that as more people come together to provide the data they also are providing their two penneth worth of what they think the problems are. Because you always have the case where these people have their own personal objectives."

"write down the specification for the data requirements so what I'm saying is to model within this scope for this detail, this is what we need. We need a list of all the machines and a guestimate or a rough sketch of how they have laid out the shop floor just so we can develop something that looks similar"

"it's fairly consistent that I just talk to the manager, the champion of the project. I ask for information basically, and I suggest that the best way of getting information when it comes to tricky little bits of logic is to go to the shop floor and found out there. Now we usually have a sort of mutual agreement that goes I ask for information, you give me information, now we can say that, if you can't get the information then I'll go down on the shop floor, but you'd understand what sort of problems that causes, I'm an outsider and work study went out fifteen years ago. I usually leave the responsibility to them to find out the information I need, which is all the cycle times etc."

"So all those little exceptions that we do on the shop floor, you know "oh well that normally happens, but ten percent of the time that production breaks down we divert it to that other machine" so all these little things are quite important aspects that do seem to significantly affect the performance overall therefore they need to modelled therefore to understand hoe they operate properly we need to talk to the people who have got the hands on experience which are the people on the shop floor."

General Insights Into The Modelling Process

"It sometimes sounds alarming when a project just finishes without any result, but that is not strictly true, there has been a lot of education and a lot of learning and spin-offs into other projects"

"What we found was that although intuitively you would think that it would be better to shunt parts later in the week, in fact it causes more scatter and problems. So it defied initial logic."

"Well, I'm learning their system and they are learning more about the system. And I've always been in the position over the last six years of being the person who knows the system more than anybody else, because I'm the person who knows all the information, I've got the information to hand"

"You usually have a main contact who is maybe the champion of the project who is denoted as being the person responsible for co-ordinating the company side of things when it comes to commitments of time and information. That is usually the case. Regardless of the size of the project really, there is always one person who is championing."

"I think that one of the more fundamental stuff is to work out a time plan. So the time plan is used for two phases, the first phase is involved with data collection, data validation and data verification. and model validation. And the second phase is experimentation. So the first phase and what we do when we do a time plan is to split that up and for a medium sizes project lets say were talking two weeks or something like that depending on the size of the project for model building once all the data is collected because the data collection can take months sometimes, but we almost really start projects halfway through that collection. So the lead time to develop a model is variable, however if you assume that all the data that I want is there ready for me on disk, in excel spreadsheets or whatever, then the actual contact time in terms of model building will be four to six weeks. Erm right and the experimentation phase four five six weeks, of course the individual experiments might take maybe two and a half days. A day to run the experiment, a day to interpret the results and half a day to write up the results. So maybe two three experiments a week, it depends on the nature of the project."

"You usually find the person on the shop floor, first of all hasn't heard of simulation and sees you coming in as a consultant. So he is obviously threatened f anybody who is wearing a shirt and tie. And you are throwing him these terms, quite innocently you are talking about simulation, now if you were just to say simulation to someone you know we know it to mean computer simulation of manufacturing systems, but we just refer to it as simulation, it can mean aircraft simulators or whatever. This is probably the last thing in their mind, you know, computer based simulations tools for design and manufacturing. SO they are put off by words like that, buzz words that we take for granted, so you have to very careful not to put people off at the first stage. Production people who are fire fighting at the time and you are trying to get them away from the fire and talk to them that last thing they want to be is bombarded with buzzwords which need to be explained to them. And yes they do have a different perception of what is happening on the shop floor and in the organisation than other people. Different people within the hierarchy have different visions, managers, you know production managers have a different view of what is happening on the floor and what is going to be happening on the shop floor. Whereas the guy on the shop floor is just handling the day to day problems."

Case Study D

Case D - Model design procedure

1. **Define the problem**
2. **Extract useful information**
3. **Discover "levers to change"**
4. **Build model "on the fly"**
5. **Collect data**

Steps 4-5 Iterative cycle.

Step 1 - Define the problem

"sometimes however, there isn't such a thing as "the problem", sometimes there are loads of things and different perspectives on these things."

"You are either simulating because there is something there that needs to improved that exists. OR because "they" want to do something new. In either case, someone has decided it's cheaper and/or less risky to simulate than do it in practise. Inevitably when you are doing something new, people won't really know what it is and how they want to do it. They might have a vague idea of the quantities required or the nature of technology required, but they don't REALLY know."

"Essentially, in my experience of simulation either developing simulation tools or doing simulation projects is that they don't know what they want and I don't think it's because they are thick, its because nobody knows."

2 - Extract Useful Information

"You have to sit down with the client and extract the data which is most useful and talk to as many people as you can. You also have to be there and see what is going on"

"You find it out by talking to people and observing the system, it may just be two people."

"I think the companies that I have worked with, the people operating the plants have been pretty bright and tend to work in teams. And though there is usually different perspectives on it, my experience of manufacturing plants, certainly as far as existing plants are concerned. You don't get massive disagreements. When you are talking about new plants, that is a different matter again."

Step 3 - "Discover "levers to change""

"You are looking for the "levers to change". You are looking for what you can control, what it affects and why.

What are the outputs you are trying to measure ?.

And what can they do to ?

If it is in manufacturing, you are looking typically at what processes are involved and how they are interconnected. What effects do they have on one-another"

Step 4 - Build model on the fly

"If you are using a visual interactive system. The n you tend to build the thing on the fly, and so you start sketching if you like with it, to see what would happen. So what you certainly don't do is that you talk to them and go away and develop a model and come back. What you is that you start doing step models and say roughly these are the main things."

"Very quickly you have got to start messing about, with computer based models. And what you have got to try to do is to ensure that computer based model is sufficiently convincing to carry the people with you, because if you go in there with a bad model, they just will not accept you. But equally it has got to be something that can be modified and refined until you get it to a stage where people can use it. .. its a tricky one. ..And that's where I think modern software is quite helpful."

"One other point that became very clear is that it is important to separate out different parts of the model in a modular type approach"

Case Study E

Case Study E - Model Design Procedure

1. **Determine the problem**
2. **Develop a strategy & Identify the Key Performance Indicators**
3. **Draw up logic**
4. **Collect Data**
5. **Develop Model**

Steps 4-5 Iterative

Step 1 - Determine the problem

"It's important to identify the nature of the problem, is it a complex problem, do they understand the interactions ?"

Step 2 - Develop a strategy & Identify the Key Performance Indicators

"I try to select a *viewpoint* from which to solve the problem.. that is based upon looking at the entity life cycle in the context of the problem.. what is the primary entity ?"

"Always consider what experiments are going to be run with the model.. this helps to identify the KPI's"

"I can match the KPI's to the objectives"

Step 3 - Draw up logic

"Once I know the KPI's I can model the parts of the system that effect or indirectly effect the KPI's"

"Use IDEF'ish - a kind of a made up IDEF - to model the whole system and then I can break it down into sub- areas of the system and draw activity cycles for each sub-system with bit's of arrows and whatnot connecting with other subsystems"

Step 4 - Collect Data

"If the data is available then use it, if not assume it now and collect it later if you need it"

Step 5 - Develop Model

"It's essential to get a conceptual model sorted out before programming"

"Initially, I try to scope out the whole thing with not much detail to determine the scope and boundaries of the model"

"I then can model each sub-system to different levels of detail depending on their impact on the KPI's so the system is divided into self contained areas and each is programmed and validated as a separate element to be joined together to form the experimental model"

"Typically, a project would go something like...

5 Working Days - A quick analysis to determine objectives, modelling strategy, some simple models to conduct broad sensitivity analysis and simple experiments. Sensitivity analysis is an important investment. With it you can focus in on the key issues - without it you may send the client off on a wild goose chase, and wasting time collecting data that you'll never use.

5 - 10 Working Days - More detailed models, more experiments and possibly refine/revise project objectives, if they weren't clear enough to start with!

10 Working Days + Ongoing project"

5.1.1.3 Cross Case Analysis of Case Study Results for Research Question 1

The data elicited from each individual case study was subjected to a cross case analysis to compare and contrast the procedure of the different expert modellers. The terminology of each expert is compared and a number of points regarding influencing factors of influence and the conduct of particular activities.

Difficulties employing a cross case analysis are encountered due to the iterative and parallel nature of the procedure, particularly during the phase where models are being designed and developed. For example case study C describes six activities that take place iteratively during model design and development :

- Discuss system boundaries
- Discuss level of detail
- Black box operations
- Draw activity life cycle/flowchart
- Develop computer model
- Data collection

Whereas case study D employs one term to describe the whole process

- Build model "on the fly"

With this problem of differing terminology in mind, some boxes in the following tables are blank, and other tables contain terms which cover more than one activity.

Activity 1 - The Problem

Case Study	Terminology Employed
A	Define the problem
B	Analyse problem
C	Define requirements
D	Define the problem
E	Determine the problem

Table 5.3 – Terminology employed by Case Study subjects to describe Activity 1

Insights and knowledge pertaining to activity 1

- The problem is often not clear or fully understood.
- The problem is often a collection of problems.
- Symptoms are sometimes presented as problems.
- Clients sometimes assume a solution to a problem without exploring alternatives.
- Different people have different perceptions of existing systems and problems.
- Systems that don't yet exist are based wholly on assumptions.
- The modeller has to quickly understand the system
- People have different ideas about what simulation is and what it can do
- Part of this stage is a 'sales' job.

Activity 2 - Objectives

Case Study	Terminology Employed
A	Define questions
B	Define objectives
C	Set modelling objectives
D	Develop a strategy

Table 5.4 - – Terminology employed by Case Study subjects to describe Activity 2

Insights and knowledge pertaining to Stage 2

- Objectives are the key to the management of the project and the model design and development.
- Objectives enable the identification of the system areas that should be modelled.
- Performance Indicators should be attached where possible to this identification to take place.
- Any constraints - budgetary, resource or time based should be included.
- With some projects, especially where there is a lack of understanding concerning the system (i.e. the system is being modelled to understand the problem) objectives are difficult to define. The danger in this situation is that the whole system ends up being modelled.

Activity 3 -Investigate/Understand the system

Case Study	Terminology Employed
A	Eyeball plant / Talk through operation
B	<no clear stage>
C	Walkthrough System
D	Discover "Levers to Change"
E	Identify Key Performance Indicators

Table 5.5 – Terminology employed by Case Study subjects to describe Activity 3

Knowledge and insights pertaining to activity 3

- The aim of this activity is to gain an understanding of the system to begin abstracting it for modelling purposes.
- There is generally a principle contact in the organisation who will educate the modeller on the operation of the plant.
- Information regarding the detailed operation of particular systems is best obtained from those directly responsible.
- Any formal description such as a quality document is only an abstraction, there are many ad-hoc operations that take place without the knowledge of managers.

Activity 4 - Conceptualisation

Case Study	Terminology Employed
A	Develop basic model
B	Develop model
C	Discuss level of detail /model boundaries and black box operations
D	Build model on the fly
E	Draw up logic

Table 5.6 – Terminology employed by Case Study subjects to describe Activity 4

Knowledge and insights pertaining to Activity 4 - Conceptualisation

- The aim of this activity is essentially to abstract the system into a model that can be translated into a computer program
- There are three dimensions to this abstraction
- The scope or boundaries of the model
- The level of detail within the model
- How to actually represent a particular system element
- The complexity and visibility of the system have a strong influence on the difficulty of conceptualising a model of the system
- The process is driven by the objectives. The modeller is essentially asking themselves, "Is this particular system element or characteristic going to affect the performance indicators we are interested in?" - This process is one of the causes of iteration because to answer this question may require some computer modelling.

Activity 5 - Representation

Case Study	Terminology Employed
A	Write system description and draw flow chart
B	Sketch paper model
C	Draw activity life cycle diagram / flowchart
D	No clear step
E	No clear step

Table 5.7 – Terminology employed by Case Study subjects to describe Activity 5

5.1.1.4 Action Research Data for Research Question 1

As the organisation had no previous experience of using simulation, the action research yielded useful insights that were not contaminated by previous experiences. As outlined in section 4.3.3, two significant projects were carried out by the researcher which yielded benefits for the both the organisation and the study. The first project yielded results, which drove capital investment in new machinery and changes to the shift patterns of the lathe operators, which increased the throughput of the finishing area and a decrease in the volume of work in progress. The results of the second project suggested that the data in the business case developed for the purchase of an additional batch furnace was flawed and prompted a review of operations in the forge area. The action research provided an understanding of two real life simulation projects against which the case study data could be interpreted.

5.1.2 Research Question 2 - "What impact has the increase in use of VISS had on the life cycle of simulation projects and the activities of modellers and clients?"

5.1.2.1 Questionnaire Survey Data for Research Question 2

Q - Time for each stage

The respondents were asked to indicate the maximum and minimum time they typically spend on each stage of the project.

A mean value was taken as some respondents indicated an average time. There were also a number of comments stating that the percentages could vary considerably under different situations.

Stage	Percentage Of Total Project Time
Definition of Objectives	11
Determination of Scope and Level	14
Data Collection	23
Validation of Conceptual Model	15
Model Programming	14
Verification	25
Total	105

Table 5.8 – Percentage of total project time spent on each stage

Only 14 percent of the total project time is spent programming models. However, 25 percent is spent verifying the models.

Q - Conceptual Model Validation Methods.

The respondents were asked to rank the following techniques in order of "usefulness".

Technique	Most Useful --- Least Useful			
	1	2	3	4
Personal Reflection	2	2	6	6
Discussions with clients.	13	3	1	0
Showing Clients Diagrams	5	6	2	2
Showing them simple computer models.	6	4	2	4
Discussion with a third party.	0	1	1	11

Table 5.9 – Conceptual Model Validation Methods

5.1.2.2 Case Study Data for Research Question 2

The case study transcripts were analysed to elicit findings concerning the use of graphical interactive software tools during the simulation project. Table 4.8 (section 4.3.2 above) shows that all the case study subjects employ one of the two leading graphical simulation packages currently available in the UK.

Case Study A

"I think it must do when you are using a graphical interface, when you are using a logical language like SIMAN I think hardly at all, I mean if you are writing in FORTRAN, I suppose you do a flow chart and then you will translate that into FORTRAN constructs, and one has to admit that you go for a particular construct that you are happy using or that you have used recently. I find that when I am using SIMAN I am always I am always using a particular construct, I mean you can do the same things with SIMAN in so many different ways. I tend to go in and do it with whatever I've been using most recently and with what I am most familiar, and that is how I used FORTRAN".

"I believe that when I am using ARENA and using the graphical bits and pieces, I think it does tend to influence the way I view the system. Whereas when I used just SIMAN, it didn't".

Case Study B

"I suppose the general technique that I would use and this would apply to a new plant or an existing one, though it is more applicable to an existing one. Is to get a feel for what they are saying; go away, bung something on the computer, take it back as if it is a valid model, although underneath you suspect that it's not. But you create something they can discuss around which I suppose is a bit like having a flow diagram. I personally think that flow diagrams aren't that meaningful to people"

"So I suppose my method is to bung something up, visually on screen and go through it with them and say "Is this right ? Is this right, and so on"

"The most important thing is to get it up there, because the other problem you have at this stage is that you may be dealing with people who have never seen simulation before. So they haven't a clue what you are talking about and until they have seen it, then they start to click on and they'll say "Oh I can do this and this" and they'll also say "This is wrong, this is what actually happens", and they start to tell you more about the system".

"basically, you show them the model and you go through and explain in some kind of sequence which will normally be through the direction of flow along a line for example. What is going on, what you have put in and you actually get them to discuss it and you get to points were they say "Hang on, that's not quite right" and you just make notes as you go through, this needs changing etc. And that way you develop and validate the model and depending on the complexity you have to repeat this process."

"You need to use various sorts of validation techniques available. The key one, is pointing at the screen and pointing at things and saying 'Does this work like that ?".

"One thing I used to notice was how poor people were initially at relating what they could see to what was actually going on, so you would get a machine that was blocked on screen and all the machines in front were bunged up and everything behind was empty, and they would look and think the machine with the blockage was the problem, but of course it is something downstream that is at fault. It is the relating what you can see to what the actual problems are and there is some experience factor or art not science involved in being able to pick those things up and do that"

"I think that the software you use has a limited effect, I have only used SEEWHY and WITNESS, though my impression is that these things are pretty much of a mushiness. I think the way that you plug in the keys is different, but the basic elements in simulation are pretty similar. I think personally, that the modeller should be able to divorce themselves from the software they are using".

"One thing I strongly suggest to people, is that they forget the package and get down with a piece of paper and work out what the model should be. OK, at some point you have to convert that into the building blocks of the package that you are using"

"I think it does perhaps colour your perceptions because you have to consider what you can achieve with the package that you have got. And that is going to affect the way that you build the model and what you include in the model, but I think that it is becoming less and less of a constraint as packages and PC's become more powerful".

"This is where I am developing my conceptual model. I suppose I go through two steps, one was converting the system into a conceptual model and then converting the conceptual model into a Witness paper model"

"What I am doing here is thinking in terms of Witness building blocks, saying I need a machine here, I need a conveyor here which is all Witness names, you know, buffer etc. So effectively what I was doing was here is a layout that they have given me and then re-drawing that layout in Witness building blocks or black boxes. These would be bits of A4 with the diagrams and bits of annotated text. And then on the computer, all I was doing was I wasn't thinking that much at the computer, I was basically just typing in what I'd worked out what I was going to do. I mean it is not quite as simple as that, because you get to a bit where you are not quite sure how you are going to handle it and you need to develop it on the computer"

Case Study C

"I draw down on a piece of paper what I will be generating on the screen, so I draw the actual elements, so I draw a dotted line for a conveyor and give them the actual names that I would give them in a model. Then, because witness works on input and output and actions then what I would do is write next to the boxes what the input would be, so if condition one is met then pull from this machine or that machine and I would write how long the conveyors would be and what the cycle times for the conveyors would be and I would jot this around the individual machines as I am writing this down.

"I usually get a mental picture once I have visited the site once I have an idea of what the objectives are, I'm already thinking how to model it. I'm already developing that part of the model which I'm going to be defining from the specking out of data values. I asking questions like 'What kind of machines have you got ?' and then thinking about how I can model that in Witness. I'm thinking in parallel as they are answering, how can I model this, how can I model that ? so I suppose there is a continuous activity of thinking how can I model that as well as understanding how it works in real life"

<When asked whether the software influences the process of model design>

"Yes very much so, and that asks the question of how do you decide what software to use"

Case Study D

"It depends what kind of software you are using. If you are using a visual interactive system, then you tend to build the thing on the fly, and so you start sketching with it, to see what would happen. So what you certainly don't do is that you talk to them, go away and develop a model and come back. What you do is that you start doing step models and say roughly these are the main things".

"Well the notion of interactive model building is very important, which is quite different from experiences with SIMAN/CINEMA where you have to start to sit down write some code and then tie in the graphics. Whereas if you take the approach of 'lets paint this on the screen', just to get a rough model. Then you can be fairly sure that what you see is what you get, because you can monitor these systems. If it is discrete part manufacturing, then most of the software is designed for that, and if they have a reasonable library of process times then it's not difficult to build an approximate model in a few hours and then take it to people and say 'I know this is incomplete, but this is what we've got' and people can agree with the sequence of operations. The difficulty then comes in terms of trying to represent the detailed event logic and what goes on before and after different processes".

"The problem with most current software is that the representation of event logic is clumsy and not easy to understand"

"Well in the manufacturing sector, it hasn't been like the draw diagrams then code approach for over ten years, which is why I'm saying throw most of the textbooks in the bin."

Case study E

"ARENA allows me to translate the IDEF diagrams directly onto the screen using the different views so I can have separate areas of the screen for the separate IDEF models"

"In the first few days, I do a few simple models to do some broad sensitivity analysis to focus the objectives"

"I try to get the clients involved in developing the model, so by the end of the project they are capable of developing their own models and I can offer advice where it is required"

5.1.2.3 Action Research Results for Question 2

Throughout both projects, the researcher was able to make observations regarding the strengths and weaknesses of using VISS. The headings below describe the phases of the life cycle with examples of how VISS was used.

Problem Formulation and Objectives Definition

VISS as an education tool

As stated above, the organisation had never employed simulation as a management support tool. As a consequence, the project team wished to understand what simulation was and what it could do for them. By demonstrating a simple queuing system and constructing the model interactively with the team, they were able to understand how simulation differed from static analysis techniques and how it differed from other manufacturing computer technologies such as MRP and CAD/CAM. By demonstrating the technique and the results that could be generated, there was a sense of "buy-in" to the project and an understanding on behalf of the team of what was required of them to ensure success.

The problem was then formulated in terms of how it could be addressed by simulation and a set of objectives established for each project.

These objectives set the scope of each project and therefore the scope of the models that needed to be developed in order to solve the problem.

Model Design and Development

VISS as a development tool

All of the model development was carried out by the researcher / analyst away from the project team. The researcher was able to develop the models as a series of modular components. The logic of the model was developed first and verified with data constructed by the researcher to test the model. The data was then added and verified against data collected from the real system.

VISS as a validation tool

Model validation was carried out using two methods. Firstly, the logic of the model was validated by the team working through animation's of the model. This way, they were able to physically point to the screen and highlight errors and inaccuracies not only in the physical and logical flow of material around the system but also in performance indicators such as queue sizes and lead times of parts as they changed over time. These abstractions were displayed as animated bar charts and plots and when they strayed out of acceptable boundaries, it gave an indication of the possibility of invalid logic or data. The ability to step through discrete events allowed the researcher to identify errors and debug the model.

Model Experimentation

VISS as an analysis tool

The ability to watch the execution of the model over time and have performance indicators displayed alongside the representation of the system was considered to be extremely valuable by the management team. The effects of events such as machine breakdowns and the introduction of new batches could be seen as they happened and this provided insights into how the system behaved that could not be determined by the aggregation of statistical output provided at the end of a simulation run.

Summary

Rather than following a structured approach of identifying the problem, collecting data, developing and model and then validating it and conducting experiments. The projects were highly iterative and were indicative of a prototyping approach to model development. This approach was helped by the ability to develop models quickly and easily using the VISS. These models were then used to identify areas of the systems that warranted attention and in turn, further modelling.

5.1.3 Research Question 3 - "What is the role of model representation techniques in projects using Visual Interactive Simulation Software?"

5.1.3.1 Questionnaire Survey Data for Research Question 3

Q - Please tick any of the following techniques you use in model design.

No. Of Respondents	Technique
9	Structured English/Pseudocode
3	Entity Cycle/Activity Cycle
5	Condition Specification
2	Soft Systems Diagrams
0	Petri Nets
19	Flow Charts
2	Stochastic State Machine Diagrams
3	Event graphs
3	IDEF
0	SSADM

Table 5.10 – Use of Model Representation Techniques

Q - If you have developed your own system, why?

No. Of Respondents	Reason
3	You have tried the other techniques but don't feel they are applicable to model design.
10	You have never learned any the above techniques

Table 5.11 – Use of model representation techniques

5.1.3.2 Case Study Data for Research Question 3

As in the previous section (4.3.1), the case study transcripts were analysed with respect to the research question - "

Case Study A

"I mean if you are writing in FORTRAN, I suppose you do a flow chart and then you will translate that into FORTRAN constructs, and one has to admit that you go for a particular construct that you are happy using or that you have used recently."

"Yes, absolutely the way I am going, along exactly the same path <using Graphical Interactive Software as a sketch tool> . I tend to write the system behaviour down in words and I then tend to go into ARENA and construct it in a graphical image."

"I used to draw up what I call a flow chart. Which is just little rectangles and Diamonds and output things. Very simple, though I tend now to go from the words on paper to the graphical image. And if I get a particularly difficult problem, I write it down in SIMAN and then I translate it to the graphical image."

Case Study B

"I'm not a fan of flow charts. With anything like this, I suppose the general technique I would use and this would apply to a new plant or an existing one, though it is probably more applicable to an existing one. Is to get a feel for what they are saying. go away, bung something on the computer, take it back as if it is a valid model, although underneath you suspect it's not. But you create something they can discuss around which I suppose is a bit like having a flow diagram. I personally think that flow diagrams aren't very meaningful to people."

"Well they always switch me off, I can't be bothered to study them and you get all these arrows and people tend to put arrows going back and forth and it becomes a bit spaghetti like and it's very difficult to describe a system very well in a flow diagram."

"I don't think it communicates much to somebody else unless it is done very, very well. So I think they have a limited use, and I feel the same way about activity cycle diagrams, I think they become just as complicated with complex systems. I mean if you have a single server queue then wonderful, but you are dealing with things were you have hundreds of interactions, you are just beyond the scope of being able to model with these things."

"I don't think you need any formal modelling tools apart from note taking"

Case Study C

"I haven't drawn a diagram of any specification because that would always just represent like a rough sketch of the layout of the shop floor. So I haven't done anything like that."

"Well there is no formal sketches in the proposal, during the initial discussion period we are sketching all the time. Erm yes during the initial stages there is a lot of this sketching out."
"Well there is no formal sketches in the proposal, during the initial discussion period we are sketching all the time. Erm yes during the initial stages there is a lot of this sketching out."
"Its like a flow chart that represents what the simulation is going to be doing. So two machines one of which is passing parts to the other would be two squares on a bit of paper with an arrow saying you know 'shaft' with pull or push and you know if there is an empty kanban behind there then fill that."
"So that is very much an informal I would say to modelling."
"There is no point presenting anything like that to any production manager 'cos he's thinking, look I'm not interested at this stage in how it works, I just want to think of it as a tool that you are going to use to give me some results"
"So a lot of those sort of conceptual drawings keep to myself and any drawings I do supply as part of the proposal which have been zero to date. But I do a lot drawing at the initial talks which are usually simple flow charts"

<u>**Case Study D**</u>

"I mean frankly if you draw things on a piece of paper, it doesn't take very long. But it doesn't actually tell you very much, it tells you about the statics, but not about the dynamics. And it's usually the dynamics you are interested in"
"Erm, played around with them with IDEF, we tend to use Activity Cycle Diagrams and Petri Nets from time to time. And some of the current software forces you to do event-graphs anyway .Erm again I'm talking about MicroSaint. That's not the same as SSADM where you are into all the detailed documentation and cascade, it is much more detailed, it does rather assume you know what you are doing at the start."
"Do I use these things? <model representation techniques>. Oh yes as a matter of routine. Yes"
"If you are coding, it allows you to identify events and activities and so on, and if you are not coding, it forces you to think about the interaction."
"I use a lot of scratty things. But I've never found that any formal approaches can be applied one hundred percent, you always end up using other bits, and they force you to think about certain things. but erm, they all have their disadvantages. So I find them useful, but I don't find them essential."

<u>**Case study E**</u>

"I use IDEF, well parts of IDEF to model the whole system into logical areas and then I can break these down into sub - areas of the system and draw activity cycles for each sub-system with bit's of arrows and what not connecting with other subsystems"

"I can then translate the IDEF boxes into an on-screen version. Using the VIEWS function of ARENA you can set up hot-keys to jump to a whole screen for each sub-system"

5.1.3.3 Action Research Results for Question 3

Model representation served various purposes during both the projects with the collaborating company.

Layout Diagrams

- Project 1

The first representations developed were sketches of the layout of the shopfloor. These were drawn by the representatives of the company during the initial meetings to discuss the aims and objectives of the simulation project. The representatives used these sketches to educate the modeller about the system, in terms of the physical resources and the operation of the plant. Standard routes for parts were developed by following the process routes of selected products through the various resources on the sketch. The shop floor layout sketch was later abstracted into a series, each box a logically distinct sub-system representing a functional area of the system.

- Project 2

Layout diagrams were again the first representations developed during the project. These were employed to identify the process routes of products through the system resources. The layout and number of resources in the system were less than the first project so further abstraction of the system was not required.

Entity Cycle Diagrams

- Project 1

During the project, the modeller drew flow chart type diagrams for the routes of the main part types. These diagrams were given to the project team and other members of the company to comment on their validity and to add further detail.

- Project 2

As there were a large number of different products processed by the system, a table was produced which listed the resources visited by each part type. This table was amended with details concerning the special operations carried out on each part type.

Program Translation Sketches

In both projects, the modeller was developing computer models, a number of the sub-systems were too difficult to model on the computer without sketching the event logic on paper. These sketches were life cycle diagrams of each subsystem composed of a hybrid of flow-chart symbols together with the simulation software blocks. This enabled the modeller to validate the functional logic of the sub-system before committing it to the VISS blocks.

5.2 Concluding remarks

This chapter has presented an analysis of the data collected through the research techniques (Chapter 3) against the three research questions derived from the literature review (Chapter 2). The table below summarises the key findings:

Research Question	Summary Of Results
What do modellers do prior to experimentation?	• A simulation project life cycle composed of a highly iterative cycle of various activities. • The process is driven by the project objectives, which are based upon a formulated problem.
What impact has the increase in use of VISS had on the life cycle of simulation projects and the activities of modellers and clients?	• Visual Interactive Simulation Software is employed from an early stage in the life cycle of project. • Education - To demonstrate what simulation is and what it can do • Validation - Interactive sessions allow visual validation
What is the role of model representation techniques in projects using Visual Interactive Simulation Software?	• Model representation techniques are employed for 4 reasons 1. Reflection 2. Translation 3. Documentation 4. Validation/Communication

Table 5.12 – Summary of data analysis

6. Findings and Conclusions

6.1 Introduction

This chapter presents the results of the research to address the questions raised in chapter 2 against the literature. A revised model of the simulation life cycle is proposed and supported by evidence from the research, the phases of this life cycle model are then explored in more detail with knowledge and practices extracted from the case study and action research results. It then explores the implications of the findings with respect to industry and academia. The shortcomings and limitations of the findings are also discussed and avenues for further research are proposed.

6.2 Research question 1 "What do modellers do prior to experimentation?"

This section brings together the results of the research to answer the above question. A revised model of the simulation life cycle is proposed together with knowledge and practises for the conduct of a simulation project derived from the case studies and the action research.

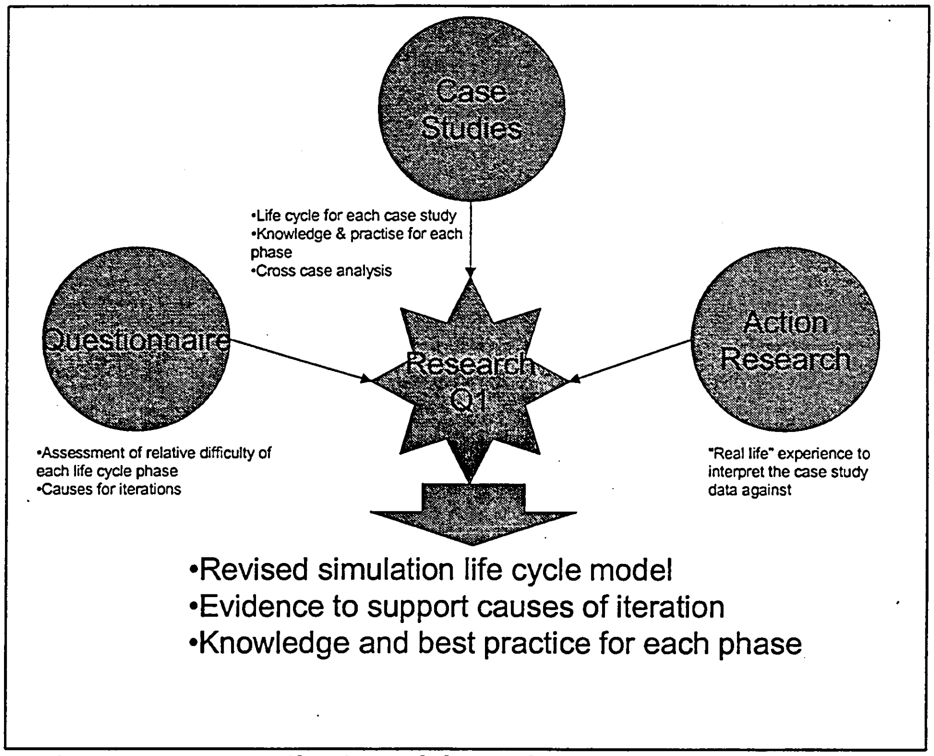


Figure 6.0 - Contribution of the techniques to Research Question 1

6.2.1 The Nature Of The Simulation Project Life Cycle

The results suggest that there is a strong tendency towards a highly iterative approach to simulation model development. Whilst most of the procedures examined in Chapter 2 acknowledge the fact that simulation projects do not progress in a sequential manner, the high degree of iteration and parallelism suggested by the case study results and the action research is not reflected in the literature. This conclusion is also supported by a number of statements made by the case study subjects regarding how simulation projects are represented in the literature.

As the analysis conducted in Chapter 4 indicated, it is very difficult to separate out any "stages" of simulation projects at all. The modellers appear to be engaged in cycles of activities rather than a series of stages. Pidd (1996) when discussing modelling as a non-linear process quotes Hollyoak (1990) who, when investigating ill defined problem solving, observed how people operate in parallel lines of thought and that they continuously restructure their ideas. Their concern to understand the problem context goes hand in hand with a desire to produce a model which will be useful, as well as technically correct. The results of the questionnaire concerning the percentage of total project time spent on each stage were accompanied by comments suggesting considerable variation or statements indicating that the stages are not sequential. These comments lend weight to the suggestion that many stages are repeated and often conducted in parallel.

Despite this highly iterative approach to the project life cycle, there is a suggestion of a progression from the early design stages of a project to conducting experiments and implementing results. The life cycle appears to be characterised by a progression through four phases (Figure 6.1). The word phase is used rather than stage as the latter suggests a sequence with a clear start and finish. The modeller and team are engaged in cycles of activities and each phase can be characterised by the prominence of particular activities.

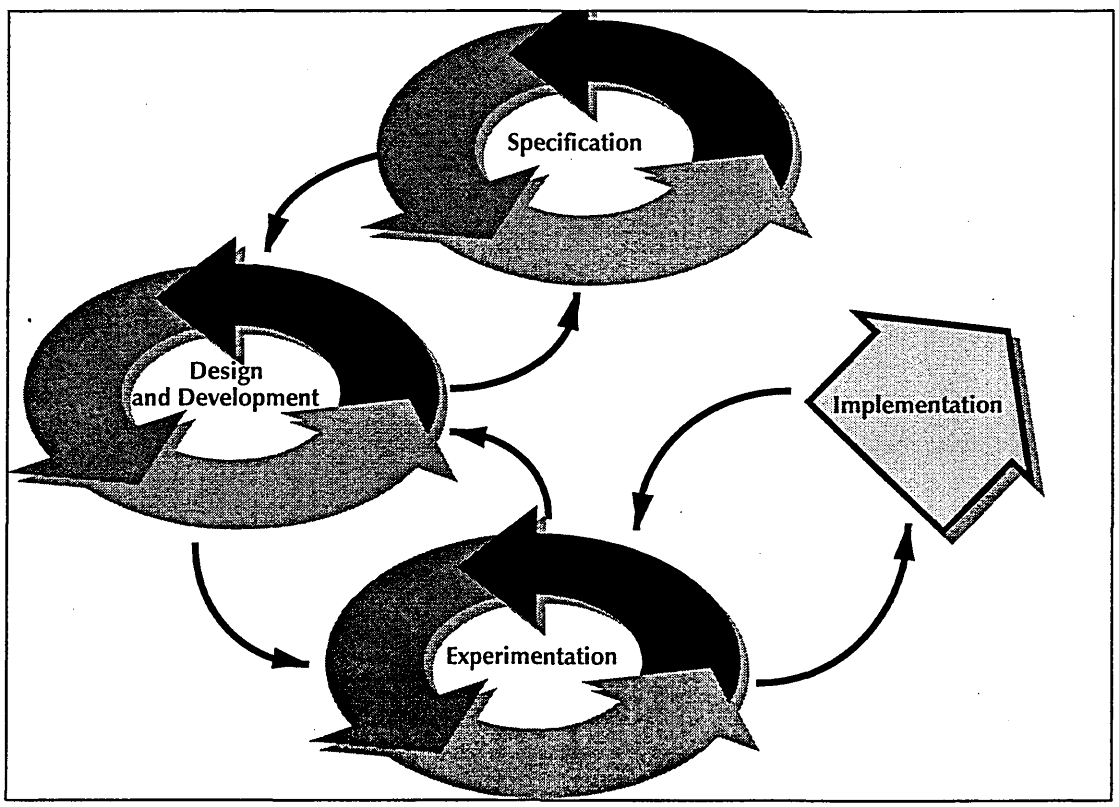


Figure 6.1 - The proposed simulation project life cycle

This representation of the life cycle is somewhat different to those proposed by the authors in Chapter 2. The reasons for differences will be discussed in more detail in the subsequent sections of this chapter. However, it is worth noting the major differences at this point.

The greatest contrast appears to be the point at which computer models are developed. In most of the older approaches (Law and Kelton (1991), Sargent (1984), Banks (1986), Balci and Nance (1985), a computer model does not appear until fairly late in the cycle. This is usually after considerable analysis of the system and the collection of data to develop statistical distributions for machine times etc. The case study evidence suggests that computer models are now developed at a much earlier stage of the life cycle.

The manner in which models are developed also appears to be quite different. Sargent (1984), and Gass (1987) suggest an approach similar to that traditionally taken to develop software applications. In practise it appears that the approach taken to model development is quite different from this traditional "waterfall" approach. It is possible that the main reason behind this change in approach is due to the increased use of VISS and the rise of desktop computing over mainframes.

6.2.2 Causes of Iteration in the Simulation Project Life Cycle

By analysing the case study results and the action research, a number of causes of the iteration are proposed.

Prototyping

All the case study subjects describe a prototyping approach to model development. They all state that they try to develop an animated model very early during the project in the knowledge that the model is incomplete and likely to be inaccurate. This model is then refined, improved, complexity increases and sometimes decreases until an acceptable model is developed and experimentation can begin.

Resolving Perspectives

At the start of the project the business "problem" is defined collectively by representatives from the organisation. As different people become involved as the project progresses they offer a different perspective which can lead to a re-evaluation of the problem to be solved.

Modular Development

There appears to be a tendency for modellers to break down systems into logically distinct areas and develop sub-models of these areas. The development of these sub-models requires a cycle of activities. Powell (1995) calls this approach decomposition and Pidd (1996) uses the phrase "divide and conquer" to describe this characteristic of model development.

System Changes

All systems change over time, any model representing a system may have to reflect those changes to be considered valid.

Invalid Assumptions

Invalid assumptions have a considerable impact on the degree of iteration. As more information is discovered about the system, invalid assumptions about the problem, the system and data will emerge. The degree of invalidity will have some affect on the iteration of the modelling activities ranging from small changes to the development of a completely new model.

Greater Understanding

As the modeller and the project team acquire more knowledge and information concerning the system, they are able to reflect upon the problem and the objectives and change the objectives and the scope of the model to increase the effectiveness of the exercise. This is an important point and is explored in the next section.

6.2.3 The evolving model

The case studies suggest that most simulation projects begin with a simple model that consists of black boxes, assumptions and "guestimate" data. However, this model provides a focus for interaction and consideration of possibilities for development.

The term evolve is employed here for a reason. Traditional computer applications are "developed", that is, functionality and complexity is added against a specification. That is, the result, i.e. the application is known at the outset. In contrast, despite having a specification of sorts via the objectives, the scope and level of detail of a simulation model cannot be known at the start of the project.

The functionality, scope and level of detail of a model change over time as a result of previous model prototypes. The simulation team and other stakeholders consider the implications of these prototypes against the modelling objectives

Continuing this concept of modelling as evolution as against development. Much of the benefit from the development of a computer application is derived once the application is installed and in use. In contrast, much of the value of simulation models is derived during the development of the model.

CASE STUDY EXAMPLE

CS A refers to the project with the objective of determining the appropriate volume of a vessel for processing chemicals. However, during model development, insights gained through reflecting on the results of the prototypes, lead to the question "Should there be a vessel at all ?"

This evidence certainly casts doubt over whether the "waterfall life cycle" Boehm (1981) is valid for representing the simulation life cycle. It is interesting to note the increased use of Rapid Application Development (RAD) and Joint Application Development (JAD) for software development (DSDM Manual 199?). These two approaches share many characteristics with the evolution of simulation model such as a high degree of client involvement and a prototyping approach to system development.

6.2.4 The four phases of the life cycle

The life cycle diagram (Figure 6.1) based upon the research results proposes four life cycle stages.

- **Specification**
- **Design and Development**
- **Experimentation**
- **Implementation**

The research questions posed by the literature review concentrated on the early stages of the simulation project life cycle. Therefore, this section focuses on the two phases of Specification (6.2.4.1) and Design and Development (6.2.4.2). However, as suggested in the previous section, there is no clear boundary between Design and Development and Experimentation. Further discussion concerning Experimentation can be found in section 6.7 - considerations for further research.

6.2.4.1 Specification

This section draws on the results of the research to describe the characteristics of the Specification phase of the simulation life cycle and positions the proposals against the literature.

Aims of the Specification phase

According to the case study results, the primary aims of this phase are.

- **Formulate the problem to be solved**
- **Define objectives based upon the problem**

Alongside these two primary aims, there are a number of secondary aims.

- Identify the stakeholders of the project.
- Educate the clients as what simulation can and cannot do.
- Develop a project plan.

6.2.4.1.1 Problem Formulation

Formulate a valid, clear and acceptable definition of the problem.

Typical Problems

Formulate a valid, clear and acceptable definition of the problem.

- Key Performance Indicators (KPI's) deviating from a range of acceptable values
- Implications of impending change
- Lack of understanding concerning current behaviour of system

Methods of problem formulation

- Workshops
- Interviews
- Benchmarking
- Brainstorming
- Identification of Critical Success Factors (CSF's) & Key Performance Indicators (KPI's)

Obstacles to problem formulation

- Different perceptions of the system and problem
- Problem does not currently exist or is not visible
- Counter intuitive behaviour of cause and effect
- Pessimism and/or obstructive behaviour
- Lack of expertise
- Lack of or inaccurate data/information

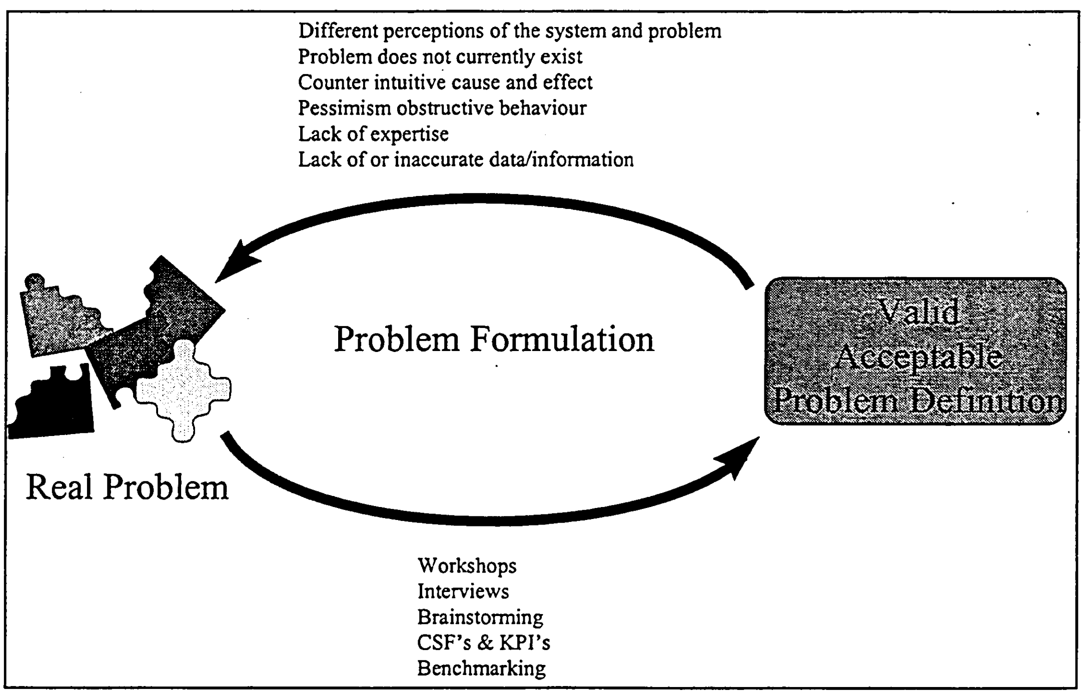


Figure 6.2 - Problem Formulation

6.2.4.1.2 Objectives Definition

Objectives should be focused, acceptable, measurable, achievable, and subject to deadlines and constraints.

What do objectives do?

- Provide a project time scale and enable identification of milestones
- Drive the project
- Provide a basis for determining the scope and level of detail of the model(s).
- Give indications of resource requirements

Focus

Objectives definition is often carried out in conjunction with problem formulation. The problem or a part of the problem should form the basis of the focus in the objectives. This focus not only gives a sense of direction to the process, but it begins to define the *scope* of the model that is to be developed, an important factor in determining the complexity of the model and hence the duration and cost of the simulation project. Model scope is explored further in section 6.3.1.1 below.

Measures

Where possible, objectives should contain performance indicators (PI's) relevant to the formulated problem. Identifying and defining PI's is important for three reasons.

Experimentation

The experiments conducted with the model will generate output data. It is vital that consideration is given to the data that is required from the experiments and the format in which it is required. This has considerable impact on the way the model is developed.

Model Scope and Level of Detail

Determining the performance indicators gives the modeller a mechanism for determining the scope and detail of a model. When investigating the system the modeller can ask themselves or others a question.

"Does this system element or characteristic affect the performance indicators in the objectives?"

If the answer is "no", then for the purposes of experimentation, it is not necessary to model it.

Achievability

It is important to consider the degree of improvement of the performance measures for a number of reasons. Firstly to ensure the team consider whether such improvements are achievable, secondly to provide a goal for the project and finally to consider the implications of such measures.

For example, reducing the lead time of a particular product by five percent may be possible by making changes to scheduling rules, but reducing it by fifty percent may involve considerable capital investment and changes to working practises or even be impossible. Issues of this nature should force the team to consider whether the objectives are acceptable and what constraints are imposed.

Acceptability

The project team should define objectives that are acceptable to the stakeholders of the project. These stakeholders should have been identified as part of problem formulation.

Constraints

Any constraints should be identified and outlined in the objectives if at all possible. Constraints typically refer to capital expenditure, working practises or operational procedure. An example from the case studies refers to an attempt to improve throughput in a facility without having to work additional shifts. This constraint could have an impact on the development of the model and the experiments that can be conducted. In this situation, is it necessary to model shift working at all?.

Action research evidence A

The first project that was initiated at the collaborating organisation suffered at the outset from not having a set of clearly defined objectives. The stakeholders felt that the finishing area needed improving and that simulation could give some insight into what improvements needed. The project commenced with the objective of modelling the finishing area to identify bottleneck resources. As a result, the project and the model became difficult to manage. The entire finishing area was modelled in considerable detail, which took a long time and a lot of effort. Another problem was that the stakeholders already new which areas needed improvement so the project suffered from a lack of "buy-in" and commitment as the benefits were slight compared to the amount of effort. The project petered out and was nearly shelved. However, it was re-started with clearly defined objectives to try and decrease the variation in lead times of three particular products by altering the scheduling of the material and changing the shift patterns of the lathes. Once these objectives were in place, the project was easier to manage and fulfilled the expectations of the stakeholders.

6.2.4.2 Design and Development (D&D)

This phase begins once Specification is drawing to a close, although it may begin much earlier, especially where some modelling is required to develop a formulated problem or conduct some sensitivity analysis when defining the objectives.

This phase is primarily concerned with the design and development of a model with which experiments will be conducted to enable the project objectives to be met.

Without achievable, focused, measured and acceptable objectives, this phase can rapidly become an academic exercise in developing a model merely for the sake of it. The main reason for this is that objectives become the benchmark by which the modeller/analyst determines the scope and level of model detail, also how the basis for experiments are derived and to define a finish point for the project.

This section explores the activities which make up design and development, as has been explained in the previous sections, these phases are characterised by a high degree of iteration of the activities, such that it is difficult to distinguish between them when engaged in the design and development of a model.

- **System Investigation**
- **Model Formulation**
- **Model Development**

However, it should be noted that there is a trend of emphasis from investigation and formulation in the earlier stage of this phase to model development prior to the beginning of experimentation.

Each activity will be discussed separately, though it will be clear that strong interrelationships are present.

6.2.4.2.1 System Investigation

Identify the elements of the system that should be included in the model.

The Case Study subjects suggest that from a modelling perspective, discrete part manufacturing systems typically consist of three types of elements.

- The products being produced.
- The resources and personnel that add value to the products or support the value adding processes.
- The rules that govern the interaction of products, personnel and resources.

The modellers in the case studies appear to be asking themselves the question:

"Does this element affect the performance indicators in the project objectives?"

If the answer is "yes", there may be a case for including it in the model. Conversely, if the answer is "no", then there is no immediate justification for inclusion. However, the question above can be very difficult to answer. To make it easier, the modellers in the case studies talk of "adopting a viewpoint" or "selecting a primary entity" or "immersing" themselves in the system. Case study D discusses finding the "levers to change" the outputs of the manufacturing system.

During the early stages of design and development, the emphasis should be to determine the scope of the model, rather than a detailed investigation of particular elements. The experiences of the case study subjects suggest that it is better to have a model that is too simple rather than too complex because more detail can be added at a later stage. This principle is reflected in the KISS (Keep it simple stupid!) acronym cited by Pidd (1996) when discussing model development.

Methods of system investigation

Each case study subject mentions how important it is to physically walk through the system guided by someone who understands the problem and the system. Case study A calls this person "the principle contact".

Each of the case study subjects discussed how the operation of the shop floor is often different from that which is understood by the management team or presented in quality documents. In traditional manufacturing systems, especially low technology plants with little automation, there are many operational rules and control decisions that are not recorded or represented in any quality systems, procedures or production planning systems. However, they have a considerable impact on how the system operates and they can only be discovered by talking to the personnel involved in the day to day running of the system.

Workshops and focused interviews represent the formal techniques of collecting information from personnel. However, the case study evidence suggests that experts tend to take an informal approach to collecting information.

The problem with this approach is that each person will have a different perception of the system and how it operates, sifting through this mass of information and deciding what is useful can be a difficult decision. Again, using the objectives as a benchmark is the best way of reaching a decision.

Despite the importance of collecting data from those involved in the day to day operation of the system, computer stored data can yield large amounts of useful data very quickly. Table 6.1, below lists the data collected from various systems by the case study subjects and during the action research.

	Production Planning Software	Shop floor data collection	Accounting System	Cad
Parts	Bills of material Process Times	Process Times		Bills of material
Resources (machines and personnel)	Process times Capacity Availability Efficiency	Downtime Set-up times	Personnel availability/skill profile Cost information	Shop floor layouts
Rules	Process flow Shift patterns Contingency			

Table 6.1 - Computer sources of information

However, there are a number of pitfalls associated with the use of computer stored data. The information recorded is not 100% accurate and the modeller must make judgement as to how much confidence can be attached to it.

Action research evidence B

The salary records for each department contained process times for the different material on the machines in the finishing area as the personnel were paid on a piece work basis. It was easy to determine process distributions for the different processes. However, when the project team were presented with a model, they felt that the process times were too long. A discussion with the foreman followed who pointed out in confidence that the actual process times were *less than half* those quoted to accounts. This reliance on the computer stored data had nearly doubled the utilisation of the simulated resources.

Case Study D also suggests that one should not be tempted to model areas in great detail simply because there is a lot of data available as these areas are likely to be fairly well understood. It is more likely that the areas where little data is available will be those against which more understanding is required.

6.2.4.2.2 Model formulation

How should the system elements be represented in the model?

To what level of detail should they be modelled?

Model formulation is best illustrated by an example.

Action research evidence C

During the first action research project, it was clear that the cutting area had an impact on the lead time of the three products, which were the focus of the objectives. The cutting area therefore had to be included in the model. This raised a number of questions regarding how to actually model the cell and to what level of detail it should be modelled.

Should the saw operators be modelled?.
Should the material handling be modelled ?
Should set-up times be modelled ?
Should breakdowns and intentional downtime be modelled?

Modelling any of these characteristics mean that data would have to be collected and validated, the model would become more detailed and therefore require more time spent in development and validation.

At the simplest level of detail and highest abstraction, the cutting area can be considered a "black-box" (Figure 6.3) where material enters and is processed and then emerges after an elapsed time.

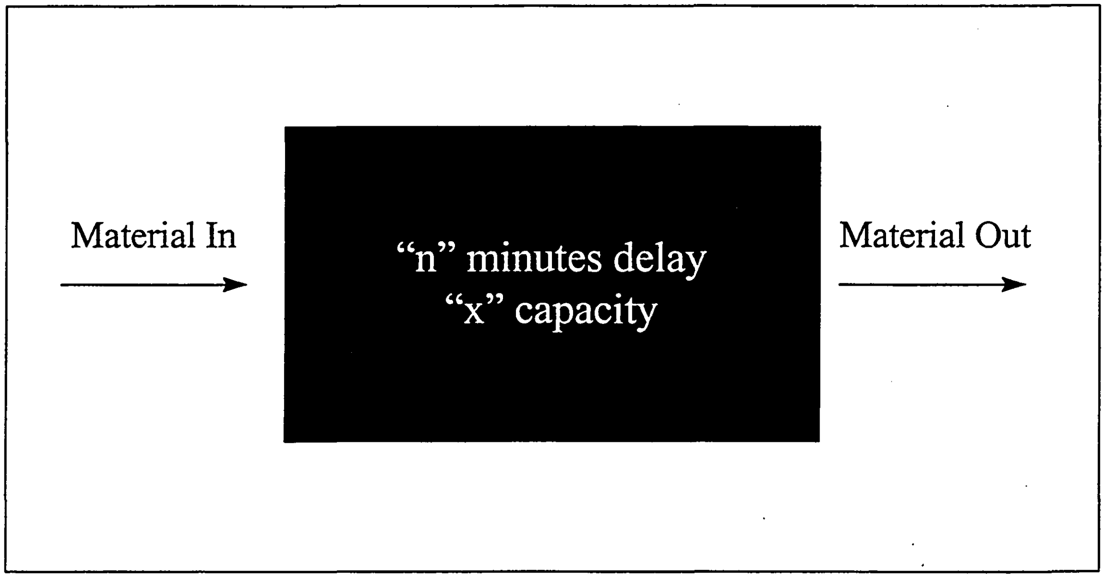


Figure 6.3 - Black Box Modelling

At this level, the delay "n" minutes represents a sum of the process time for an entity, plus some proportion of set-up time, material handling time, and possibly downtime. This level of detail may be satisfactory, as it is possible to manipulate availability by altering the capacity "X". The data available from such a "black box" would be:

- Min, Mean, and Max throughput times.
- "Parts In" queue statistics.

The data that would be unavailable would be.

- Utilisation statistics for individual machines.
- Internal queue statistics.

If this data is required, the black box method is not sufficient and more detail needs to be included in the model. This adds considerable weight to the argument that the objectives should be related to specific and measurable performance indicators, otherwise the level of required detail is very difficult to establish.

Methods of model simplification

The acronym KISS (Keep it simple stupid!) is re-iterated many times in a wide variety of disciplines. Pidd (1996) proposes that the modeller should bear it in mind when considering the level of detail of simulation models.

1. Inclusion and Exclusion

Another method of simplifying a model is to either include system characteristics into another characteristic, or simply to exclude them from the model altogether. Black boxing resources is one example of inclusion, but there are other applications of the concept. This example re-iterates why careful consideration must be given to defining what the output of the model is to be, prior to any formulation.

2. Grouping

Grouping is very effective technique for modelling discrete part manufacturing systems. By grouping families of parts with similar attributes together, the modeller is able to reduce the complexity of the model whilst retaining validity.

6.2.4.2.3 Model Creation

Section 6.2.4.2.1 presented Model formulation which describes how a model of the system is formulated in the mind of the modeller. Model creation occurs when this mental model is translated into code and the model becomes an entity in its own right. This activity is influenced to some degree by the software that is being used to create the model and the software manuals cover the details. However, a number of generic practises and concepts arose from the case studies and action research.

Modularity

The case study subjects appear to take a modular approach to model development. That is, the overall model is broken down into manageable "chunks" and created accordingly. These modular sub-models are validated independently and then joined together to form the total model.

Separate Data and Model Logic

Another common concept is that of separating the logic and data of the model as much as possible. Case study C attempts to keep as much data as possible in spreadsheets so that different scenarios can be executed without changes to the logic of the model itself. This separation of logic and data also enables the development of the model without any significant data collection to take place. The model can be developed with rough cut or "guestimate" data in order to provide a basis for validating the logic of the model.

Validation

The creation of a model in a VISS also allows validation to take place. All the case studies suggest that the modellers will actually sit with the client and watch animation's of the model on the screen. In this way, the dynamics of the model are revealed, a factor which limits the use of static representations for validation purposes.

Action Research Evidence E
During the development of the model for the forge workshop, the client team was able to watch the cycle of a forging campaign on the screen of the computer. The forging manager commented that the number of bars waiting in the queue for the furnace seemed too large at the beginning of each week. It emerged that if there were a sufficient number of bars left un-forged on a Friday afternoon, then an additional shift would work on the Saturday to clear the backlog of work. It is unlikely that this would have been noticed had a paper representation been used to validate the model.

6.3 Research Question 2 - "What impact has the increase in use of VISS had on the life cycle of simulation projects and the activities of modellers and clients?"

Visual Interactive Simulation Software (VISS) has had considerable impact on the manner in which simulation models are developed. The previous section has explored many of the effects and therefore this section presents a summary of these effects.

- An increase in the degree of iteration in modelling activities and the project stages involved in model building.
- A decrease in the use of formal model representation techniques.
- The use of VISS as an interactive validation tool.

6.3.1 Impact 1 - An increase in the degree of iteration in the simulation life cycle.

A number of authors cited in chapter 2, presented approaches to model development that shared many characteristics of the sequential "Waterfall" software development cycle proposed by Boehm (1981). This cycle was developed in a period when all simulation models were written as programs in a language, typically FORTRAN. As such, they were subject to certain development rules outlined by the waterfall model and constrained by the availability and speed of the computer technology available at the time. These constraints meant that simulation models had to be developed in the sequential manner suggested by the authors cited in chapter 2.

With the arrival of powerful desktop computers and the development of VISS software, models could be created and executed much more rapidly in comparison to the traditional method. As a result, the prototyping models with interactive validation became possible. The prototyping approach meant that the simulation life cycle was characterised by a much greater degree of iteration than it had been prior to the technological developments.

6.3.2 Impact 2 - A decrease in the use of formal model representation techniques.

As the above statement answers one of the three main research questions of the thesis, a detailed discussion of this impact is given in the next section of this chapter. However, to present a complete answer to this particular research question, a summary of the reasons for this impact is given here.

- A number of the case study modellers felt that model representation techniques do not portray the dynamic nature of systems particularly well.
- Any model representation can rapidly become highly complex and difficult to understand by both modeller and client.
- The use of a model representation technique for validation purposes requires a client to understand the protocol and syntax of the technique.

6.3.3 Impact 3 - The use of VISS in Design and Development.

The case study evidence suggests that the graphical interface and animation capabilities of VISS software are used to validate models. The case study subjects all mention the creation and validation of models with the client. At least three describe interactive validation sessions where the client is pointing at the animation on screen and asking questions about the logic of the model. The action research example sited in the section 6.3.1.1, indicates how useful being able to watch a model execute over time is compared to a paper flow chart type representation.

6.4 Research Question 3 "What is the role of model representation techniques in projects using Visual Interactive Simulation Software?"

The results of the research indicate that model representation techniques serve a number of purposes at different stages of the simulation project cycle. However, the development of Visual Interactive software environments has eliminated much of the need for formal representations that existed during the early days of simulation modelling.
Despite this decline in the use of formal representation, model representation still plays a significant role in a simulation project.
During the initial stage of project both the modeller and client employ specification, layout diagrams and flow charts as a means of:

- **Communication & Education** - The client can educate the modeller about the system using layout diagrams and flowcharts indicating the sequence of operations.
- **Focus** - As a tool for focusing discussion and brainstorming on areas of the system, particularly during problem formulation.

Whilst the modeller is engaged in the design and development of the computer models, model representations are employed for the following reasons.

- **Reflection** - As an aid in conceptualising the system, realisation of the scope and level of model details.
- **Translation** - To convert a conceptual model into the program syntax of the simulation package.
- **Organisation** - When dealing with complex event logic, all the modellers employed various techniques to order and identify the interactions of the system away from the computer model.

Somewhat surprisingly, the case studies indicate that model representations are rarely employed for documentary purposes only, furthermore, all of the modellers rarely employed model representations for validation purposes, preferring to let the client validate a programmed model rather than a representation. This reluctance was based upon a number of factors:

- **The use of a model representation technique for validation purposes requires a client to understand the protocol and syntax of the technique.**
- **A number of the modellers felt that model representation techniques do not portray the dynamic nature of systems particularly well.**
- **Any model representation can rapidly become highly complex and difficult to understand.**

6.5 Implications for Industry

This section outlines a number of implications for industry arising from the conclusions of the research. These implications are explored from three perspectives:

- Customers and Clients of a simulation project.
- Modellers and analysts providing the service.
- Software vendors.

6.5.1 Users/Customers

Project Planning and Control

Given the highly iterative nature of simulation projects and the fact that there are a lot of unknown factors at the beginning, customers have to be aware that it will be very difficult to lay down a detailed project plan.

In the IT sphere, the concepts of Rapid Application Development (RAD) and Joint Application Development (JAD) have been developed to address similar issues that occur in applications development projects. There may be justification for investigating whether any of the RAD project management techniques can be transferred to simulation projects. Techniques such as Value Stacking which identify critical business areas for focusing effort and Time Boxing, a mechanism for setting deadlines for deliverables when the exact nature of the those deliverables are unclear suggest that they could prove useful in the development of simulation models.

Providing data

As the cost of hardware and computer software continues to fall, the biggest expense on any simulation project will be the staff involved. As data collection represents the most time consuming activity of the life cycle, it becomes cost effective to minimise it by ensuring that data is available as far as possible. However, as the areas that are being simulated are usually those that are not well understood by the stakeholders, there is a strong possibility that they have limited data.

Identification of Stakeholders

Section 6.2.4.1 Discusses the importance of identifying the stakeholders of the problem to be solved and those who have a stake in the implementation of the results of the exercise. Identifying these people is the responsibility of both the modeller and the client.

6.5.2 Modellers/Analyst

Skills

Section 6.2.4 presents knowledge and techniques from the case studies and the action research. Given that simulation is sometimes considered to be an exercise in statistics and computer programming, it is surprising to discover the range of skills and knowledge also required to develop a useful simulation model.

Meeting business requirements

There is a tendency amongst inexperienced modellers to treat a simulation project almost as an academic exercise to produce an all singing all dancing simulation model.

Unfortunately, this tendency often results in producing a model that is too large, difficult to use and fails to address the problem.

To avoid this situation, the modeller should constantly refer to the objectives and ask whether modelling a particular system characteristic will make a positive contribution to meeting the objectives.

They should also ensure that the client stakeholders are monitoring whether the objectives still reflect the current and future business requirements.

6.5.3 Software Vendors

Modular Modelling Capability

One of the approaches to model development highlighted by the case studies was the tendency of modellers to break the system down into logically separate parts. Interfaces could be developed that enabled the development of separate models that used common features from a repository, this would enable sub-model components to be brought together as a larger model.

Training in modelling

Chapter 2 presents the findings of studies conducted by Cochran et al. (1995) and by Law and McComas (1989) which led them to propose that the success of a project is more dependent on methodology than on the software tools employed. They also argue that simulation literature and training place too much emphasis on software selection and model coding. With these facts in mind, vendor training courses should include modelling skills and training in project management alongside the teaching in how use a particular piece of software.

6.6 Implications for Academia

This section explores the implications for academia following the research findings. The literature and the questionnaire survey indicate that up to 50% of practising simulation modellers first encountered and learnt the technique at university. The first section therefore explores the implications for teaching simulation, the second focuses on research issues, particularly where this study can be extended.

Teaching

As outlined in section 6.5.3, more emphasis should be placed on training methodology and modelling than is currently given in most vendor courses.

Research

This section is divided into two sub-sections, the first considers further research against the aims of this study, particularly where the results or findings require further work. The second suggests research efforts outside of the aims of this study, but suggested by the conduct of the research and the findings.

6.7 Further research against the aims of the study

It is clear that there are two research efforts that would extend and enrich this area further. The majority of this study has been based on qualitative research techniques as they lend themselves to research of an exploratory nature, particularly where the actions and motivations of people are concerned. In this way, it belongs to the right hand side of Kolbs (1979) learning cycle (Figure 6.4) previously presented in Chapter 2.

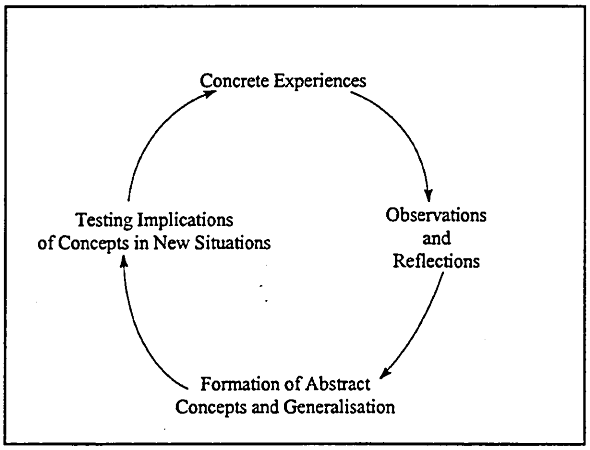


Fig 6.4: Kolb's Experimental Learning Cycle

The next stage is to apply the proposals and findings generated from the observations and reflections of the Case Studies and the Action Research and apply them in an experimental fashion. This deductive process will in turn produce new experiences and insights from which new theory can be generated, thus completing the learning cycle. The experiments conducted by Willemain (1995) in which modellers were asked to think aloud during a 60 minute model formulation exercise provide an interesting and applicable experimental basis to test the findings of this study.

The findings suggest that the simulation life cycle is a highly iterative process where it is difficult to draw dividing lines between the different phases of a simulation project. Yet, the study concentrates on the early stages of projects and pays scant attention to the later stages of experimentation and implementation as it was felt that these were well covered by the literature examined in the review. Although much of the literature focuses on experimentation, it does so from a statistical perspective. The richness of the case studies suggest that there is a wealth of qualitative information concerning experimentation that could be captured in much the same way as this study captured knowledge, techniques and tools concerning specification and design and development. The fact that VISS has had a significant effect on the manner in which models are designed and developed may indicate that experimentation may have undergone a similar transformation over recent years. It follows therefore that another study should continue to explore the remaining phases of the simulation life cycle in a qualitative manner.

6.8 Conclusions

- The study has demonstrated that the novel combination of a questionnaire survey, case studies and action research has proved to form a powerful methodology to explore the dynamics and interactions of the early stages of the simulation life cycle.

- The research findings have identified that the simulation life cycle is a highly iterative process where it is difficult to draw dividing lines between the different phases that make up the cycle.

- The model builder has to undergo a number of highly iterative procedures, which involve significant interaction with the stakeholders of the simulation project in order to develop a valid representation of the problem.

- The results indicate that a major impact of the development and wider user of VISS is that computer models are generated at a much earlier stage in the simulation life cycle and used not only to produce data, but to understand the nature of the problem being addressed.

Glossary

The following section provides a definition of the terms frequently used throughout the study.

Action Research	A research project that is undertaken to solve specific managerial problems and, at the same time, to generalise from the specific and contribute to theory.
Case Study	Research that generates descriptive data in the form of peoples written or spoken words or observations. The case studies in this research are focused around practising simulation professionals who are engaged in developing simulation models to solve real problems in industry.
Model	Discrete event simulation model.
Model Data	The information that describes the inputs, outputs and current state of the simulation.
Model Logic	The structure and rules of the model.
Model Representation Techniques	A graphical representation of a simulation model that is not language specific (e.g. Petri Nets, ACD's & Event Graphs).
Simulation	Discrete event simulation.
System	The components of the real world that are being modelled. Typically a manufacturing system (Supply chain, factory, workshop, cell or machine).
Visual Interactive Simulation Software (VISS)	Software that provides a graphical interface during model development and execution.

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Appendix A - Questionnaire

Walt Disney World Swan Hotel
Lake Buena Vista, Florida

As part of a three year research project studying Simulation Model Design, we are investigating model formulation and representation. We would be grateful if you would spend a few moments filling in this short questionnaire.

If you would like further information on our work, please contact us at the School of EngineeringSheffield Hallam University, England.

Dr. Terence Perera - t.perera@shu.ac.uk OR Ben Tye - b.s.tye@shu.ac.uk.

Where did you first encounter simulation ?.

[ ] College/University
[ ] Course at work
[ ] As part of a project at work
[ ] Vendor Presentation

How did you learn simulation ?.

[ ] College/University
[ ] Short Course
[ ] Self Taught
[ ] Vendor Course

Do you have a degree/professional qualification in the following ?.

[ ] Production/Manufacturing Engineering
[ ] Mechanical Engineering
[ ] Operations Research
[ ] Systems Modelling
[ ] Software Engineering
[ ] Other (please specify)
....

What is your background ?.

[ ] Business Management
[ ] Operations Management
[ ] Systems Analysis
[ ] Manufacturing Engineering
[ ] Other (please specify)
....

What is your current Profession ?.

(PleaseSpecify)....................................
....

How long have you been building simulation models ?.

[ ] Under 5 years
[ ] 5 - 10 years
[ ] 10 - 15 years
[ ] 15 - 20 Years
[ ] Over 20 Years

Roughly, how many simulation models have you built in this time ?

(Please Specify)
....

Please rank the following phases in order of difficulty (4 = easiest; 1 = hardest)

[ ] Definition of Objectives
[ ] Determination of scope and level of model
[ ] Data Collection
[ ] Validation of Conceptual Model

Please circle the typical minimum and maximum percentage of project time you spend on the following sections.

Definition of Objectives	10 20 30 40 50
Determination of scope and level of model	10 20 30 40 50
Data Collection	10 20 30 40 50
Validation of Conceptual Model	10 20 30 40 50
Model Programming	10 20 30 40 50
Verification of Programmed Model	10 20 30 40 50

Please tick any of the following techniques you use in model design

[ ] Structured English/Pseudocode
[ ] Entity Cycle/Activity Cycle
[ ] Condition Specification
[ ] Soft Systems Diagrams
[ ] Petri Nets
[ ] Flow Charts
[ ] Stochastic State Machine Diagrams
[ ] Event graphs
[ ] IDEF
[ ] SSADM

Other (Please Specify)
....

If you have developed your own system, why ?

[ ] You have tried the other techniques but don't feel they are applicable to model design.
[ ] You have never learned any the above techniques.

If you have never learned them, do you feel you would like to ? Yes/No

Model Design In Manufacturing Systems Simulation

Ben Tye **Dr. Terence Perera**

Sheffield Hallam University, School Of Engineering, Sheffield S1-1WB, UK

The effectiveness of a manufacturing system simulation exercise can be significantly reduced if inappropriate decisions are made during the initial model design.. This paper presents an overview of model design in manufacturing systems simulation based on the current literature and a practical perspective from a series of case studies with a number of simulation modellers and active simulation academics.

1. Introduction

Simulation is sometimes perceived in it's entirety as an exercise in computer programming and experimentation. Whilst the computer is obviously the mainstay of a simulation project, many important elements of the exercise are often overlooked. The early stages of a simulation project are vital to the success of the whole venture. Problem formulation, objectives definition, model formulation and model representation form the foundations upon which the whole project is carried out.

This paper explores these early stages of the simulation model building life cycle from a theoretical and practical perspective. A review of the current literature is presented together with the results of ten case studies conducted with leading UK academic and consultant simulation experts.

2. Background.

In the domain of manufacturing systems simulation, little research has been conducted concerning model design. Townsend and Lamb [1988] in creating factory simulations for low technology industries lament the "paucity of literature on the subject" and conclude that "although simulation model development receives greater emphasis in simulation manuals, the input creation is at least of equal importance".

Despite this, many sources have stressed the importance of conceptual modelling, albeit in different terms. Townsend and Lamb [1988] add that "the creation phase of a simulation model determines both its utility and validity" whilst Rozenblit and Lui [1990] emphasise the importance of 'Requirements definition'. From the field of information systems modelling, Hatami [1990] stressed the need for 'specifying data requirements' whilst Kangalosso [1993] states that " an inadequately formed and poorly understood conceptual model makes it difficult to predict and detect the consequences of a change in a concept or a rule ".

A recurring problem is the lack of a consistent terminology within modelling literature. Oral and Kettani [1993] employ the term *Conceptual Modelling* to describe the whole process of initial model design where as Balci [1990] and Nance [1987] break the process down into the three stages of *System Investigation, Model Formulation* and *Model Design*. Figure 1 compares the use of different terms describing model design from a number of different sources.

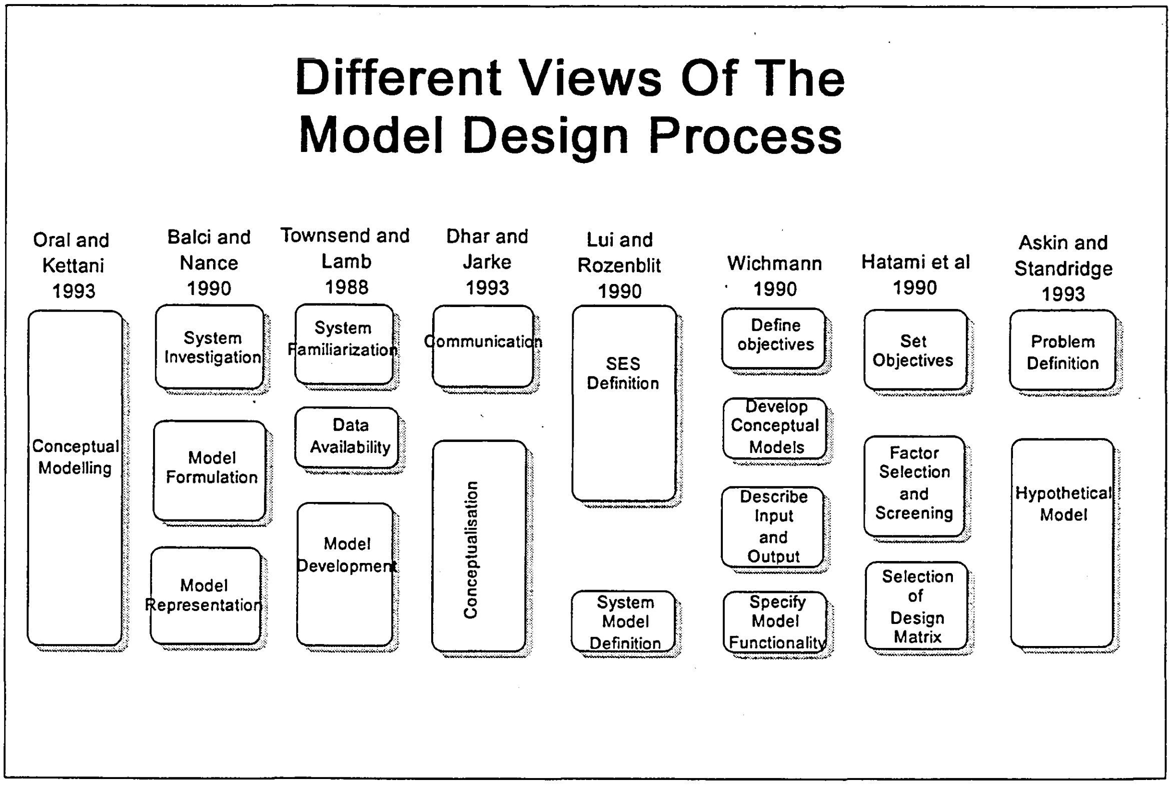

Figure 1 - A comparison of Terminology

Balci [1990] and Nance [1987] have developed a general representation of the simulation process as a number of phases. The Simulation Life Cycle (Figure 2) is stated as being iterative in nature and movement both up and down the cycle is common and to be expected when errors occur during one or more of the stages. Balci also states that the life cycle is a procedure for *general* modelling practises and as such may require additional indicators for specific areas of application. Since this paper is not concerned with programming and experimentation we focus on the shaded boxes of the life cycle (Figure. 2).

As the four stages of problem formulation, system and objectives definition, model formulation and model representation occur before programming and execution, they can be considered to constitute a process of model design. The first part of this paper discusses these processes from a theoretical perspective based on a literature review. The second part is concerned with determining *how* experts conduct these stages when simulating a manufacturing system.

3. Problem Formulation

Albert Einstein once said that the correct formulation of a problem was even more crucial than its solution. In any simulation project, the starting point is always some kind of problem. In existing manufacturing systems, the 'problem' is usually that the system in question is exhibiting unhealthy symptoms or has the potential to behave in a way that is considered undesirable by the stakeholders of the system. Common symptoms of problems in manufacturing systems are: lead times are highly variable and/or unknown, production schedules quickly deteriorate, poor plant capability, random increases in work in progress and the presence of "Fire fighting" activities i.e. unnecessary sub-contracting and overtime. When designing a manufacturing system, typical 'problems' are usually related to the physical components of the system, ie.

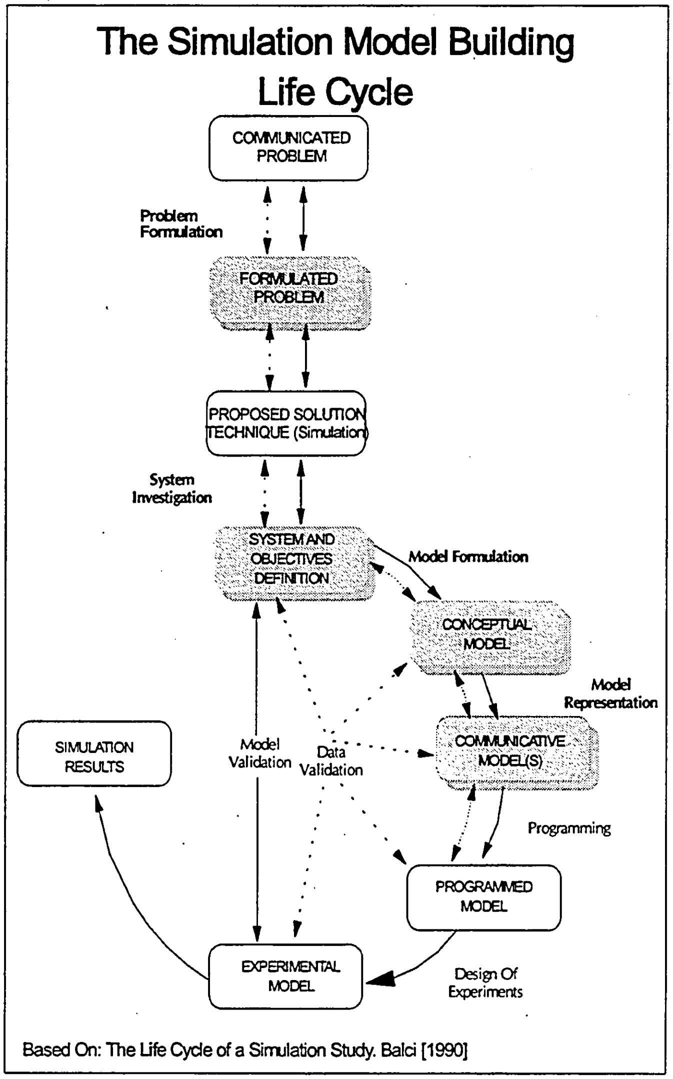

Figure 2 - The Model Building Life Cycle

number and capacity of machines, material handling systems and staff, or to the development of control systems, ie. sequencing, scheduling, maintenance strategy. In order to identify applicable solutions, it is important that the root cause is correctly identified, many simulation projects have gone over-budget and even failed due to the incorrect formulation of a problem.

However, identifying causes is sometimes not an easy task. There are many obstacles that can prevent correct problem formulation. Balci [1985] identified 20 indicators that may hinder the correct formulation of a problem. Examples include, the problem is too complex for the modeller to understand, people personalise problems, the root causes are time dependent and effects are identified as the problem rather than the cause.

4. Definition Of Simulation Objectives

Once a problem has been formulated, the stakeholders and modeller must define an objective for the project. Objectives definition is perhaps the most important stage of a project for it essentially determines the experiments that will be conducted using the model.

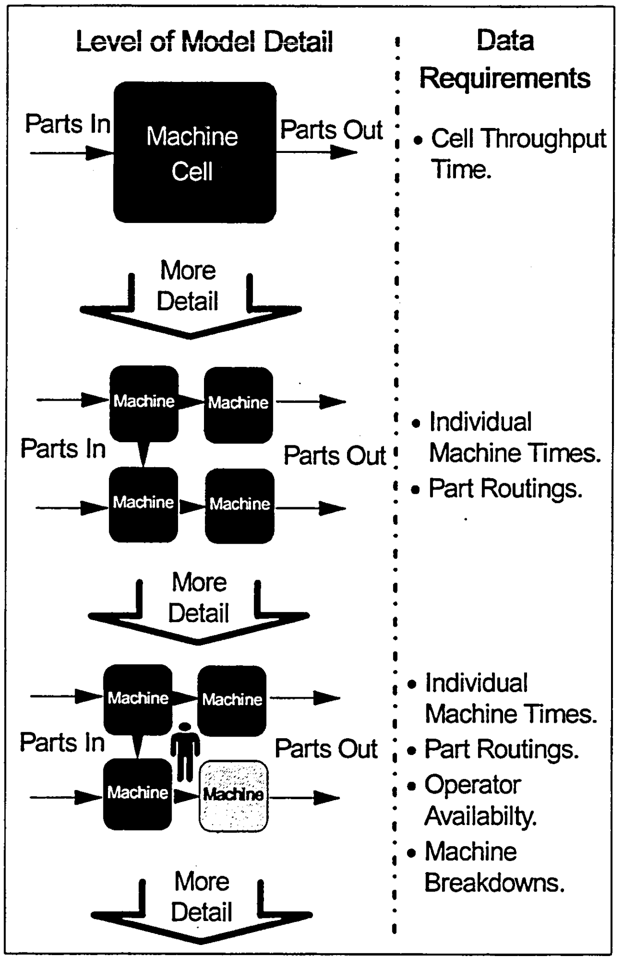

Figure 3 - Level of Model Detail vs Data Requirements

Objectives must have some kind of measurement attached in order to measure the success of the project, for example, "Reduce lead times by ten percent" is an objective with an attached measure. They also often have some kind of limit or constraint, for example reducing product lead times by ten percent is quite straightforward if millions of pounds is invested in new capital, however, the real question is how to do it without spending any substantial sums of money.

The most common applications for simulation in manufacturing in the UK are Plant Layout and Utilisation, Analysing material Control Strategies (MRP, JIT, etc.,), Analysing Required Staff Levels, Short Term Scheduling and Loading and Capital Investment Analysis [DTI 1991].

Simulation objectives determine what data needs to be generated by model during the experimental stage. In the above example, the model must generate lead times under different operating conditions, therefore to conduct experiments, the variables that affect lead times in our system must be identified and included in the model. Identifying what these variables are and deciding whether to model them constitutes the process of Conceptual Modelling.

5. Conceptual Modelling

The formulation of the conceptual model is where the modeller decides what system elements to include in the model and to what level of detail they should be represented.

The scope of the model must be sufficient enough to contain the problem. As long as the problem has been formulated correctly the scope of the model is fairly easy to determine. When modelling manufacturing systems, the model boundary can usually be represented by the input and output points of material to and from the area that contains the problem.

Considering to what level of detail the model should represent the system is a more complex issue. It is essentially a trade off between the length of time it will take to collect the data needed to model a particular system characteristic and whether modelling it will significantly affect the experimental results with respect to the modelling objectives. Figure 3 shows how the increase in model details generates an corresponding increase in data requirements.

As a rule of thumb, models should always include as little detail as possible as more data can always be gathered at a later stage, rather than spending lots of time collecting data that has no real impact on the experimental results. Figure 4 is a diagram developed by Robinson [1994] that shows the relationship of diminishing returns between level of model detail and total project time.

6. Model Representation

Model representation is the process by which the conceptual model is translated into a form that can be communicated to another person and then translated into a form executable by a computer.

Before the late eighties, model representation was essentially a paper based process. Models were represented by one of the many available techniques. Balci [1990] identified these as :

a) structured, computer assisted graphs,
b) flowcharts,

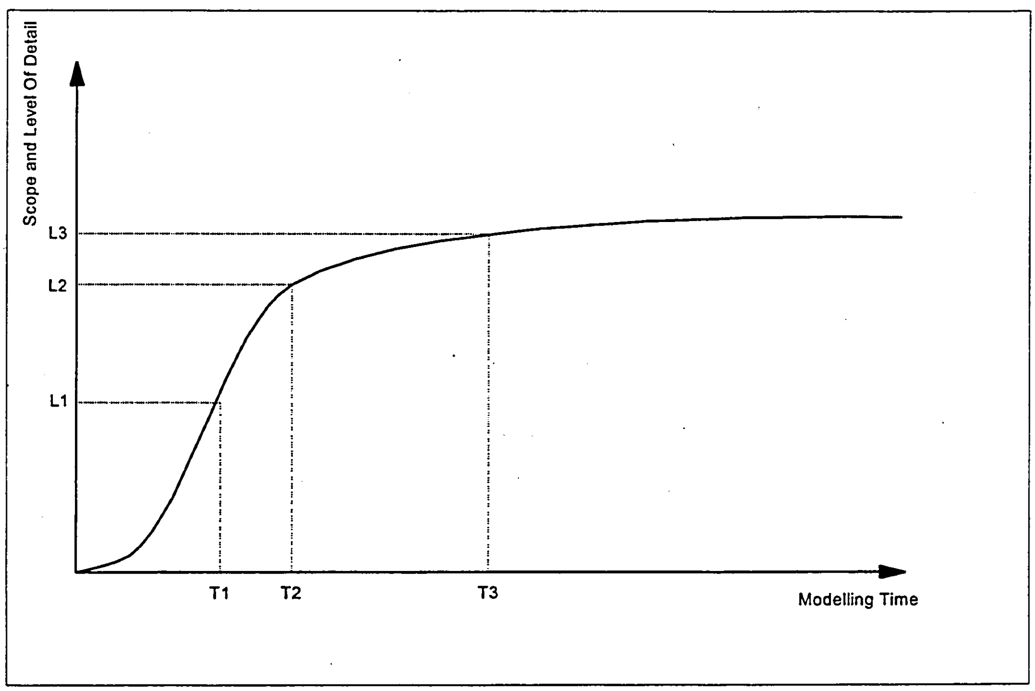

Figure 4 - Model Time vs Scope and Level of Model Detail

c) structured English and psuedocode,
d) entity-cycle (or activity cycle) diagrams,
e) condition specification [Overstreet and Nance 1985]
f) more than a dozen diagramming techniques.

Ceric and Paul (1994) have reviewed many of the available diagramming techniques employed during model representation. Examples include Petri nets, Activity Cycle Diagrams (ACD's) and Event Graphs.

Recently, a number of steps have been made to use model representation techniques to generate simulation programme code. Schruben [1992] developed the SIGMA programme that generates executable code from Event Graphs, Pflughoeft and Manur [1994] generated C++ code from ACD's and Keinbaum and Paul [1994] are developing a Graphical User Interface to support automatic programme generation of simulation models for manufacturing systems.

7. Case Studies with Simulation Practitioners.

As part of a continuing research project concerning model design, interviews have been conducted with ten simulation model builders in industry and academia in an attempt to gain a practical perspective on the model design process in manufacturing.

As noted in the literature survey, the stages of model design are described by many people in different terms. This called for a delicate approach to data collection in each case study in order to elicit and preserve the collected information and knowledge.

The discipline of Knowledge Elicitation is a rich source of techniques for data collection, Welbanks matrix of 'Types of Knowledge' by 'Knowledge Acquisition Methods' [198??] enabled us to select the most suitable techniques. The types of knowledge we are seeking to extract fall under the headings of Facts, Rules, Procedures and Experts Strategy. The techniques suggested to elicit these types of knowledge are (a) Interviews, (b) Talking Through Specific Examples and (c) Observing Protocols.

The main problem we faced was one of language. Every modeller uses different terminology to describe their procedure and the techniques they use. Therefore, the tools employed must be flexible enough to extract information without damaging its structure and meaning.

Wood and Ford (1993) describe a technique for structuring interviews during knowledge elicitation. Their approach consists of two stages, the first *descriptive elicitation* is used to derive the terms and concepts used by the subject. This is then followed up by a *structured expansion* stage in which subjects are interviewed using their own terms and concepts to elicit more detailed information about procedures and relationships.

Interview procedure

The programme for each interview was conducted as follows.

1. *Telephone Questionnaire* - Questionnaire to elicit 'Hard' facts concerning each organisation. Size, Number of simulation projects etc., Staff directly involved.

2. *Descriptive Elicitation Phase* - The first stage of the interview was a general investigation into the subject and their modelling practise. Typical questions explored the subjects history and their methods of building models. These questions were open ended, but structured in such a way to elicit the terminology and concepts used by the subject.

3. *Structured Expansion Phase* - The second stage of the interview was conducted using

the concepts and terminology elicited in the descriptive elicitation phase. This was intended to reveal the details of the modellers procedures.

Contact of interview subjects

The pilot case study subjects were contacted through a number of sources. Five leading simulation academics and five full time simulation consultants were interviewed over a three month period.

8. Conduct of pilot interviews

The interviews began with an explanation of the research project. The issues for exploration were not explicitly stated in order to avoid a bias response. The subject was also asked if they minded the interview being recorded on tape.

The questions began with the subject being asked to describe their history, in terms of computer modelling. If they attended a college of higher education and what they studied there, where they first encountered simulation.

The subject was then asked how they became exposed to simulation. As well as being a fact gathering stage, this was intended to reveal examples of model building that could be referred to at a later stage.

The interview was then guided to one or two of these particular examples. The subject was asked about the following topics.

- The formulation of problems and modelling objectives.
- How the conceptual model was formed.
- Whether any representation techniques were employed.

These topics were examined, by using a number of prompts to guide the subject to talk in their own terms about what they did and why. For example, one subject described the 'Mental Model' which can clearly be taken as a term synonymous with Conceptual Model.

Although the subjects began by discussing these areas in the context of one project, it was not difficult to then expand the discussion of each topic from a general perspective.

All these points were investigated and special attention was paid to why certain actions were carried out and what sort of tools and protocols were employed.

Rather than using a set of pre-written questions that must be asked during the interview, a checklist was employed. This list was referred to periodically during the interview and as each issue was explored it was ticked off the list. This ensured that while the interview was covering the issues, it was not forced to follow a predetermined order. More importantly, this checklist could be amended and issues for exploration added during the interview.

9. Case Study Findings

The interview transcripts were analysed by both authors according to the established protocol of content analysis. Statements referring to any aspect of the characteristics under study were highlighted and extracted.

The model design process is less formal than is indicated in the literature. Clear boundaries between many of the life cycle stages are difficult to draw and the degree of iteration in the project life cycle is much greater than is emphasised in the literature.

Fishwick [1990] has noted this and concluded that although formal methods are essential for organisational purposes, they do not always characterise the model development process from a practical perspective.

Problem Formulation

Problem formulation in manufacturing simulation is a process of discussion with various members of the manufacturing system from the shop floor operators to the production director. All the modellers indicated that it is important to have representatives from all areas of the manufacturing system present at the problem formulation stage to enable different perspectives on the problem to be aired. It is common for people from the same organisation to have different views of the same system. This stage requires considerable skill and diplomacy, particularly where an individual or group is directly responsible for a 'problem'.

Objectives Definition

Once the problem has been formulated the project objectives are defined. Sometimes only a broad objective is stated because some more detailed system investigation has to take place because the problem is not clearly understood.

Surprisingly, all the modellers indicated that the objectives usually change at some stage during the project. This occurs due to a number of reasons a) the problem has not been identified correctly b) the system changes during the project and c) the data to model a particular characteristic is unavailable.

Model Formulation

Once objectives have been defined, each modeller carries out a thorough system investigation. This was described by three of the consultant modellers as "immersing oneself" in the system. A walk-through of the production system following the path of parts, study of plant layout diagrams and discussions with machine operators and supervisors allow the modeller to gain an understanding of the system. The conceptual model is forming, the modeller is looking for the system characteristics which affect the variables in the objectives. One modeller described this process as "identifying the levers of change".

Each modeller uses a number of methods to simplify the level of detail in the model. In systems with a high variety of part types it is often easier to model a single part that is representative of a group of similar part types, a group of machines can be represented by a single machine with multiple capacity. Factory facilities can be modelled as a 'black box' with a time delay, shift patterns can be ignored if there is no change in labour quantity and machine operators do not need to be modelled unless the quantity of personnel available affects the capacity of the system.

Model Representation

The next step is to begin representing the system so the modeller can begin to consider how to write a programmed model. Three of the modellers used one of the reported representation techniques - ACD's. These diagrams were employed when they were trying to work out how to model complex interactions of model elements for programming purposes. However, they commented that they are not good for showing clients as a tool for validation purposes because they inform you about the statics of the system, but not the dynamics you are interested in.

One of the modellers had learnt and employed ACD's in the past, but no longer employed them for simulation. "I personally think that flow charts are not very meaningful to people.... it's very difficult to describe a dynamic system with a flow diagram... I feel the same way about Activity Cycle Diagrams".

All the experts carried out a similar procedure for model representation.

- Step 1 - Draw a physical layout of the manufacturing system.
- Step 2 - "Black Box" each process or cell and indicate the flow of parts between each box.
- Step 3 - Convert this flow chart into a set of Simulation Language blocks on paper. The paper model in each case was a hybrid diagram of a)simulation language elements i.e. queues, servers, branches b)written descriptions of events c) "black boxes" of operations d) arrows indicating material flow and control lines.

In each case this model representation was used a reference for generating a basic programmed model. It was rarely shown to the client as each modeller felt that it was important to show the client a programmed model because it represented the system dynamics.

This programmed model emerges at a very early stage in the life cycle. The model is sometimes a very crude representation of the system but serves an important purpose. It allows the clients to understand *how* a simulation model functions and enables them to understand what the modeller requires from them in terms of information and data.

At this point, much of the model data is approximated. All the modellers felt that it was important to capture the logic of the system before and extablish the scope and level of model detail before any extensive data collection takes place.

There then follows a cycle of interactice discussion with clients and more model programming until the model is deemed valid enough to conduct the experiments that enable the objectives to be met.

10. Conclusion

The case studies have highlighted a number of points that are not apparent or emphasised in the literature;

- The division of model design stages presented by Balci and others are much less evident in practise.
- The degree of iteration in the life cycle is much greater than indicated in the literature and is not due solely to mistakes made in previous stages, but is more a case of cyclic refinement.
- The modelling objectives change more often in practise than the theory would lead one to expect.
- The use of formal graphical representation techniques is lower than anticipated.

Some of these points may be due to the increase in availability of powerful graphical interactive simulation software for PC's. Many of the life cycle classifications were developed a number of years ago when computer availabilty was limited and expensive.

Further work is being conducted to refine the life cycle for manufacturing applications in the light of the above points. Expert knowledge pertaining to each stage will be attached as a set of pointers and guidelines which will undoubtedly form a useful tool for novice and expert alike.

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