Discrete Event Simulation – present situation and future potential

A strategic approach to performance enhancement in manufacturing systems

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Department of Product and Production Development
Chalmers University of Technology
Göteborg, Sweden 2002

THESIS FOR THE DEGREE OF LICENTIATE ENGINEERING

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Published and distributed by:
Department of Product and Production Development
Chalmers University of Technology
S-412 96 Göteborg, Sweden

ISSN 1651-0984
Rapport nr 7

Printed in Sweden
Reproservice at Chalmers University of Technology
Göteborg 2002

Abstract

This thesis focuses on Discrete Event Simulation as a time saver, applied to manufacturing industries in order to increase performance, productivity, and profitability throughout their conducted processes.

The thesis provides a base for implementation and more effective use of Discrete Event Simulation in manufacturing systems by applying Discrete Event Simulation technology through an overall performance aspect. A top view of the technology is achieved, including the situation in industries today, through case studies and literature studies and concluding with a future approach on the use of Discrete Event Simulation. The future approach consists of:

Firstly, a *framework* is presented to set the scene *when* to use Discrete Event Simulation.

Secondly, a *methodology* is proposed to shed light upon *how* to conduct a Discrete Event Simulation project.

Thirdly, Discrete Event Simulation *software* for shorter and less complex problems is presented, to enable production engineers to become Discrete Event Simulation *users*.

Fourthly, a description on how Discrete Event Simulation can be used to create ORDER and to structure the *data*, *information*, and *knowledge* of the processes in manufacturing systems.

The results of the research shows that *genuine production-engineering knowledge* is an irreplaceable source, essential for achieving maximum competitive advantages and enabling performance-increasing activities to be successful. *Structured* and correct *data* and *information* are needed for DES projects to become as powerful as they *can* be. However, *structured* and correct *data* and *information* are needed anyway for any process, which is a subject for improvement.

Keywords: Discrete Event Simulation, Performance enhancement, Productivity development

Acknowledgements

Some people say that being a PhD student is a lonesome road, and most of the time is spent within the four walls of an office, studying, writing and thinking. However, in this case that is not true. Without the help from many others with ideas, discussions, team working, projects and financing the task should not even be close to finished. The persons mentioned below are some of those people, who have contributed to this thesis.

First of all I would like to thank my supervisor, Professor *Anders Kinnander* at Chalmers, for the guidance, ideas, and discussions.

The Swedish research program PROPER has been a valuable supporting source for me both in terms of financing, courses provided, discussions, and contacts with other people within the research perspective. In the research group, many companies and persons have been involved since the project started in the spring of 2000. Fruitful discussions and experience-sharing have been made with e.g.:

Peter Calås SKF, *Mats Jackson* MDH, *Mats Ågren* ABB, *Peter Gröndahl* KTH, *Mats Björkman* LiTH, *Kjell Björklund* ABB, *Bengt-Göran Rosén* HH, *Anders Carlson* Posten, among many other persons from companies such as, SOLME AB, Flextronics, Ericsson, Volvo, SKF, ABB, Posten, KTH, LiTH, LTH, and others.

I also would like to take the opportunity to send my special gratitude to:

Thomas Grünberg, co-author of one of the appended papers, for many interesting discussions on various topics, both at work and privately.

Joacim Johnsson, main author of one and co-author of another paper, for excellent team work in research, studies, lecturing, and in private life.

Pär Klingstam, main author of one of the appended papers, for fruitful discussions and support on simulation knowledge.

Ulf Eriksson, co-author of one of the appended papers, for valuable insights in the simulation "jungle" and interesting hours behind the computer screens.

Jürgen Kaiser, co-author of one of the appended papers, for attention-grabbing discussions on resetting and simulation as well as other areas.

Peter Nordell, for numerous discussions on performance measurements and other topics, as well as enjoyable private life events.

Kerstin Johansen, for fruitful cooperation within the PROPER project.

Stefan Tangen, for numerous discussions on performance, productivity, and profitability.

Chester Wickenberg, my advisor in English, for giving this thesis a more precise touch.

I would like to thank all my past and present colleagues at the department of Product and Production Development for all their friendly support and sharing of the delightful working environment. Special thanks to:

Peter Almström, Bertil Gustafsson, Göran Stigler, Ann-Charlotte Hansson, Sture Johansson, Henrik Westberg, Fredrik Gunnberg, Marcel Escurcell, Daniel Wiklund, Rolf Berlin, Dick Olofsson, Li Xiao, Lena Bendrioua, Patrik Dahlman, and others.

Many simulation practitioners have been involved in this work during the research, and I am very grateful to have been given the opportunity to meet and discuss the simulation topic with, among others:

Torbjörn Danielsson, Johan Olsson, Edward Williams, Fredrik Henriksson, Bengt-Göran Olsson, Per Gullander, Lars Randell, and Lars Holst.

I would like to turn my gratitude and the readers attention to my family and friends, for the never-ending support and sharing of what life has to offer for the day being, both in joyful and hard times:

To all my *grandparents*, for sharing their wisdom and experiences in life.

To my *cousins* and their *parents*, for their support and friendliness at all times.

To the friendly people at *OK Alehof,* and *Ale-Surte BK*, for all the joyful events.

To my friends Karlo Madjarevic, Thomas Dalebjörk, Kanita, Melita, and Halid Cukur, and others, for all enjoyable life-sharing experiences.

Last but not least I would like to give my warmest appreciation to the ones I love, *my mom, Birgitta*, *my dad, Ingemar,* and my always understanding *sister, Karin*. Thank you for the encouragement and life-sharing throughout all times!

Göteborg, October 2002

Björn Johansson

Appended Papers

Paper 1:

Klingstam P., Johansson B.: *"Towards a Strategic Framework for Logistic and Production Flow Simulation"*, In The New Simulation in Production and Logistics: Prospects, Views and Attitudes, Eds. Mertins and Rabe, IPK Berlin, Eigenverlag, Berlin, Germany, pp. 45-54, 2000.

Paper 2:

Johansson B., Grünberg T.: *"An Enhanced Methodology for Reducing Time Consumption in Discrete Event Simulation Projects",* In the 13th European Simulation Symposium: Simulation in Industry, Eds. Giambiasi and Frydman, SCS Europe Bvba, Marseille, France, pp. 61-64, 2001.

Paper 3:

Johansson B., Johnsson J., Eriksson U.: *"An Evaluation of Discrete Event Simulation Software for "Dynamic Rough-Cut Analysis""*, In Proceedings of The 35th CIRP International Seminar on Manufacturing Systems "Manufacturing Technology in the Information age", Seoul, Korea, pp. 348-355, 2002.

Paper 4:

Johansson B., Kaiser, J.: Turn Lost Production into Profit. -Discrete Event Simulation Applied on Resetting Performance in Manufacturing Systems, Proceedings of the 2002 Winter Simulation Conference, ed. E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, San Diego, California, Dec 8-11, 2002 (Accepted for publication).

Paper 5:

Johnsson J., Johansson B., Kinnander A.: Information structure to support Discrete Event Simulation projects, (working paper).

Contents

1 Introduction

In the beginning there was nothing. God said, 'Let there be light!' And there was light. There was still nothing, but you could see it a whole lot better.

Ellen DeGeneres

1.1 Research motive

The human race has been striving for *division of labour* since the Stone Age (Wild 1972), even if it was not put on paper until Adam Smith wrote *Wealth of Nations* in 1776. Maslow's *Theory of Human Motivation* (Maslow 1943) describes the motives for humankind to make *division of labour* increasingly effective, which in turn brings forth human society evolution. From the Stone Age until today the division of labour has had massive impact on the human world.
The phrase *Survival of the fittest* used by Herbert Spencer in the 19th century while commenting on Darwin's book *On the origin of species* (1859), can surely be applied on today's manufacturing industries, not only locally, but even in a *global* perspective. Today, in the western world, the aspects of the Swedish Technology Foresight (IVA 2000) and the American version of it, Visionary Manufacturing Challenges for 2020 (2002), is about to come true, according to the over 130 academics from around the world who participated in forming these visions.

The predictions for manufacturing industry according to Visionary Manufacturing Challenges for 2020 (2002):

1. The competitive climate, enhanced by communication and knowledge-sharing, will require rapid responses to market forces.
2. Sophisticated customers, many in newly developed countries, will demand products that are customised to meet their needs.
3. The basis of competition will be creativity and innovation in all aspects of the enterprise.
4. The development of innovative process technologies will change both scope and scale of manufacturing.
5. Environmental protection will be essential, as the global ecosystem is strained by growing populations and the emergence of new high-technology economies.
6. Information and knowledge on all aspects of manufacturing enterprises and the marketplace will be instantly available in a form that can be effectively assimilated and used for decision-making.
7. The global distribution of highly competitive production resources, including skilled workforces, will be a critical factor in the organisation of manufacturing enterprises.

The other group of academics predict that the future for manufacturing technology in the year of 2015 is, according to Swedish Technology Foresight (IVA 2000):

1. The customer wants individualised products
2. Individuals and companies can live locally and act globally

3. Production is pursued in project form
4. Circular business systems; the customer buys functions
5. The intellectual fund is the most important means of competition

As can be observed, some of the predictions from Visionary Manufacturing Challenges for 2020 (2002) correlate with the ones from IVA (2000), which is promising for both visions to come true. In fact, some of the above stated visions are already showing up in industry today, such as individualised products, circular business systems, the customer buys functions, etc.

The above described visions, IVA (2000) and Visionary Manufacturing Challenges for 2020 (2002) deal with important performance factors for successful manufacturing industries, such as flexibility, dependability, speed, and quality.

However, there is, and always has been, one vital resource needed in order to achieve any kind of results concerning manufacturing technology, and many other things in life… *time*.

Time is a resource that can be used to produce and consume other resources; this is what makes time valuable, and this is what makes humans struggle over it. By carrying out operations more effectively and efficiently, we try to gain time in life to be able to experience, see, do, learn, and develop new things. *Time* is therefore also the most vital key factor, in life and in manufacturing technology. However, humankind does not yet easily manipulate the course of time. But, it will perhaps become useful in the future if $E=mc^2$ (Einstein 1916) can be applied in manufacturing development, in order to "slow down" time to complete more tasks in less time. Nevertheless, today, other key factors for success *can* be manipulated. This thesis will describe the performance key factors most related to manufacturing technology, and provide information on how they can be controlled effectively by using Discrete Event Simulation.

Simulation is a powerful, but also, therefore, a dangerous tool to utilise. Simulation *can* give the answers to difficult, complex, and often seemingly impossible problems and *dynamical* effects in and on a system. However, the questions that have to be faced must not only be accurate for correct answers by the simulation model, but also interpreted by other persons involved in the model-building and data collection which is the base for the *dynamical* behaviour of the finally modelled system.
Using a simile, one can say that simulation is like looking into a crystal ball and have visions of the

future. It is powerful, indeed! However, what if the visions from the crystal ball are fallaciously interpreted?

1.2 Research background

A research project, called Productivity Development in Manufacturing Systems (Kinnander and Gröndahl 1999), was started in the year 2000. This project is a part of the PROPER programme (Programme for Production Engineering Education and Research), funded by The Swedish Foundation for Strategic Research. This project aims to assist the Swedish industry in finding improvements to reclaim a higher productivity development, which used to be a genuine strength in Sweden as an industrial country. The main actors in the project are:

Kerstin Johansen:
New product introduction and industrialisation, processes, publication example: Product introduction within extended enterprises (Johansen and Björkman 2002).

Peter Nordell:
Productivity and efficiency in business economic manufacturing systems, publication example: Profitability development through resetting reduction in manufacturing systems (Kaiser et al 2002).

Stefan Tangen:
Productivity measurement and improvement of automatic assembly systems, publication example: RATOC - a simple method for productivity improvement in robot workcells based on the theory of constraints (Tangen 2002b).

Thomas Grünberg:
Factors and methods for improvement of performance, publication example: Operations Process Mapping, A Model For Process Mapping and an Application (Grünberg and Karlsson 2002).

Björn Johansson:
Discrete Event Simulation as method and tool for performance improvement.

The companies, universities, and programmes shown in *Figure 1* are supporting the five PhD students.

Figure 1. Universities (top), Programmes (top), and Companies (below) participating in the PROPER programme: Productivity development in manufacturing systems (Kinnander and Gröndahl 1999).

1.3 Problem description

When *time* is short, many companies often tend to focus on the short-term economical aspects in their business, such as dismissing staff, increasing outsourcing, selling the company, or even going out of business. These acts by managers of companies in Sweden have had some serious consequences on the Swedish economy during the last decade. Many companies now have foreign owners, and even more companies have been outsourcing the core-production facilities, either to foreign companies in Sweden, or moved the production-site abroad. This trend is still going on!

The handling of these aspects, essential for economical prosperity and growth, lowers the budget for future prosperity and economical growth. In Sweden, production engineering has suffered large losses in the striving for attention on important key factors for successful enterprises. This can be verified with numerous examples from the Swedish industry, where foreign companies have been successful in taking over Swedish production sites and making them profitable. The left part of *Figure 2* represents the actions of many Swedish companies today. However, these actions *have* to be turned around in order to get the effect showed in the right part of *Figure 2*. To make an effort towards solving these ”anorectic” activities in Swedish industry, this research project was started, mainly in order to identify and evaluate the key factors that drive productivity growth in industry, but also to find potential acts to perform in the companies to get the spiral going in the upward direction again, according to the right part of *Figure 2.*

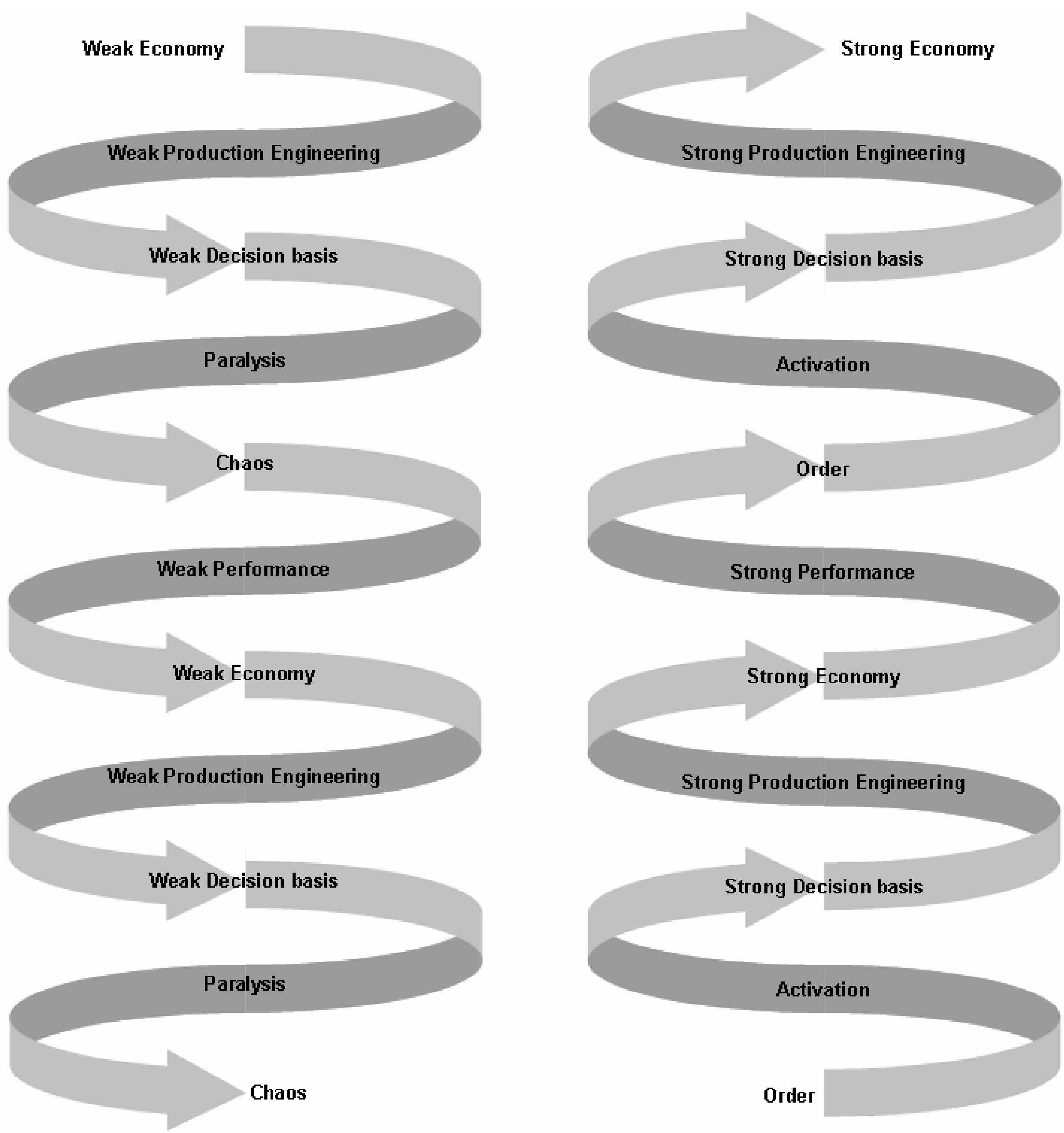


Figure 2. Left: decreasing prosperity and no development. Right: increasing prosperity and development.

This thesis will enlighten the possible potentials of Discrete Event Simulation as a tool and method for increased performance in industrial companies in three ways, according to the evaluation theory described in Stevrin (1991):

- Control, with the ambition to describe.
- Learning, with the ambition to understand.
- Development, with the ambition to change and improve.

1.4 Research questions

RQ 1: *How can DES be integrated into the life-cycle of a process in an efficient way?*

RQ 2: *How should a DES project be conducted to suit the unique present prerequisites of each process?*

RQ 3: *What kind of DES software is suitable to use in early life-cycle stages?*

RQ 4: *How can DES increasing the contribution to the overall performance of a company?*

1.5 Research objectives

The overall research objective is to find, structure, and document the *real* potential features of DES, both negative and positive, as a tool for performance enhancement in industrial companies.

Firstly, this needs to be done in order to enable everybody to understand the *true* potential of DES as a performance enhancer.

Secondly, to reveal and bring understanding to the risks and opportunities which come with the use of DES.

Thirdly, to shed light upon the requirements for using DES as a performance enhancer.

1.6 Thesis structure

Chapter one puts the research in its context and describes the motive for it, followed by the description of the problem area, and sums up with research questions and objectives, ending with a description of the scientific procedures.

Chapter two is contributing to the thesis with a frame-of-reference on performance, including performance factors, -measurements, -tools, and -methods.

Chapter three consists of a frame-of-reference on Discrete Event Simulation, mainly describing questions concerning how, what, and when with a DES focus.
Chapter four describes five case studies and their contribution to the research forming this thesis.

Chapter five summarises the results from the appended papers and puts them into a total context.

Chapter six critically reviews the results, answers the research questions, corresponding to the objectives.

Chapter seven concludes the thesis and urges future research by formulating new research objectives.

Chapter eight discusses the future research of the area.

1.7 Scientific procedures

During the work with this thesis many contacts with companies in Sweden (e.g. ABB, SKF, Posten AB, Scania, Ericsson, Flextronics, Volvo Cars, Volvo Trucks, SAAB, ABS Pump, etc.) and some abroad (e.g. Samsung, Fraunhofer Institute, etc.) have been made and mostly in-depth analyses were conducted in the form of case studies: *See Definition 1. Case Study* in *List of Definitions* Extensive literature studies also have contributed to the foundation of this thesis. Some of the case studies will be presented in Chapter *4, Case Studies*, and some of the literature studies in chapter *2, Performance*, and chapter *3, Discrete Event Simulation.*
At the beginning of this research project, explorative studies were made (Yin 1994), in order to establish a base to form research questions from.

1.7.1 Quantitative – Qualitative research

The description of the research problem decides if the research is to be qualitative or quantitative. Quantitative research is researching for knowledge that measures, describes, and explains phenomena, or searches for knowledge to investigate, interpret, and understand phenomena (Patel and Tebelius 1987).
In qualitative research, historical studies on the problem should be made, concerning how different explanations affect the way the problem should be handled. The main tool for the researcher in qualitative research is comprehension, which is why the problem must be understood in a wider perspective (Patel and Tebelius 1987).

1.7.2 Objectivity – Subjectivity

The scientific viewpoint and the research problem determine how the research deals with objectivity and subjectivity. Qualitative research is based on other people's inner thoughts, and interpreted through the language. It is a difficult task to stay objective and great care must be taken when interpreting the results from conversations with other people (Patel and Tebelius 1987). The researcher therefore is responsible for the quality of the research.

1.7.3 Participant - Observation

In participant-observation, the researcher is not just a passive observer. Instead, the researcher may actually participate in the case study in different roles (Yin 1994). The main advantage with this approach is the possibility to study events in their context at the same time they happen. The main disadvantage is that participant-observation requires more attention, and is more expensive than the mere observing approach (Patel and Tebelius 1987, Yin 1994).

1.7.4 Case study methodology

Yin (1994) defines the case study methodology as an empirical enquiry that

- investigates a contemporary phenomenon within its real-life context, when
- the boundaries between phenomenon and context are not clearly evident, and in which
- multiple sources of evidence were used

1.7.5 Research methods used

During the research conducted when building this thesis, the above research methods have been used. Tablets 1 and 2 below show what kinds of research were used for the different parts of the thesis.

Table 1. Research methods used during the case studies 1-5

CASE STUDY	QUANTITATIVE	QUALITATIVE	PARTICIPATED	OBSERVED	LITERATURE STUDIES	CASE STUDY METHODOLOGY
1		x		x		x
2		x		x		x
3	x			x	x	x
4		x	x		x	x
5		x	x		x	x

Table 2. Research methods used during the research building papers 1-5

PAPER	QUANTITATIVE	QUALITATIVE	PARTICIPATED	OBSERVED	LITERATURE STUDIES	CASE STUDY METHODOLOGY
1		x	x		x	x
2		x	x		x	x
3	x			x	x	
4		x	x		x	x
5	x			x	x	

1.8 Delimitations

Standards such as CIMOSA GRAI/GEM or GERAM and alike, for use in the DES framework, will only be discussed briefly in this thesis. For further information on these standards see Klingstam (2001), Vernadat (1996), AMICE (1993), Doumeingts et al (1995), and IFIP-IFAC Task Force (1998).

Project management is not dealt with in this thesis, only in the context of Discrete Event Simulation projects.

2 Performance

It is much more difficult to measure
non-performance than performance.

Harold S. Geneen

2.1 Introduction to Performance

This chapter will provide a frame-of-reference concerning performance objective on different levels in a process. The overall performance of a company consists of many processes, and they can be described from many different views. This thesis will mainly follow the established theory on performance objectives described by Slack et al. (2001), while other views will be briefly discussed and commented.

During the conduction of the research for this thesis, the research group agreed on a mutual definition of: Performance, productivity, profitability, effectiveness, and efficiency. The relations between these terms are discussed in Tangen (2002a), and shown in *Figure 3*. The definitions can be found in *List of Definitions*.

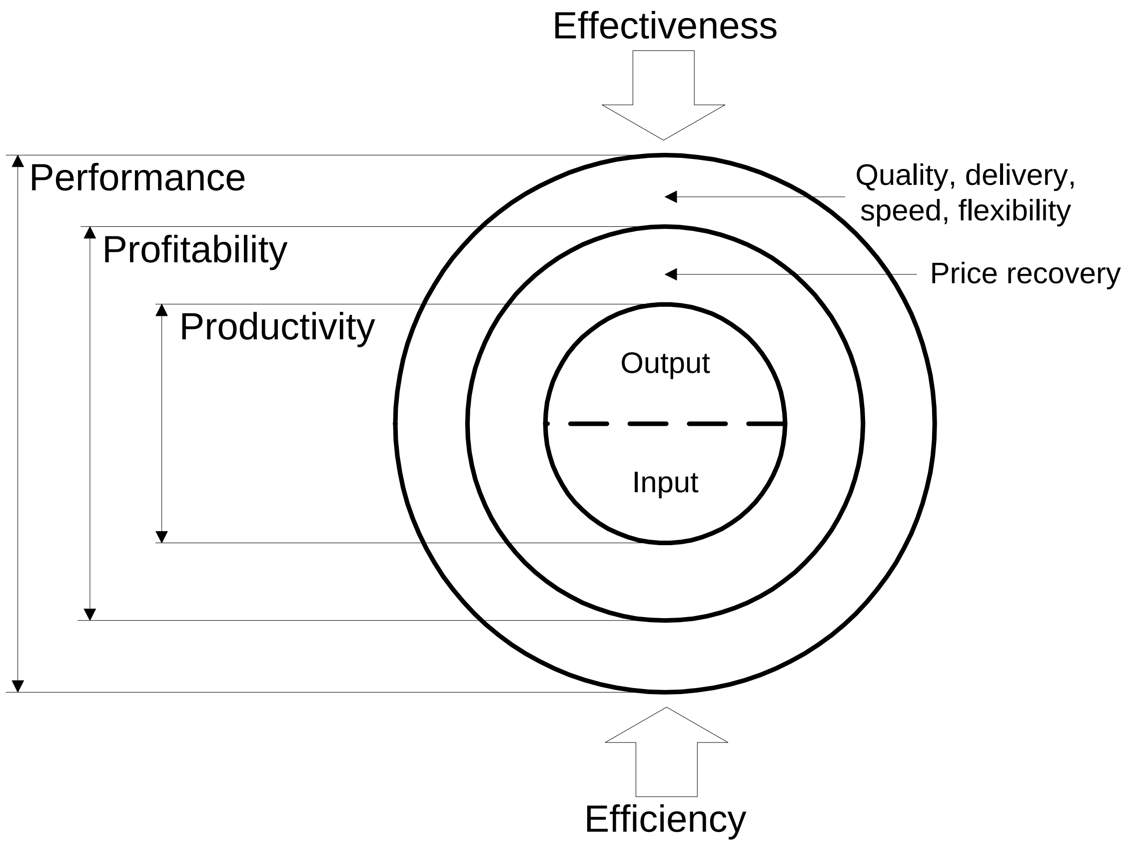


Figure 3. Relations between Productivity, profitability, performance, effectiveness, and efficiency (Tangen 2002a)

Performance is the overall indicator, as can be seen in *Figure 3*, and includes productivity, profitability and other central terms. In turn, the overall performance can be divided into smaller parts, factors, and measurements. They are shown in *Figure 4*. The lower part of *Figure 4* also shows some examples of methods and tools used to affect the overall performance.

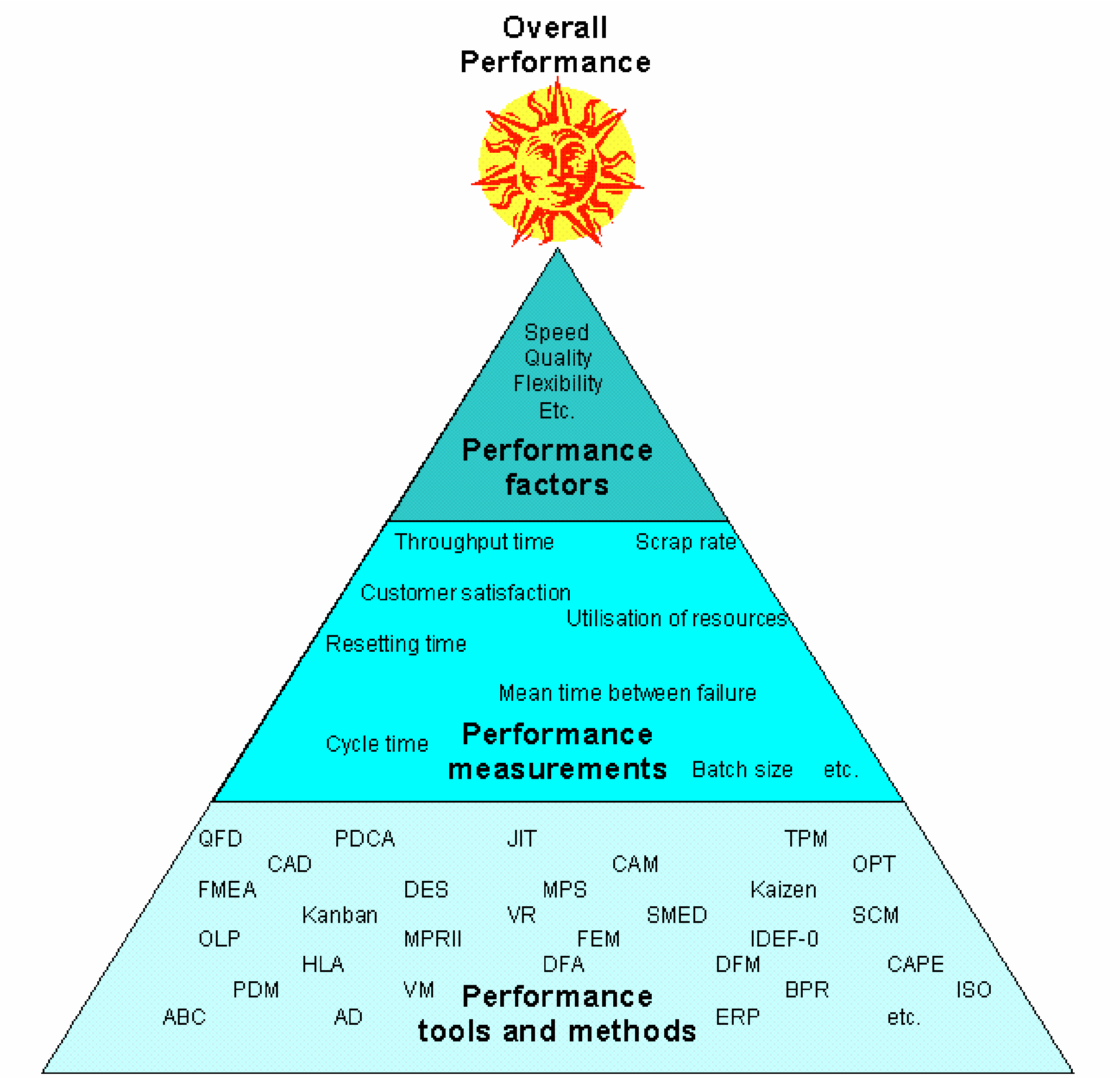


Figure 4. A performance pyramid, describing different levels of performance.

2.2 Performance factors

For organisations to succeed in the long term the contribution of its process functions is of vital importance (Slack et al 2001). Slack continues by naming five performance objectives, here called performance factors, which are the key factors for success.

Do things right, would prevent mistakes and provide the customer error-free goods or services which are fit for their purpose. These five performance factors are shown in *Figure 5* below.

Do things fast, would minimise the time between a customer asking for goods or services and the customer receiving them in full. Including minimising your organisations WIP (Work In Process).

Do things on time, would increase the reliability of the organisation's processes for the customers, by delivering the goods or service on time.

Change what you do, would increase the flexibility of the organisation in order to be able to satisfy a customer's special needs, or to be able to adapt to a changing market.

Do things cheaply, would enable a price advantage compared to other companies, while still allowing a profit to the organisation.

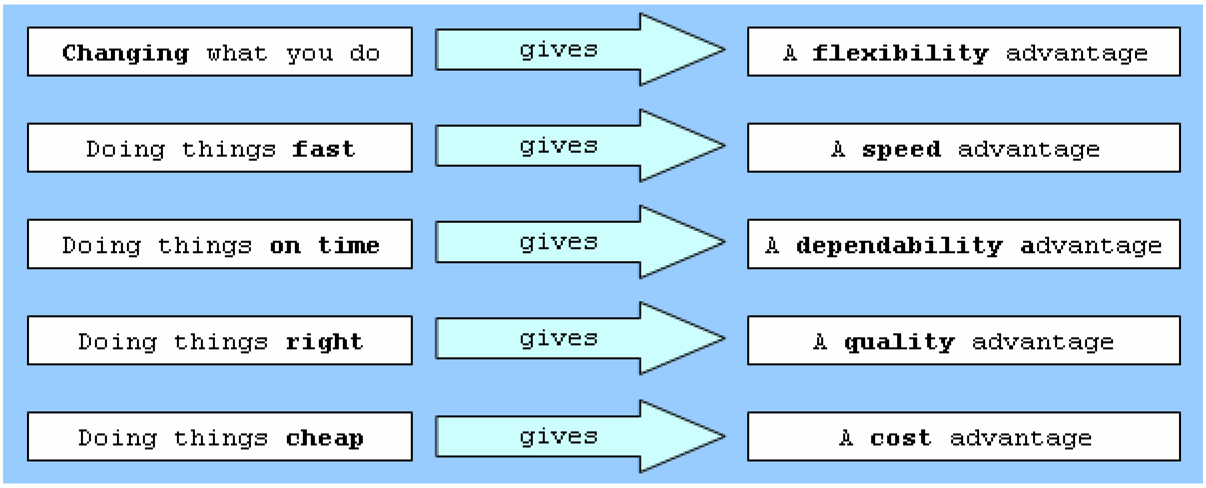


Figure 5. A process contributes to business strategy by achieving five performance factors.

While encouraging and improving these five performance factors, many other secondary factors will be improved as well, for example: While improving the quality of the processes, not only is an advantage in customer satisfaction achieved, but also less rework is needed, less raw materials are used, less working hours are used, less WIP, etc. *Figure 6* below shows the relations between these five performance factors and their internal and external effects on an organisation.

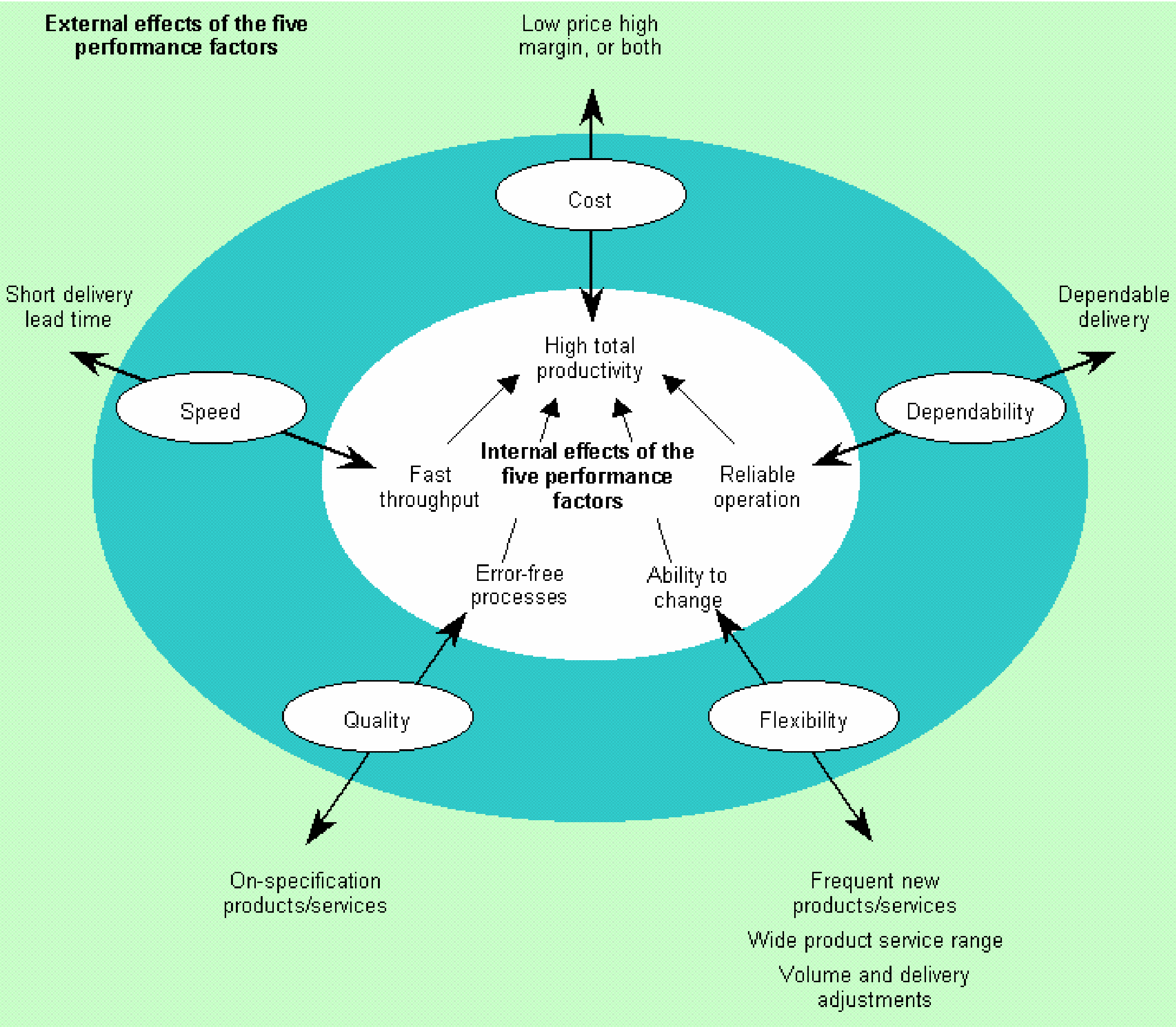


Figure 6. Performance factors have both internal and external effects, internal cost is influenced by the other performance factors (Slack et al 2001).

In this thesis, overall performance covers the impact of all acts to which a process is exposed, both internally and externally, according to *Figure 6*.

Many other publications concerning performance factors are on hand (Kaplan and Norton 1996, Cross and Lynch 1998-1999, Maskel 1989, Dixon et al 1990, Bititci and Carrie 1998, Grünberg and Karlsson 2002, etc.). Depending on their definition of each factor and structural approach, they are different. However, they mainly cover about the same interests as Slack et al (2001). The difference often tends to depend on the specific approach: they might have a desire to fancy one or the other factor. In order to fulfil the targeted processes, the most critical factors are needed. In the end it all comes down to one thing: Increase the overall performance of the targeted process. However, if the definition is too concentrated on one factor the risk for suboptimisation is very high.

2.3 Performance measurements

The factors in section *2.2 Performance factors* above have to be quantified in order to be controllable. Performance measurements are used to quantify the factors (Neely 1993). This enables the performance measurements to act as indicators for the factors. However, the performance measurements have to be carefully selected in order to cover the factor with minimum risks for suboptimisations. If these measurements are wrongly selected and then used to manage the organisation, it may have disastrous consequences. Even when they are rightly selected, one must often consider whether the measurements are useful as indicators in the present situation. Perhaps the measurement is not suited to use at the time being?

There may be a need for many performance measurements to monitor only one performance factor, and one performance measurement may also monitor parts of more than one performance factor at the same time. On the next page in *Table 3* some typical partial performance measures are shown for each key performance factor (Slack et al 2001).

Table 3. Examples of Performance measurements for the five performance key factors described in Slack et al (2001)

Performance factors	Some typical measures
Quality	Number of defects per unit Level of customer complaints Scrap level Warranty claims Mean time between failures Customer satisfaction score
Speed	Customer query time Order lead time Frequency of delivery Actual *versus* theoretical throughput time Cycle time
Dependability	Percentage of orders delivered Average lateness of orders Proportion of orders in stock Mean deviation from promised arrival Scheduled adherence
Flexibility	Time needed to develop new products/services Range of products/services Machine resetting time Average batch size Time to increase activity rate Average capacity/Maximum capacity Time to change schedules
Cost	Minimum delivery time/average delivery time Variance against budget Utilisation of resources Labour productivity Added value Efficiency Cost per process hour

These performance measurements can be useful by identifying potential improvement areas as well as monitoring the extent of a recently made improvement (Slack et al 2001).
Additional and more specific information on performance measurements can be found in, for example: Bititci and Turner (2000), and Wilson (1994).

2.4 Performance tools and methods

There are thousands of performance tools and methods to use in order to monitor and influence the measured processes, which in turn are indicators for the factors that are shaping the total performance of a process. Many of these tools and methods are shown in *Figure 4* (Chapter *2 Performance*), and a handful of them will be mentioned and very briefly described here, mainly the ones that can complement and/or be a substitute for Discrete Event Simulation.

2.4.1 Scheduling

Scheduling is a substitute for DES when it comes to gaining control of a process on short notice. Scheduling is a systematised way of taking control of a process by manipulating different performance measures (Anderson 1994). There is no applied theory or discipline behind scheduling, according to Baudin (1990). However, some performance measurements are of major interest while trying to optimise a process using scheduling. These factors can be, according to Anderson (1994):

- Lead times
- Buffer sizes
- Capacity utilisation
- Staff levels
- Material flow
- Variances in demand

2.4.2 Process mapping

Process mapping is a great *complement* to DES activities since a valid process map describes the process to be studied in a standardised approach, which demands less effort to understand than examining the real system. The information from the process mapping is an important tool for analysis of the process flow. The process map in many cases is the first step to take when it comes to improvement work in an existing plant (Loch and Terwiesch 1999, Narasimhan and Jayaram 1998).

There are a number of different standards to follow while creating process maps (Olhager 2000). However, the main issue is that the same standard is used throughout the organisation, to increase the understanding. A typical process map standard consists of a few different kinds of elements, which are combined and connected with arrows to show the relations between the elements. An example from the case study 3 is shown in *Figure 7*.

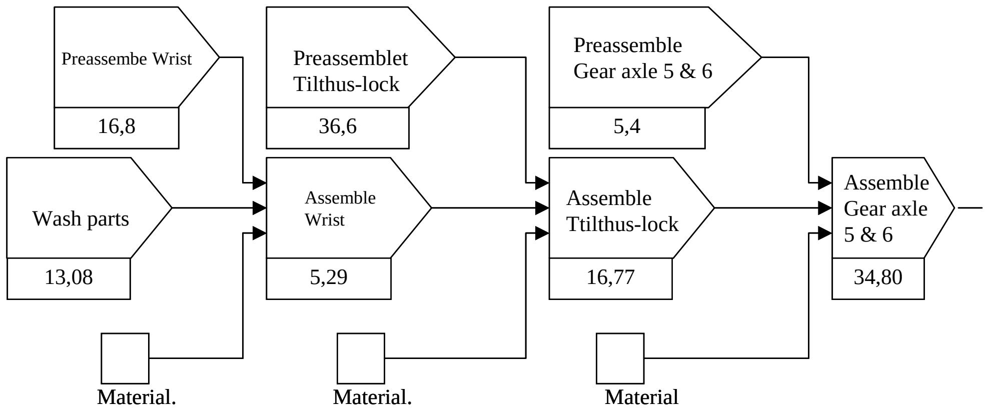


Figure 7. A part of a process map from case study 3 (Grünberg et al 2002a)

During the creation of a process map there will frequently come forth areas where improvements can be made. This is where the process map is a *substitute* to the DES activities.

2.4.3 OEE

OEE stands for Overall Equipment Effectiveness, which is a measurement method to gain overview and control of the losses in a manufacturing system. The measured losses can then be used as input parameters for a DES model. The DES model will then evaluate the losses in their *dynamic* behaviour and, hopefully, in the end some answers can be found on how to lessen the impact of the losses on the system, which can be implemented into the real-world. The results of the implementation of the findings can then be measured again as a follow-up, and perhaps reveal even more improvement potentials.

2.4.4 TPM

The strategy has been to cope with reduced lead-time and to increase efficiency. The original name of the concept is Total Productive Maintenance (TPM) (Nakajima 1989). TPM consist of two main aspects, i.e. a structured approach that uses a number of tools and techniques to achieve an effective plant and machinery and to measure its effectiveness. A philosophy, based on the empowerment and encouragement of factory-floor personnel from all areas, is also included.
TPM has a strict definition in five steps, (Nakajima 1988), (Suzuki 1992):

1. TPM is aimed at maximising equipment effectiveness through the optimisation of equipment availability, performance, efficiency, and product quality.
2. Establishes a maintenance strategy (level and type of PM, Preventive Maintenance) for the life of the equipment.
3. TPM covers all departments such as the planning department, the user, and the maintenance department.
4. Involvement of all staff members from top management to shop floor workers.
5. TPM promotes improved maintenance through small group autonomous activities.

TPM is an effective *complement* to DES since it focuses on measuring and improving the performance of a process. TPM also influences the order vs. chaos balance towards order, which is of great importance.

2.4.5 FMEA

FMEA (Failure Mode Effect Analysis) is a method used in a structured way to find possible risks and their effects if they appear in a system (Britsman and Lönnqvist 1993). This approach will increase the understanding of the system studied and support the creation of a future DES model. There are also some advantages to pinpointing the failure possibilities so as to evaluate and simulate different scenarios in order to find the most robust system of the examined ones. Analysing the production flow and pointing out different problematic areas, then adding a factor for the size of the problem and another one for the chance for it to happen is a common conduction of a FMEA.

2.4.6 CAD

Computer Aided Design (CAD) is a well-known and frequently used tool to support the design and redesign of products. CAD drawings can be imported in many DES softwares. This is a useful feature, which increases a DES model’s visual appearance to *look* more like the real system. Machines, products, and accessories can be imported to create a very accurate copy of the real system in the computer. This is visually only. These CAD drawings are not increasing the output statistics of the model in any way. However, they give great *support* when it comes to the acceptance of the model in the accreditation phase of the DES project; see subsection *3.4.7 Validation*.

2.4.7 IDEF-0

In 1993, IDEF-0 became a NIST standard, according to NIST (1993). IDEF-0 is based on Structured Analysis and Design Technique (SADT) (Marca and McGowan 1998). IDEF-0 has been used for decades to describe activities, and is wide-spread among researchers and in industry as a tool to analyse processes in a structured and standardised way. IDEF-0 can *support* DES projects with the structured overview of the system to be modelled. This will lessen the burden of finding all the logical couplings and relations between objects and processes, in a manner similar to the process map approach. IDEF-0 can also be used as a *substitute* for DES in some situations where the dynamics of the system is of lesser importance, since IDEF-0 cannot deal with the dynamical effects. *Figure 8* below shows an example of one level of an IDEF-0 sheet from the IDEF-0 standard literature, NIST (1993).

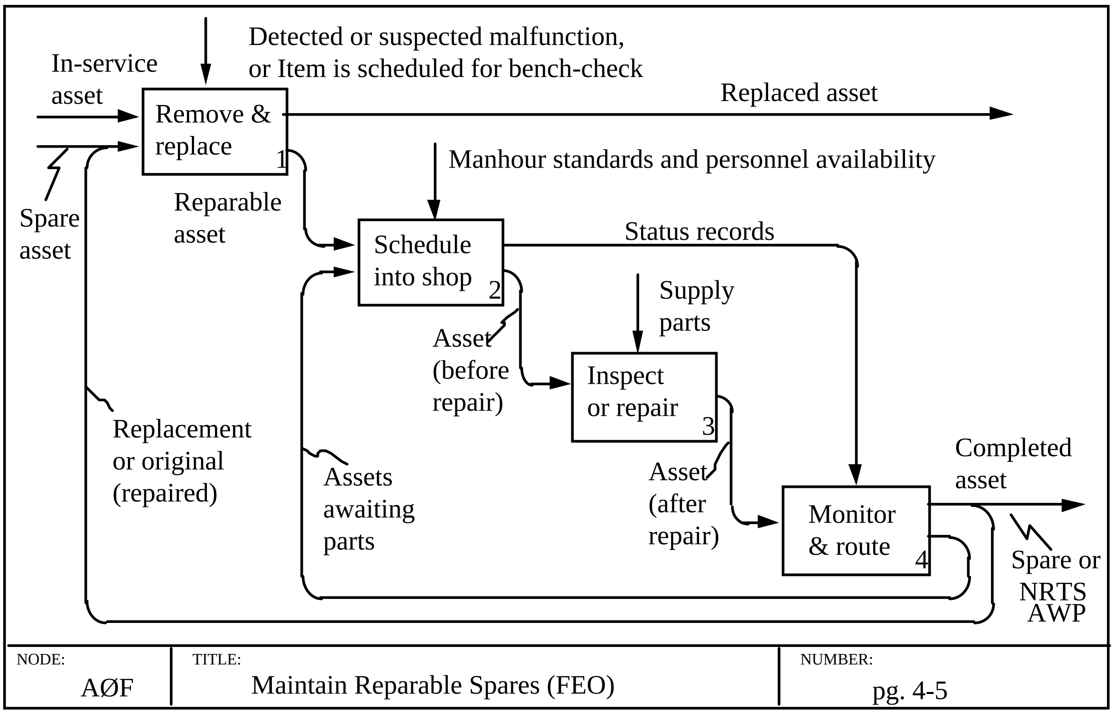


Figure 8. Example of an IDEF-0 sheet (NIST 1993)

3 Discrete Event Simulation

Most people are awaiting virtual reality;
I am awaiting virtuous reality

Eli Khamarov

3.1 Introduction to Discrete Event Simulation

Discrete Event Simulation techniques have been available for many decades, although demands for the technique have been low, and the technology-support to use the DES technique has been weak. The reason for the low demand on DES was firstly that computers were not as powerful as today, and secondly, the market was not as competitive. On the other hand, today the computers are powerful and their development is still extremely fast. The competition between companies has a global perspective. This leads to a competition that is tougher than ever before.

In years past, the industry has been focusing on shortening time-to-market, including the development times for products and processes (Mansurov and Probert 2001, Terwiesch and Bohn 2001, Driva et al 2000). Therefore, the need for a powerful decision-supporting tool is high in the global market of today (Terwiesch and Bohn 2001, Driva et al 2000). At the same time DES has been called upon as one of the potent rescuers of these higher needs for fast decision-supporting tools (Banks et al 1996, Klingstam 2001, Law and Kelton 1991), even though simulation modelling and analysis have been classified as a time consuming and expensive event (Terwiesch and Bohn 2001, Banks et al 1996). Although DES is a very potent tool, the diffusion in industries of this innovation is slow (Eriksson 2002). This is the case in Sweden, which experts classify as a country with a highly developed use of information technology in the industries. Although simulation is in good standing among industries, the number of successful simulation projects is only as few as half of the started ones (Mansurov and Probert 2001). DES is rated among the top three tools used in management science (Eriksson 2002), but what are the reasons for this lack of success among simulation projects?

Before the computer was invented, production engineers have worked with static data and methods to improve the shop floor efficiency from the first production design. Due to the continuous shortening of product lifecycles it is even more important than ever before to do *right* the first time, since there will be less time for work with continuous improvements. Structuring data and information handling to make the right decisions in early phases is needed. To meet the competitive demands, a proper methodology in line with the data structuring and information handling is also needed.

This frame-of-reference chapter will discuss Discrete Event Simulation and analyse the most commonly used DES project methodologies. However, the methodologies suffer from some limitations, which will be discussed in section *5.3 DES project methodology - Paper 2*. The need for a revised methodology to meet the demands of the more competitive and changeable market of today is also discussed.

3.2 What is Discrete Event Simulation?

3.2.1 Definition of Discrete Event Simulation

To start with, the main word in discrete event simulation is *simulation*. Simulation in general is to imitate something, in order to look or perform like this *something*. I.e., the way a snake can be brightly coloured just to look poisonous, even if it is not.
In *List of Definitions*, *Definition 7. Simulation* there is a more extensive definition, which suits the purpose of this thesis:

> *The construction of a mathematical model to reproduce the characteristics of a phenomenon, system, or process, often using a computer, in order to infer information or solve problems (Encarta).*

The first word, which is *discrete,* stands for the time-separated occurrences in the simulation model. *Definition 8. Discrete*, in, describes it as:

> *Used to describe elements or variables that are distinct, unrelated, and have a finite number of values (Encarta).*

And the final word, *event,* stands for the occurrence of interest used to form the simulation model. According to *List of Definitions, Definition 9. Event*:

> *An occurrence defined in the theory of relativity as a single point in space-time* (Encarta).

In this thesis, simulation will be referred to as the imitation of the operation of a real-world process or system over time. Discrete Event Simulation is a technique that is used in many areas to imitate a process of a real-world system or process over time in a model (Banks 1996). The model can be made in many different shapes: on a paper, in someone's mind, in a computer, a small physical model, etc. The characteristics of the DES models are that they consist of observations made from the generation of an artificial history of a system, which is used to draw inferences concerning the operation of the real-world system. Observations of the real system that is represented have to be modelled as imitations into the model (Banks 2000).

3.2.2 The characteristics of Discrete Event Simulation

Discrete Event simulation means that the model is only updated every time something happens in it, not as in continuous simulation where the state of the model is updated at specific intervals. A DES model can be described as one in which the state variables change only at those discrete points in time where events occur. An example of an event list is shown in *Table 4*.

Table 4. An example of an event list used in discrete event simulation.

Time	Event	Buffer 1	Machine 1	Buffer 2	Machine 2
0	Initiating simulation	empty	Idle	empty	idle
3	Item 1 arriving to Buffer 1	1	Idle	empty	idle
3	Item 1 arriving to Machine 1	empty	Working	empty	idle
6	Item 2 arriving to Buffer 1	1	Working	empty	idle
8	Item 1 arriving to Buffer 2	1	Idle	1	idle
8	Item 1 arriving to Machine 2	1	Idle	empty	Working
8	Item 2 arriving to Machine 1	empty	Working	empty	Working
9	Item 3 arriving to Buffer 1	1	Working	empty	Working
12	Item 4 arriving to Buffer 1	2	Working	empty	Working
13	Item 2 arriving to Buffer 2	2	Idle	1	Working

A discrete event simulation model is conducted over time ("run") by a mechanism that moves the simulated time forward, according to *Figure 9*. The system state is updated at each event along with capturing and freezing of resources that may occur at that time. *Figure 9* also shows the other related input parameters needed to generate the output from a DES model.

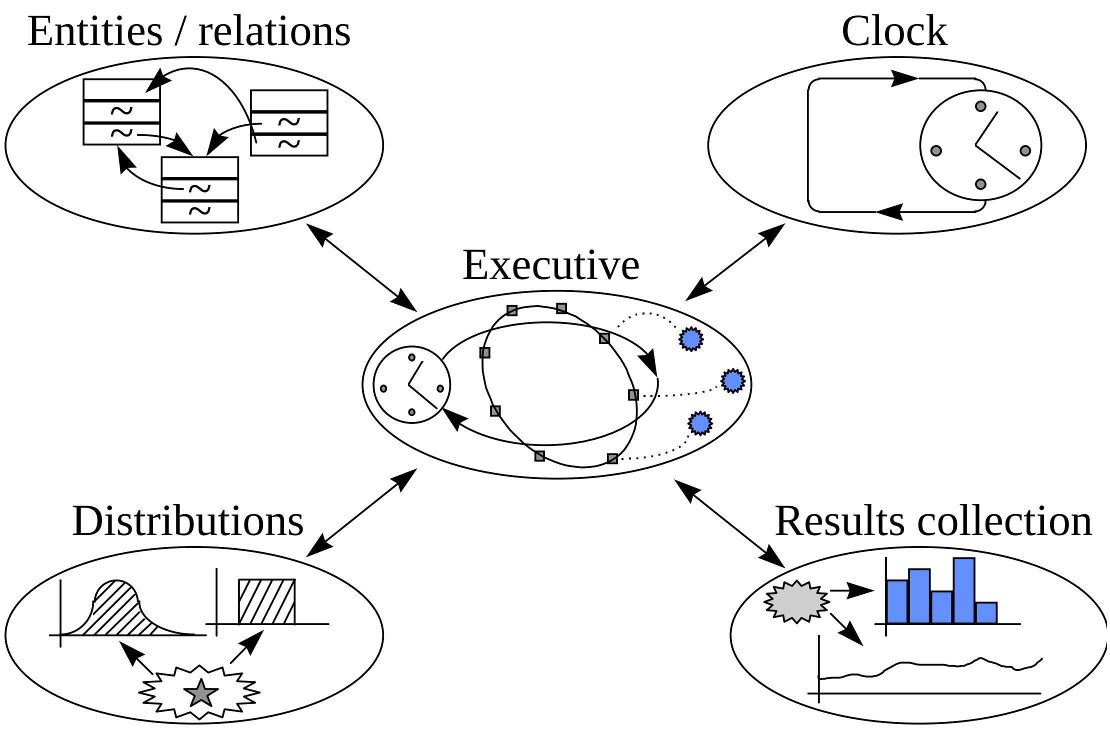


Figure 9. Structure of a discrete event simulation system, adapted from Kreutzer (1986).

DES is an indispensable problem-solving methodology for the solution of many real world problems. DES is used to describe and analyse the behaviour of a system, ask “what if” questions about the real system that one does not dare to test in the real system. DES can also be used to aid the design of new real systems, as well as be used to model conceptual systems and existing ones.

3.2.3 Advantages of DES

Discrete Event Simulation has many advantages, mostly because of the possibility to capture the dynamics of a system. That is not possible in the same way with a static analysis, such as process mapping, FMEA, etc. Some of these positive features are listed in Pegden et al (1995):

- New policies, operating procedures, decision rules, information flows, organisational procedures, and so on can be explored without disrupting ongoing operations of the real system.
- New hardware designs, physical layouts, transportation systems, and so on, can be tested without committing resources for their acquisition.
- Hypotheses about how or why certain phenomena occur can be tested for feasibility.

- Time can be compressed or expanded allowing for a speedup or slowdown of the phenomena under investigation.
- Insight can be obtained about the interaction of variables.
- Insight can be obtained about the importance of variables to the performance of the system.
- Bottleneck analysis can be performed indicating where work-in-process information, materials, and so on are excessively delayed.
- A simulation study can help in understanding how the system operates rather than how individuals think the system operates.
- "What-if" questions can be answered. This is particularly useful in the design of new systems.

On the other hand, DES is not a single-sided coin.

3.2.4 Disadvantages of DES

The disadvantages of DES can be fatal for a user with little experience, since the pitfalls are commonly not showing up at all before it is too late. Some examples from Pegden et al (1995) are shown below:

- Simulation is used in some cases when an analytical solution is possible, or even preferable.
- Simulation results may be difficult to interpret. Since most simulation outputs are essentially random variables (they are usually based on random inputs), it may be hard to determine whether an observation is a result of system interrelationships or randomness.
- Simulation modelling and analysis can be time consuming and expensive. Skimping on resources for modelling and analysis may result in a simulation model or analysis that is not sufficient for the task.
- Model-building requires special training. It is an art that is learned over time and through experience. Furthermore, if two competent individuals construct two models, they may have similarities, but it is highly unlikely that they will be the same.

However, these four disadvantages are known and dealt with, to make them less likely to happen (Pegden et al 1995):

- Vendors of simulation software have been actively developing packages that contain all or parts of models that need only input data for their operation.

Such models have the generic tag "simulators" or "templates".

- Many simulation software vendors have developed output analysis capabilities within their packages for performing very thorough analysis.
- Simulation can be performed faster today than yesterday, and even faster tomorrow. This is attributable to the advances of hardware that permits rapid running of scenarios. It is also attributable to the advances in many simulation packages.
- Analytical solution is limited to static analysis, while DES can capture the dynamics.

3.3 Areas of application for Discrete Event Simulation

Discrete event simulation has a wide application area. Anything can be modelled with discrete event simulation as long as it consists of events with some logical couplings over a specified time. However, the most frequent applications for DES are, according to Banks (1996):

3.3.1 Manufacturing applications

The manufacturing application of DES constitutes the main area of this thesis together with some smaller parts of the other areas mentioned in the sections below. Manufacturing applications are one of the most frequent usage areas of DES technology according to Cornford and Doukidis (1991), Forgionne (1983), Hover and Wagner (1958). DES used for manufacturing problem-solving can be for example:

- Analysis of assembly operations
- Optimisation of cycle-time and utilisation
- Investigating the dynamics in a supply-chain
- Etc.

3.3.2 Semiconductor Manufacturing

The semiconductor industry has had a keen eye on DES for some time. The use of DES has mainly been in the area of investigating and comparing the dynamic effects influencing the productivity while using different technologies and machines. Some examples are:

- Comparison of dispatching rules using large-facility models
- Lot-release rules for wafer fabs
- Capacity planning with time constraints between operations
- Etc.

3.3.3 Construction Engineering

During construction of new facilities it is of utmost importance not only to look into the static state of the construction, but also to understand the dynamics affecting the construction. In this case DES serves as a potent tool during the investigation of various dynamical effects affecting the construction. For example:

- Construction of a *dam* embankment

- Investigation of the structural steel erection process
- Special-purpose template for utility tunnel construction
- Etc.

3.3.4 Military applications

The military many times is one of the first and leading actors of new technology. This is also the case with DES. The military is using DES in many areas to simulate different scenarios to gain understanding and knowledge in how to act in reality when it comes to human life. The military also uses DES for more technology-based situations such as:

- Modelling leadership effects and recruit type in an Army recruiting station
- Designing and testing an intelligent controller for autonomous underwater vehicles
- Using adaptive agents in U.S. Air Force pilot retention
- Etc.

3.3.5 Logistics, Transportation, and Distribution applications

This application area is similar to the manufacturing application, although it handles the external logistics of an industrial company more than the internal logistics that the manufacturing application handles. Areas of usage for DES are, for example:

- Evaluating route planning
- Parametric modelling in rail-capacity planning
- Analysis of passenger flows in airport terminals
- Etc.

3.3.6 Business Process simulation

The potential of DES in this category is high, although it is not even close to full utilisation. Some banks, restaurants, and other business centres have been using DES to forecast the customer flow to be able to hire the right amount of personnel. Other areas of application have been shown at the Winter Simulation Conference such as:

- Product development programme planning
- Reconciliation of business and systems modelling
- Personnel forecasting and strategic workforce planning
- Etc.

3.3.7 Human systems

Human systems are a newer branch of the DES application area. There is a lot to learn with the help of DES by studying the human behaviour in a dynamic model. It has been done in for example:

- Modelling human performance in complex systems
- Studying the human element in air traffic control
- Computer simulation as a tool for studying human-centred systems
- Etc.

Simulation is commonly observed as the most popular of the classical OR techniques, according to Hollocks (1995). The use of simulation outside the manufacturing area is not as common. But, for example, in the Health sector Davies (1992) discusses the use of simulation, and in the Retail Finance and service sectors it is discussed by Sparkes (1989). However, these fields will probably use simulation more frequently in the future when the manufacturing market becomes more saturated and the software vendors are looking for more customers, who will become good potentials for future increased use and profits in these areas (Hollocks 1995).

3.4 Discrete Event Simulation Project Methodology

Many methodologies have been developed during the last decades to facilitate DES projects. Most of the methodologies have much in common, for example: Law and Kelton (1991), Banks et al (1996), and Pegden et al (1995). This section will discuss the most commonly used methodologies. The approaches are similar in many steps such as problem definition, data collecting, model-building, comparison, and analysis. *Figure 10* shows a flowchart over the steps in consecutive order to be followed during a simulation study. This DES project methodology is described in Banks et al (1996). The descriptions in the following subsections are related to *Figure 10*.

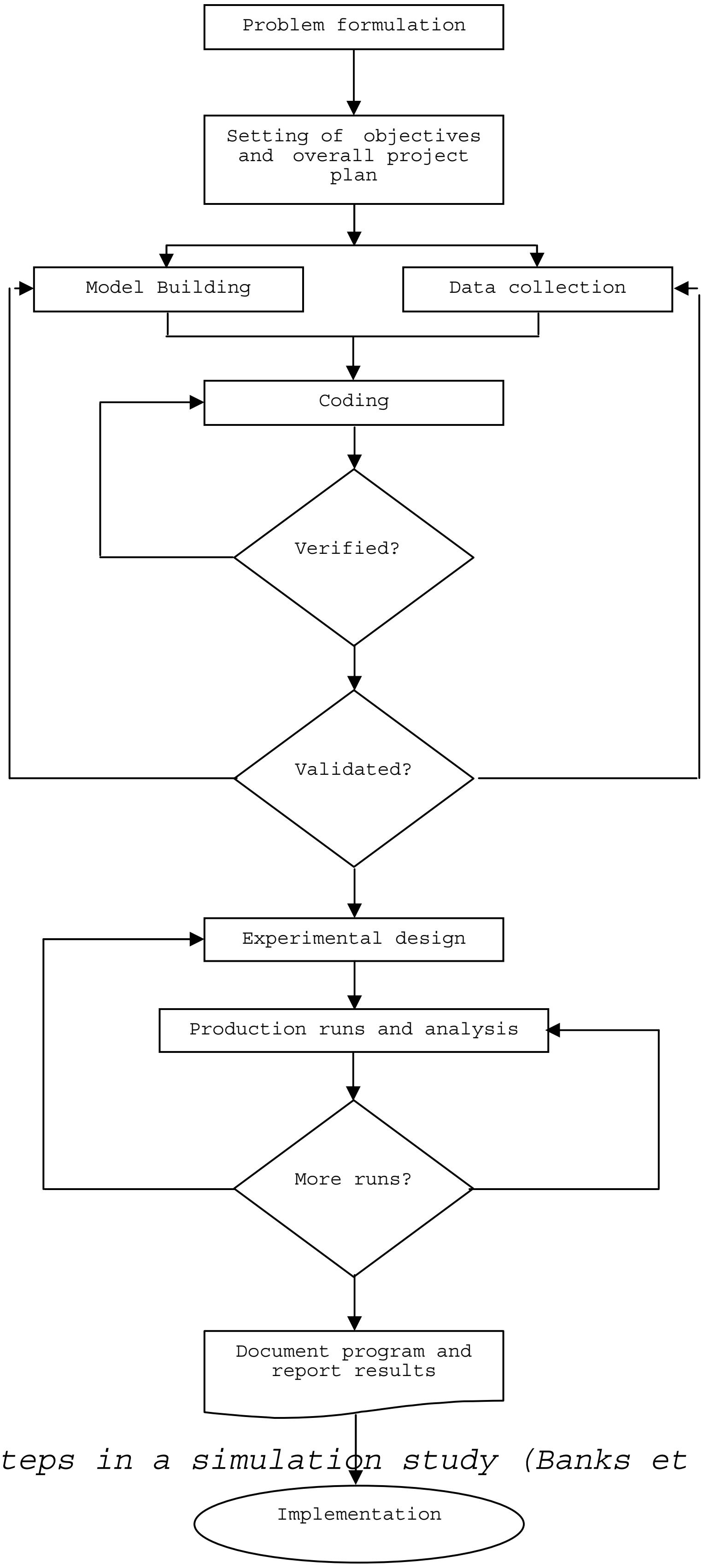


Figure 10. Steps in a simulation study (Banks et al 1996)

3.4.1 Problem formulation

DES projects are mostly conducted by specialists, and bought by someone who has a problem to be analysed (Banks et al 1996). Therefore, the statements in the problem formulation have to be precise and easy to understand, especially if those who have the problem, i.e. the clients, provide the statement. The simulation analyst must take extreme care to insure that the problem is clearly understood. On the other hand, if the simulation analyst prepares the problem statements, it is important that the client understands and agrees with the formulation. Banks et al (1996) suggest that a set of assumptions should be prepared by the simulation analyst and agreed-on by the client. Despite these preparations, it is possible that the formulation of the problem would be reformulated as the simulation study progresses.

It also has to be mentioned that before any other activity is to be conducted, it has to be made clear that DES is the appropriate tool for the specified problem (Schumacher 1998). In Banks et al (1996), based on Banks and Gibson (1997), the following list of criteria is discussed to ascertain whether a DES project is the appropriate solution method.

Simulation is not appropriate when:

1. The problem can be solved using common sense.
2. The problem can be solved analytically.
3. It is easier to perform direct experiments.
4. The cost exceeds the savings.
5. Resources are not available.
6. Time is not available.
7. Input data is not available.
8. Verification and validation cannot be performed.
9. Managers have unreasonable expectations.
10. The system is indefinable or too complex.

If the problem passes these ten questions, the chance for a successful DES project is higher. Nevertheless, many other issues influence the result. The next one on hand is the setting of objectives and overall project plan.

3.4.2 Setting of objectives and overall project plan

The questions to be answered within the simulation project are indicated by the objectives. The project plan should include a statement of the various scenarios to be investigated and analysed. Resources needed for the simulation study at large should be included, such as personnel who will be used, hardware and software requirements, stages in the investigation, and cost of the study, if any. Another task of importance at this stage of a simulation study is to decide who is responsible for the different areas mentioned above (Banks et al 1996).

3.4.3 Data collection

In the best circumstances, the client has been collecting the data needed in the format required. This would mean a great advantage both in time and in success for the simulation project. In many projects, the client indicates that required data is indeed available. However, when the time comes to implement the data it is found to be quite different than anticipated. As shown in *Figure 10*, model-building and data collection is, in most projects, a simultaneous task, although any of these two blocks can be done separately.

3.4.4 Model-Building

At this stage of the project, the real world is simplified to a series of mathematical and logical relationships concerning the components and the structure of the system to be simulated.
It is recommended not to start building too complex a model at an early stage of the project, since the level of detail will increase as the model develops. A good way to get started is to put the basic features into the model, such as arrival queues and servers. Then add details later on, for example failures, shift scheduling, and material-handling capabilities, and, in the end, add the special features for the most complex parts of the model.
Maintaining the client's involvement in the model-building is vital for success. Also vital for the construction is not to make an unduly complex model, since it is adding cost to the project, even though it does not add value to the results.

3.4.5 Coding

The conceptual model from subsection *3.4.4 Model-Building* above, is coded into a computer in an operational model of the system to be simulated. The coding also consists of interpreting the conceptual model into logical functions.

3.4.6 Verification

Verification and Validation are two very important steps in a simulation project. These two determine whether the model is good enough to use, or if more work is needed to achieve a model accurate enough.

Verification of the model includes securing that the model behaviour is the wanted behaviour according to the previously made conceptual model. This includes comparing the functionality of the computer-coded image of the system with the conceptual model.

3.4.7 Validation

Validation is the determination whether the model is a correct translation of reality according to the previously made decisions concerning level of detail, which is very important.

One of the most secure ways to validate a model of an existing system is to compare the model output (using historic input data) with the real output from the same time span, according to Law and Kelton (1991). This method is called "The correlated inspection approach"; see *Figure 11*. This method can be used with another touch that includes letting the client look at both the System data output and the Model data output, trying to determine which is the real one (Williams et al 2001).

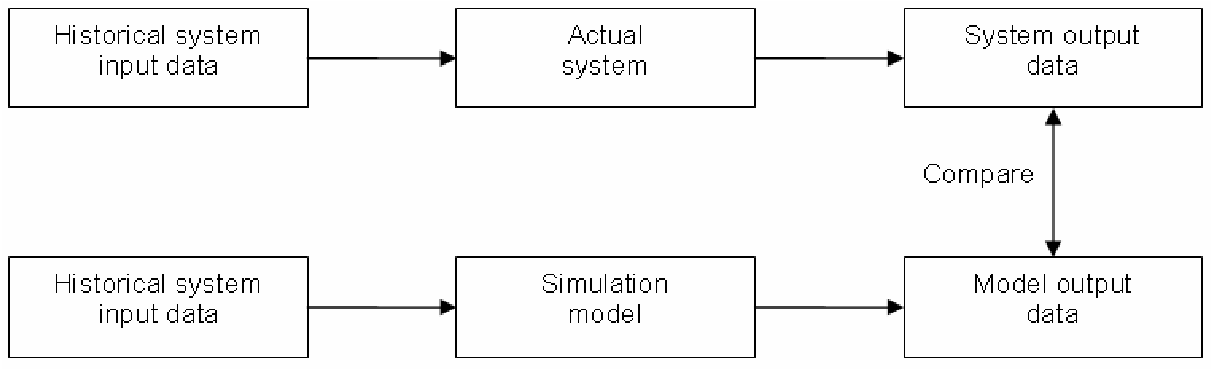


Figure 11. The correlated inspection approach (Law and Kelton 1991)

It is also of importance to build credible models, which in short means that the client has to put *trust* in the model being reliable enough to fulfil its purpose (Sargent 2000). This needs to be done in correlation with a valid model.

Another description of sound verification, validation, and accreditation phases for a simulation project is shown in *Figure 12*.

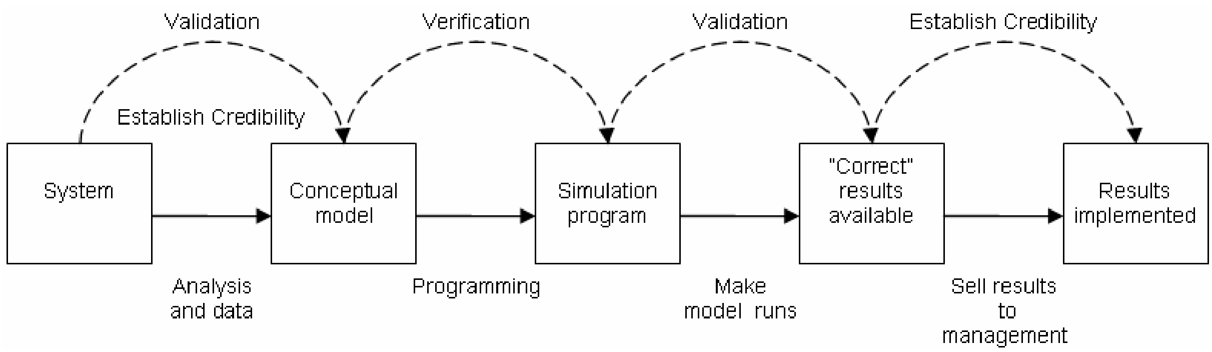


Figure 12. Timing and relationship of validation, verification, and establishing credibility (Law and Kelton 1991).

The descriptions above, used to ensure the quality of the DES model, are of vital importance to sustain the quality of the simulated system. Any of the methods is good enough to use as long as the client and the modeller agree on the model-quality.

3.4.8 Experimental design

To obtain a steady basis for analysing the outcome of the simulations, output parameters have to be set. These parameters can include:

- Versions of the model made and modified to reach the goals from the previously made project plan.
- The analysis basis to make the right conclusions according to plan.
- The simulated running time of the various models.
- The manner of initialisations required.
- Various output parameters of interest from the real system.
- Etc.

There are some good approaches to use while planning these parameters and experimental runs to be conducted with the model. One can be to make a factorial experiment, if there are interests in more than one parameter (Law and Kelton 1991). A reduced factorial design such as the one used in Karlsson (2001) will reduce the needed simulation runs to half compared to a full experiment, and it will also show what factor/factors have the most influence on the outcome of the system on a scale; see *Figure 13* in the next subsection*, 3.4.9 Production runs and analysis*. Shown in the *Table 5* is a factorial experiment with four factors influencing the output of the system. This example is part of case study 2.

Table 5. Experimental factors and their max and min values to be tested (Karlsson 2001)

Factor	Factor description	Low level	High level
A	Time between resettings	Once a week	Twice a week
B	Batch size	360 gears	840 gears
C	Automation level	Manual transport	Automatic transport
D	Line cycle-time	70 % of Normal	Normal

3.4.9 Production runs and analysis

In this stage of a simulation project the computer model is used to simulate scenarios. One example, while using factorial design of experiments, is shown in *Figure 13*. The simulated scenarios are then evaluated and analysed to estimate measures of performance for each of the different solutions.

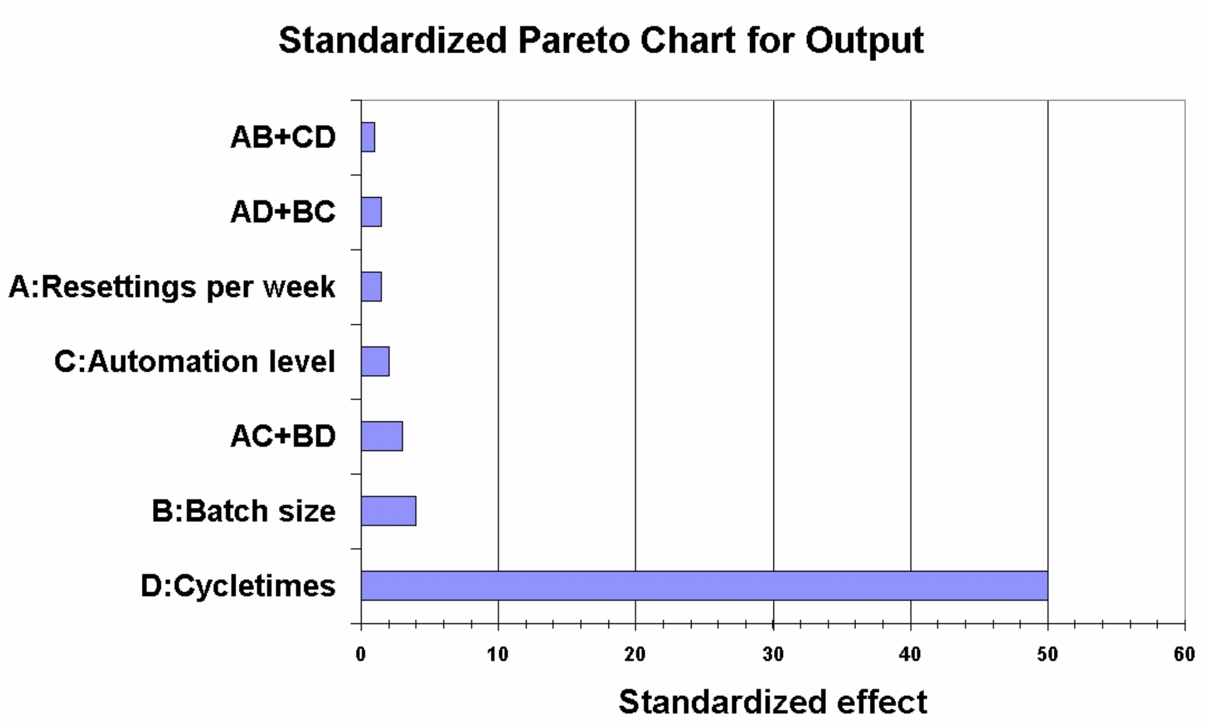


Figure 13. Standardized Pareto Chart for Output of gears from Table 5 (Karlsson 2001)

3.4.10 More runs

Based on simulation runs completed in the step above, the analyst has to make the decision whether there is a need for another scenario to be simulated. The analyst also has to determine if more runs of the same scenarios are necessary to determine the variations in outcome of the simulations made, in order to achieve statistically reliable output data (Law Kelton 1991, Banks et al 1996).

3.4.11 Documentation and reporting

Sound documentation is very important, if someone else, who did not participate in the project, wishes to learn about the model and how to use it. Another argument on why documentation is so important is if the simulation-model is to be reused. The documentation then will be of great help. The documentation will also ensure the quality of the model in matters of understanding and decision-making, which is one of the main points of doing the DES project.

3.4.12 Implementation

Finally, the goal of all the work is close at hand, this being when the findings of the virtual system come to affect the real system. The implementation of the results depends on all the above steps. If the simulation project was a success, the one thing remaining is to implement these findings into the real system. Or, perhaps, further investigations on the findings are needed to strengthen its base before it is to be implemented. A successful simulation project is not only the one with good results concerning the organisation. For example, it can be of even greater importance to avoid building a plant that is shown to be an *economically* bad investment, which for simulation reasons is a *good* result.

If the client has been involved throughout the study period, and the simulation analyst has followed all of the steps rigorously, then the likelihood of a successful implementation is increased.

3.4.13 Witness DES project methodology

Witness is one of the most well-known and one of the first commonly used and accepted DES software. The methodology outlined in the manual is shown in *Figure 14*. The methodology used in the WITNESS™ manual is of the same kind as the one described in section *3.4, Discrete Event Simulation Project Methodology*; see *Figure 10*. Almost all DES software vendors have a methodology of their own included in their manuals. In some cases, they refer to the most well known books on DES, such as Law and Kelton (1991), Banks et al (1996), and Pegden et al (1995). This is the case with WITNESS™ DES project methodology. *Figure 14* shows the flowchart over WITNESS™ DES project methodology, in which some steps of DES contain the same actions as Banks et al (1996) project methodology.

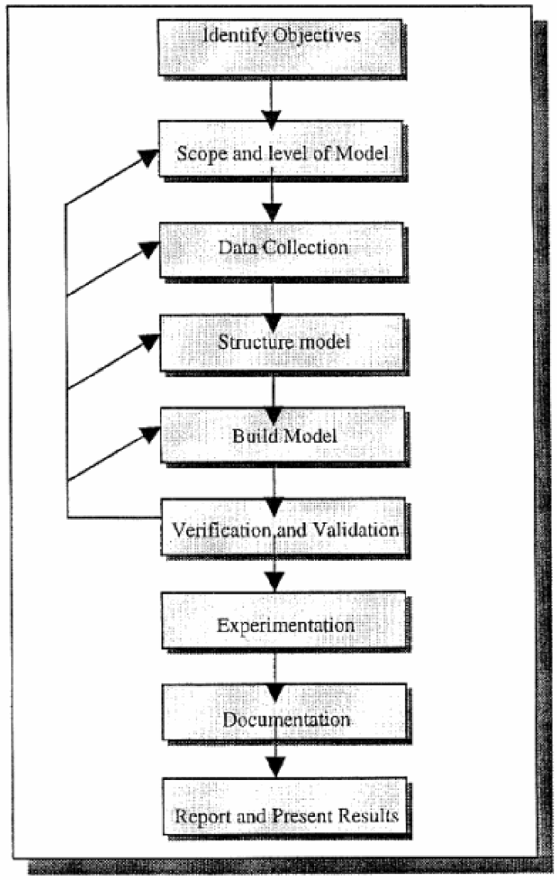


Figure 14. Steps in a simulation study (WITNESS™ user manual 1994).

3.4.14 Law and Kelton (1991) DES project methodology

The DES methodologies described in Law and Kelton (1991), shown in *Figure 15* on the next page, use another structure in terms of verification and validation than the other methodologies mentioned. The pilot runs, made in Law and Kelton (1991) DES methodology, are more significantly mentioned. This does not mean that the other methodologies leave out the pilot runs. With the exception of the pilot runs, the steps in the DES methodology described by Law and Kelton (1991) are the same as those presented in Banks et al (1996), and in the WITNESS™ user manual (1994).

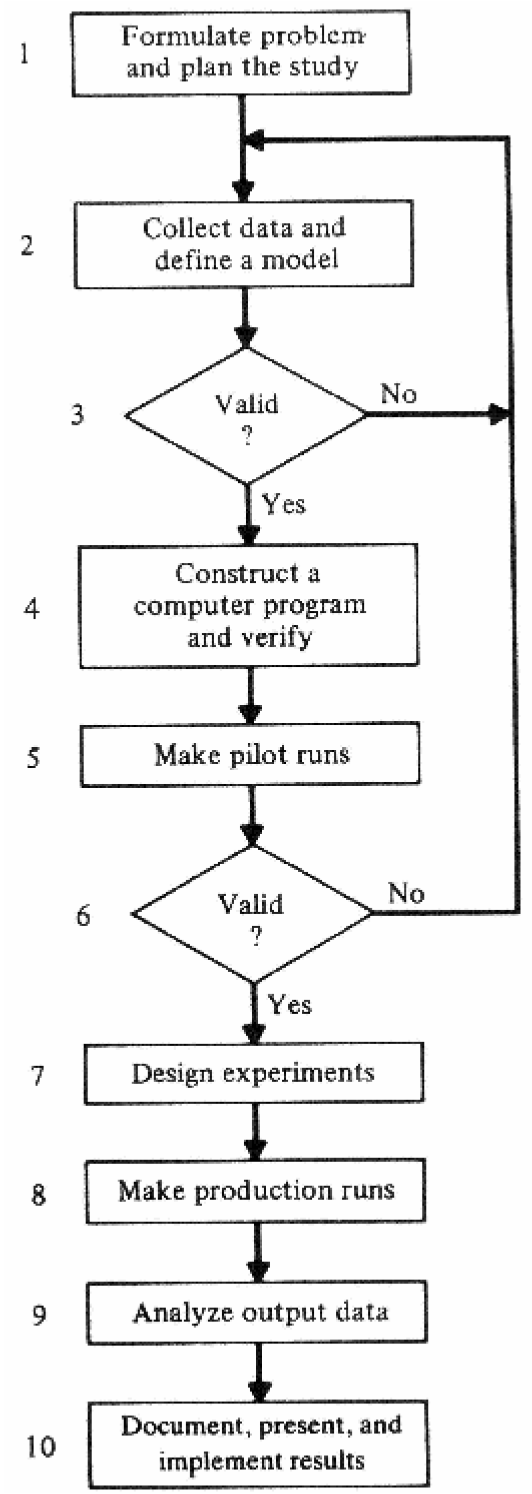


Figure 15. Steps in a simulation study (Law and Kelton 1991).

3.5 Simulation software

The software used to conduct DES projects is of vital importance for the outcome of the project. There are many tailor-made simulation softwares, suited for different kinds of DES projects, on the market today (Klingstam and Gullander 1999, Nikoukaran et al 1999, Johansson et al 2002, Rivera and Diamond 1997,Banks et al 1996, Rohrer 1999). It is also possible to use a common general purpose programming language to conduct a DES project, even though it is not recommended.

3.5.1 The History of Simulation Software

Along with the increasingly more powerful computers the simulation softwares are also developed. In the early age of the modern computer, the simulations were conducted in general-purpose programming languages, which were not as user-friendly as today. According to Nance (1995), the history of simulation software can be divided into five periods:

1955-1960 The Period of Search
During the first period, simulation was conducted in FORTRAN, which is a general-purpose programming language without support of simulation-specific routines, such as short-cut commands or pre-made building blocks. The first one to identify and develop routines that could be reused in subsequent simulation project was K. D. Tocher and D. G. Owen in the 1960s (Tocher and Owen 1960)

1961-1965 The Advent
During this period, some efforts were made to make more specific simulation-programming languages, such as GPSS and GASP, which both appeared about 1961 for the first time. GASP and GPSS used flow-chart symbols familiar to engineers, which made them more user-friendly than the previously commonly used FORTRAN.

1966-1970 The Formative Period
Major revisions were made during this period, due to rapid hardware advancements and user demands. Specifically GPSS went through major changes. In Europe the precursor of the modern object-oriented programming languages was developed, SIMULA, using the concept of classes and inheritance.

1971-1978 The Expansion Period
Efforts during this period were mainly made attempting to simplify the modelling process, but also GPSS and GASP were continually developed in some directions. GPSS/H was released with speeds of 5 to 30 times faster compilation than the standard version. GASP incorporated state events

in addition to time events, interactive debuggers were implemented, and efforts towards automatic programming were tested, though a bit overoptimistic.

1979-1986 The Period of Consolidation and Regeneration
During the early eighties a trend towards adaptation for micro- and desktop computers started. GASP appeared in two major descendants, namely SIMAN and SLAM II. SLAM sought to provide multiple modelling perspectives and combined modelling capabilities, according to Pritsker and Pegden (1979). Both SLAM II and SIMAN allowed an even scheduling approach by programming FORTRAN with a supplied collection of FORTRAN subroutines.

In the book *Discrete Event System Simulation* by Banks et al (1996) an extra period is provided, from 1987 to 1996, which is called:

1987-1996 The Period of Integrated Environments
The last period is most notable for the increased use of simulation programming languages on the personal computer as well as the development of graphical user interfaces, animations and other visualisation tools. Some packages use the "fill in the blank" in order to avoid the need to learn the programming syntax. Some of the most commonly used simulation environments were partly developed during this period, such as Automod, Taylor ED, and Simul8 which are described in appended Paper No. 3 (Johansson et al 2002).

3.4.2 Selecting simulation software

When selecting appropriate simulation software there are some important issues to keep in mind. An attempt to give advice is done in Banks et al (1996):

1. Do not focus on a single issue, consider all factors, such as ease of use, obtainable level of detail, ease of learning, vendor support and of course applicability to your problems.

2. Execution speed is important, not only for the experimental runs made overnight, but also the affection of development time and debugging.

3. Beware of advertising and demonstrations, they tend to show only the positive features of the software. A better way is to ask the vendor to demonstrate a small version of your problem.

4. Find out the true information of what the software is capable of doing instead of looking at checklists with "Yes" and "No" as their entries. For example many packages have a conveyor entity, but the level of fidelity is varying considerably.

5. Link ability between the simulation software and some major external language like C, C++ or FORTRAN is a desired feature. This will enable the use of external routines.

6. There is a significant trade-off if the simulation programme supports graphical model building, instead of only simulation language. This feature will shorten the learning curve. However, beware of the phrase "no programming needed" which will lock the software in a narrow area determined by the developer.

Extensive guides to Discrete Event Simulation software can be found in "Simulation softwares buyer's guide" published by IEE Solutions in May each year and OR/MS Today publishes a guide every two years. Additional and more specific information on Discrete Event Simulation Software can be found in, for example: Klingstam and Gullander (1999), Nikoukaran et al (1999), and in Paper No. 3 (Johansson et al 2002).

4 Case Studies

The only source of knowledge is experience.

Albert Einstein

4.1 Case study at Volvo Truck Corporation

4.1.1 Background

Volvo Truck Corporation’s manufacturing plant in Tuve was in need of making a larger rearrangement of the assembly line for truck chassis. The parallel dock assembly stations were to be transferred into a single line assembly unit. For this need, two diploma workers were assigned the task to construct a DES model of the desired new layout of the assembly line (Arne and Nilsson 2000).

4.1.2 Objectives

The purpose of the case study was to assess the following parameters for the new line (Arne and Nilsson 2000):

- Maximum capacity
- Potential bottlenecks
- The number and size of buffers

These parameters were to be analysed regarding their potential impact on a limited variant mix of different chassis to be assembled in the new line. Other observed obstacles during the case study were also to be analysed and studied theoretically, such as logistics, material handling, flow structure, and buffer usage, to be able to comment on these problem areas as well.

4.1.3 Method

During the first part of the case study, knowledge about the existing factory unit was gathered, such as data collection, logistical couplings, MTBF, and MTTR, in order to be able to build a DES model of the modified factory unit. The methodology used during the DES model-building is described in Seila (1995). The next step consisted in building a base model of the new factory unit in the DES software Extend (Rivera and Diamond 1997). In the end a design of a tryout plan for the simulation experiments was to be conducted from the base model.

4.1.4 Results

Numerous experiments were conducted and some of the results were:

- The sequencing of chassis is of vital importance for the production-line output capacity.
- The AGV system is a bottleneck for the transportation of axles to the assembly stations.
- Buffers between the different chassis stations would increase output capacity and are therefore to be preferred over trying to neutralise fluctuations in throughput time (Arne and Nilsson 2000).

4.1.5 Conclusions

The conclusion in general is: It is possible to build the new production line according to the stipulated requirements, given the following conditions (Arne and Nilsson):

- The supply of material is secure.
- The system should be flexible enough to be able to utilise the workers in a more proper manner than before, if there is some kind of resource pool introduced.
- More workers are added at the end of the chassis line to enable a gradual pull-effect in the assembly flow.
- The transportation system between axle store and axle assembly should be thoroughly investigated and potentially redesigned to enable a more efficient and safer transportation system.

4.2 Case study at SAAB

4.2.1 Background

SAAB automobile was to reorganise a part of the gearbox factory in Mölndal, where they would like to investigate whether they should have an automated or a manual transportation system to transport the gears (Karlsson 2001). To investigate this matter, a diploma worker was assigned the task to build a DES model of this part of the gearbox factory and conduct an experimental study with it.

4.2.2 Objectives

In the SAAB automobile gearbox factory, gears are to be transported from five different stations through a washing machine, which they have to share. The main task was to examine what level of automation of the transportation system would provide the most productive system.

4.2.3 Method

At the early phase of this case study, some literature studies were made considering handling systems, as well as benchmarking for already proven, successful solutions. During the DES model-building in QUEST (Barnes 1997) the methodology described in Banks et al (1996) was used as a guideline. When the base model had been built-up and verified, a reduced factorial experimental plan was prepared and conducted. During the end of the case study, a FMEA (Britsman and Lönnqvist 1993) was made as well.

4.2.4 Results

The results from the simulation runs made according to the reduced factorial experimental plan show that buffer sizes and cycle-time have the largest effect on the utilisation and throughput of gears through the washing machine (Karlsson 2001). The results from the FMEA analysis show that the greatest risk while handling the gears is to damage them while loading/unloading them between machines and transportation devices.

4.2.5 Conclusions

The main conclusion considering the assigned task is that the improvement work with cycle-times has to continue, and especially with the cycle-time bottlenecks, according to Karlsson (2001). It has to be mentioned that automatic loading/unloading of the gears is not recommended, heeding the greater risk of quality losses during the production.

4.3 Case study at ABB Robotics

4.3.1 Background

ABB Robotics, to consider themselves successful and productive, have put up these goals to be fulfilled (Grünberg et al 2002a):

- Profitable
- Decreased material costs
- Work more effective
- Better than 98% delivery performance
- Be able to handle varying volumes
- Supply complete product families, both standardised and tailor-made

One step on behalf of fulfilling these goals is the case study conducted by PhD students from the PROPER research project, shown in *1.2 Research background*.

4.3.2 Objectives

The objective of this case study was to identify potential areas for productivity improvements at ABB Robotics (Grünberg et al 2002a). In order to do that, an investigation on how ABB Robotics presently works with productivity development was conducted.

4.3.3 Method

This case study was executed in these four steps consecutively (Grünberg et al 2002a):

- An investigation of ABB Robotics through internal documents and 27 interviews from top management to line operators was conducted.
- A literature survey was performed concerning definitions, measures, and key factors driving productivity, from which a theoretical base of how to improve productivity was developed.
- A comparison between the findings at the company and the established theoretical base was made, which resulted in several identified problem areas.
- An additional deeper literature survey was conducted regarding the identified problem areas, which finally resulted in recommendations for improvement.

4.3.4 Results

The main results of this case study, for ABB Robotics to consider, can be summarised as follows:

- Information exchange in the supply chain
- Reduction of lead times
- Quality control at the suppliers
- In-sourcing of critical key components

These four points in correlation with an increased insight in performance work from top management to line-operators would enable ABB Robotics to increase their performance (Grünberg et al 2002a).

4.3.5 Conclusions

To conclude this case study, it can be stated that there is a potential at ABB Robotics, which enables an increased performance (Grünberg et al 2002a), which in time, will be able to correlate with the goals stated in the previous section.

4.4 Case study at Posten

4.4.1 Background

The post terminal in Malmö was standing ready for a large rearrangement of the incoming mail deliveries, which in turn could demand a change in the internal organisation of personnel and machines, as well. Regarding this situation, a case study was conducted to analyse the internal capacity (Grünberg et al 2002b).

4.4.2 Objectives

The main objective of this case study was to find potentials to increase the capacity in the bottleneck process, which is the "preparation of mail process" to enable automatic distribution. This main objective was divided into (Grünberg et al 2002b):

- Incoming mail into the terminal, both arrival times and volumes.
- Mail flow from the "incoming process" to the "preparation of mail process".
- Pre-deliveries of mail from mailboxes.
- Process capacities in the internal flow.
- OEE values.

4.4.3 Method

In addition to constant participation and studies of the processes during one week, and interviews with the personnel, the case study consisted in the following steps described in chronological order:

- Process mapping of the flow.
- Measurement of incoming mail, both volumes and times.
- Connecting the Mapping of the process flow with queue-, lead-time-, and personnel measurements.
- Production data analysis.
- Generating some ideas for improvement according to the findings made from above studies.
- Building a DES model of the system, using Johansson and Grünberg (2001) methodology, and calculating the potential of the improvements found with it.

4.4.4 Results

Some of the recommendations during the study were (Grünberg et al 2002b):

- Put experienced personnel on the most important tasks in each process.
- Implement clear signs showing the personnel the overall performance of their present work, including the present scheduled mail to be prepared.
- Do try to use a maximum of one pre-delivery of mail from each mailbox as late as possible, since it will lessen the pressure on peak-time of the incoming mail deliveries.
- Try to implement a system showing indications on how the scheduled production will actually behave during the closest hours.
- Control the production using queue and incoming flow measurements.

4.4.5 Conclusions

The conclusions in general from the case study indicate that there is a potential for handling future increased volumes to some extent. The process mapping and the DES model show that there is a potential for increasing the volumes by approximately 12 %, which is on the studied day, according to Grünberg et al (2002b). This can be achieved only by organisational restructuring. In addition, there are many aspects considering the processes and the technical part of the manufacturing that can be eliminated to handle even larger volumes, such as the downtimes and slack on machines, 21% and 25 %, respectively, on a bottleneck machine, according to Grünberg et al (2002b).

4.5 Case study at an automated manufacturing line

4.5.1 Background

The opportunity to this case study came up as an idea during a PROPER meeting, where two research areas crossed each other, namely: Discrete event simulation used to increase performance in manufacturing systems, and efficient resetting of flexible manufacturing systems. To be able to conduct this case study an industrial partner was involved, who provided a flexible manufacturing system for volume production at a manufacturing plant in Sweden.

4.5.2 Objectives

The main objective was to investigate if and how DES could be applied on resetting processes to enable higher utilisation of equipment in flexible manufacturing systems.

4.5.3 Method

Two diploma workers were assigned the task to build a model of the flexible manufacturing-line during 20 weeks (Axelsson and Hjelte 2002). During the case study the DES methodology described in Banks et al (1996), with some modifications from Johansson and Grünberg (2001), was used to build a DES model of the manufacturing-line in Automod (Rohrer 1999). The model-building phase at first only included the manufacturing of products. Later on, details such as scheduled maintenance, resetting flow, and an interface in Excel were added. When the base model was prepared, a plan for the experimental phase was put together. The following experiments were conducted, according to paper No. 5 (Johansson and Kaiser 2002):

1. What effect does the machine cycle-time have on the resetting time?
2. How does the number of operators available affect the resetting time?
3. Can buffers be used to achieve parallel resetting of the machines?
4. Can buffers be used to convert lost production time to productive time?

4.5.4 Results

The use of DES, with its related methodologies (Banks et al 1996, Johansson and Grünberg 2001) to map and access the resetting dilemma, has been proven successful. The results from this case study can be summarised as follows:

1. Production cycle-time location in comparison to the resetting cycle-time location has a vital impact on the resetting time of the manufacturing line.
2. Increasing the number of operators will make the resetting process more robust.
3. Increased buffer capacity will decrease the impact of the resetting process on lost production.
4. A buffer located directly after the resetting bottleneck can convert downtimes to productive time.

4.5.5 Conclusions

With the DES model of a manufacturing system including the resetting process of the manufacturing system and the related simulation runs, it has been proven that DES can be used for the evaluation of resetting processes in manufacturing systems (Johansson and Kaiser 2002). The results of the simulation experiments provided an enhanced understanding of the relation between the flow of products and the flow of work steps necessary for the resetting of a manufacturing system. The results also indicate that there is a large potential for increasing the performance of the manufacturing unit by implementing the findings from the DES model into the manufacturing system.

4.6 Overall performance applied on the case studies

In this section the case studies will be analysed in the view of the Performance factors, measurements, and methods and tools, which were described in the frame-of-reference chapter *2 Performance*.

4.6.1 Performance factors

During these five case studies, the following performance factors were the main targeted ones from the objectives in each case study:

Case study number:
1. Flexibility, dependability, speed
2. Dependability, speed
3. Flexibility, dependability, speed, cost, quality
4. Flexibility, dependability, speed
5. Flexibility, dependability, speed

Each of these performance factors covers the core of the objectives stated for each case study, which affects the overall performance of the analysed process.

4.6.2 Performance Measurements

Each of these performance factors was monitored and controlled by performance measurements in order to complete the objectives for each of the case studies.

Case study number:

1. Number of performed safe transportations, average throughput rate, etc.
2. Bottleneck throughput time, maximum capacity, number and size of buffers, etc.
3. Max/min controllable volume, % deliveries on time, throughput-rate, man-hours per robot produced, scrap-rate %, etc.
4. Max % letters exceeding forecast, % delayed letters, letter throughput rate, etc.
5. Number of resettings needed/year, utilisation of machines, average throughput time, etc.

These performance measurements, and many more, have been used in the discrete event simulation models in order to try out and find more efficient ways of performing the processes described in each case study.

4.6.3 Performance tools and methods

Discrete Event Simulation has been a major activity in each of these five case studies. It is not possible, however, to build and use a sound DES-model without using other methods and tools. To set out with a fresh and detailed process map and a CAD layout over the operation to be modeled, is a fair start in a DES project. Historically collected data from a maintenance central showing MTBF (Mean Time Between Failures) and MTTR (Mean Time To Repair) shorten the data-collecting phase and increase the model reliability. Historically collected output data enable a sound validation of the DES model, etc. *Table 6* below shows some of the performance tools used in each case study.

Table 6. Some of the tools and methods used during the case studies.

Tool and/or Method \ Case study No.	1	2	3	4	5
DES models built	x	x	(x)	x	x
Using real CAD drawings in the DES model	x	x	(x)		
Database with input data for DES	x	x	(x)	x	x
Process mapping as a base for the DES model	x	x	(x)	x	x
Manual data collection	x	x	(x)	x	x
FMEA		x	(x)		
Requirements Specification		x	(x)		
Factorial Experiment Design		x		x	

In case study 3 the tools and methods were examined and evaluated, not used directly.

4.7 Concluding discussion for all case studies

To conclude, these five applied case studies have been of great value during the research to strengthen and find the results provided in this thesis. They have also provided the author with a large amount of experience, both in order to find new ideas on how to approach problems in industry, and in academic relevance and research.

4.7.1 Case study one

Case study one contributes to the research by being a real-world complex industrial DES project, which at the same time is questioning if parallel-line or straight-line assembly is to prefer, in order to achieve the higher performance with the same resources, which enables fruitful reading and interesting encounters with both straight-line and parallel-line advocates. The simulation software Extend (Rivera and Diamond 1997) was used in this case study, which enabled the analysis of Extend in paper 3 (Johansson et al 2002).

4.7.2 Case study two

Case study two was a successful first-time DES project for this part of the company, which further contributes to the diffusion of the innovation DES into Swedish industry, and an excellent example on how DES can be used to increase the overall performance of a system.

4.7.3 Case study three

Case study three firstly contributed to sort out the view on performance, productivity, and profitability. Secondly, the case study gave a full view of the manufacturing complexity in a large Swedish company, mainly concerning working methods and the usage of DES, but also the complexity of human interaction. Thirdly, but no less important, it provided experience in the art of writing extensive technical reports.

4.7.4 Case study four

Case study four enabled a real tryout of the methodology presented in paper 2 (Johansson and Grünberg 2001), which provided good results. Valuable experience in process mapping was also attained, and, for once, a useful and working database with historical input data was on hand for the simulation model building. These are not common, according to paper No. 5 (Johnsson et al 2002).

4.7.5 Case study five

Case study five provided findings of yet another useful application area for DES, namely the resetting processes performed in a manufacturing line. Included in the results from this case study was an even more positive attitude towards DES in this large Swedish company, which already uses DES frequently. They will soon need to implement a framework for DES, such as the one presented in paper 1, which is further discussed in Klingstam (2001).

5 The future potential of DES

I never think of the future, it comes soon enough.

Albert Einstein

5.1 Introduction to research results

This chapter will provide the summarised results of the research conducted to build this thesis. It will also describe the couplings between the appended papers and provide information to answer and conclude the research questions from section *1.4 Research questions*. To be able to fully utilise DES, it is of vital importance to have a structured approach. A *framework* (paper 1) describing *when* to use DES, a *methodology* (Paper 2) describing *how* to perform a DES project, and *software* (Paper 3) to perform it *with.* These three issues do cover major requirements for a successful DES usage, when speaking about the DES itself. However, the *organisation* and *personnel* behind the operation on hand have a vital part in the conduction of a DES project; this will be further discussed in section *5.5 DES as a Performance Enhancer - Papers 4 and 5* of this chapter.

5.2 Framework - Paper 1

For companies to meet the future requirements on operations to become and stay successful, according to section *1.2 Research background*, there is a need for a structured life-cycle approach, which provides structured ways of looking at an enterprise and its business processes from different views. In order to enable DES to enter the level of Enterprise Integration; see *Figure 16*, the demand for a structured approach such as a standardised framework needs to be fulfilled.

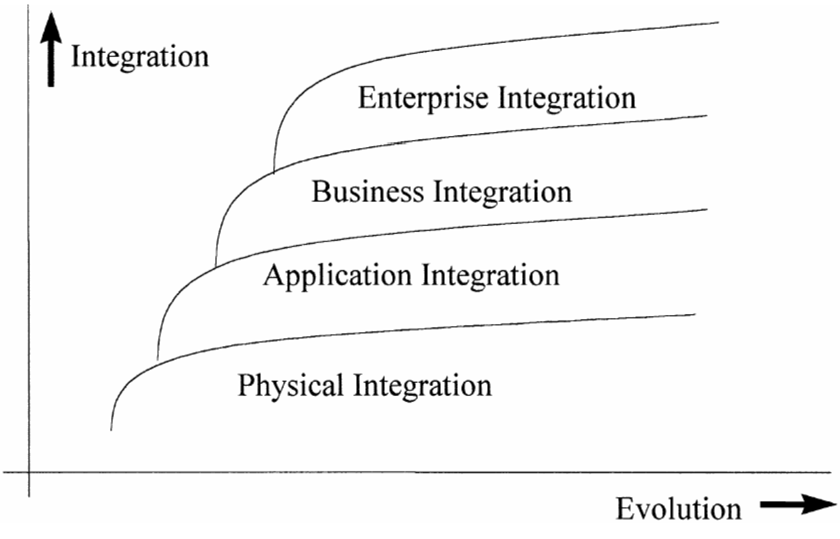
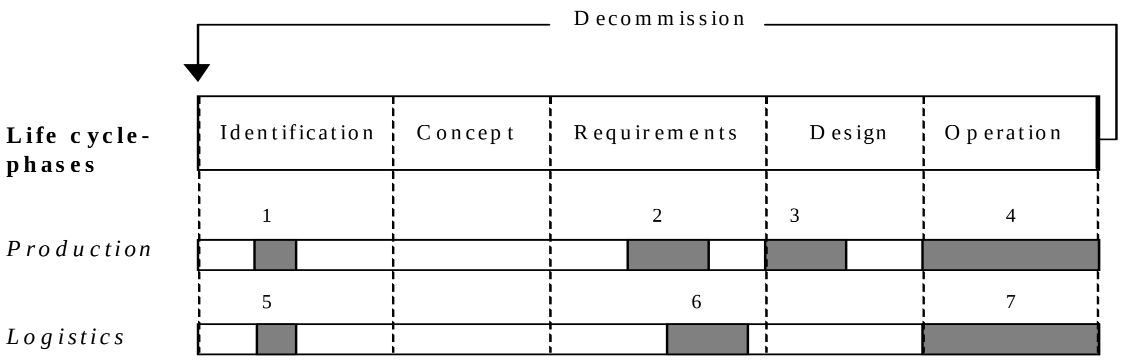


Figure 16. Enterprise Integration Evolution according to Ortiz et al (1999).

The framework has to be based on a standardised already known Enterprise Integration framework, such as CIMOSA (Vernadat 1996, AMICE 1993), GRAI/GEM (Doumeingts et al 1995) or GERAM (IFIP-IFAC Task Force 1998) in order to diffuse smoothly into the daily operations in industry.

One approach to a framework for DES, using GERAM, is proposed in appended paper 1, (Klingstam and Johansson 2000).

The approach is based on activities at different stages of a process lifecycle, in which specific events will be scheduled to use DES as a performance enhancer. *Figure 17* shows an example.



Simulation supported activities

1. Possible bottleneck detection
2. Requirement specification for specific equipment
3. Capacity analysis, cycle time analysis
4. Re-engineering and continuous improvement e.g. bottleneck detection, buffer optimisation, equipment optimisation, layout knowledge bank
5. Possible bottleneck detection
6. Rack flow analysis, evaluation of possible scenarios
7. Re-engineering and continuous improvement

Figure 17. An example of strategic simulation-supported activities for production and logistical operations (Klingstam and Johansson 2000, Paper 1)

Additional information on this proposed framework can be found in *Integrating Discrete Event Simulation into the Engineering Process* (Klingstam 2001). Holst (2001) and Randell (2002) also discuss this issue of using the GERAM standard along with DES projects.

5.3 DES project methodology - Paper 2

As described in frame-of-reference section *3.4 Discrete Event Simulation Project Methodology*, there are many methodologies to follow when conducting a DES project, however the existing methodologies are lacking in the targeting of the goal. The purpose many times is not the mere conduction of the DES project. It is the results, found and applied on the real-world problem on hand, that most often are of highest value. However, there is also a value in understanding and process familiarity, which is gained through conducting a DES project. This matter will be further discussed in section *5.5 DES as a Performance Enhancer – Papers 4 and 5*.

If the conclusion, after consideration of the ten questions in frame-of-reference subsection *3.4.1 Problem formulation*, is to conduct a DES project to find out more about the dynamics of the system to be analysed, then there is time to set the objectives of the study and decide the output criteria to be evaluated. When doing this it is essential that the objectives are measurable in correlation with the performance measurements of the system, defined in frame-of-reference chapter *2 Performance*. If the objectives are concrete and measurable, the likelihood of a successful and fast DES project is increasing. The conduction speed of the DES project depends highly on whether the objectives are concrete, abstract, or an optimisation of some kind. If the objective of the DES project is to optimise a system it will more likely take as long time as planned or, in many cases more time than planned. Table 7, from paper 2 (Johansson and Grünberg 2001) shows "+" if a DES project can be completed ahead of schedule, and "0" if it cannot.

Table 7. Impact of the objective set in early stages of a simulation project (Johansson and Grünberg 2001, Paper 2).

Time / Objective	Shortest Possible	Set to A date	Infinite
Concrete	+	+	+
Abstract	+	0	0
"Best possible"	0	0	0

Another important aspect, which is overlooked in many cases, is the fact that no process is the same as another. I.e., there are no two systems exactly the same in the real world, which also means that there are never the same prerequisites for two DES projects. Yet, they will follow the same "recipe", or methodology, which is not always a good thing to do. However, most of the steps in a simulation study can be generalised to fit into almost every project, but one has to take heed and not "use" the "recipe" without further thought *why* and *how* to interpret the methodology used.

It is also of great importance to bear in mind that it is mostly not the DES project itself that is the targeted goal of conducting it. The model itself will not likely change anything in the real world. However, the *results* of the DES project and the *implementation* of the findings will more likely change something in the real world. I.e., the effect of a DES project is finalised when there are changes made in the *real system*.

Paper 2 (Johansson and Grünberg 2001) addresses the above mentioned two problems, *Figure 18* on the next page shows an alternative methodology proposed to be used in correlation with the other ones, such as Banks (2000), and Law and Kelton (1991). The methodology shown in *Figure 18* is intended to make the modelling people not to only follow a methodology like a cookbook, but to actually create their own recipe needed to build the intended model.

There are many other authors trying to contribute to the increasing enhancement of DES project methodologies (Klingstam 2001, Holst 2001, Randell 2002, etc.). One thing which is even more important than the methodology, while conducting a DES project, is the *knowledge* of the system to be simulated. This will be further discussed in section *5.5 DES as a Performance Enhancer – Papers 4 and 5*, and *that* aspect is not stated by many (Karjalainen et al 2000).

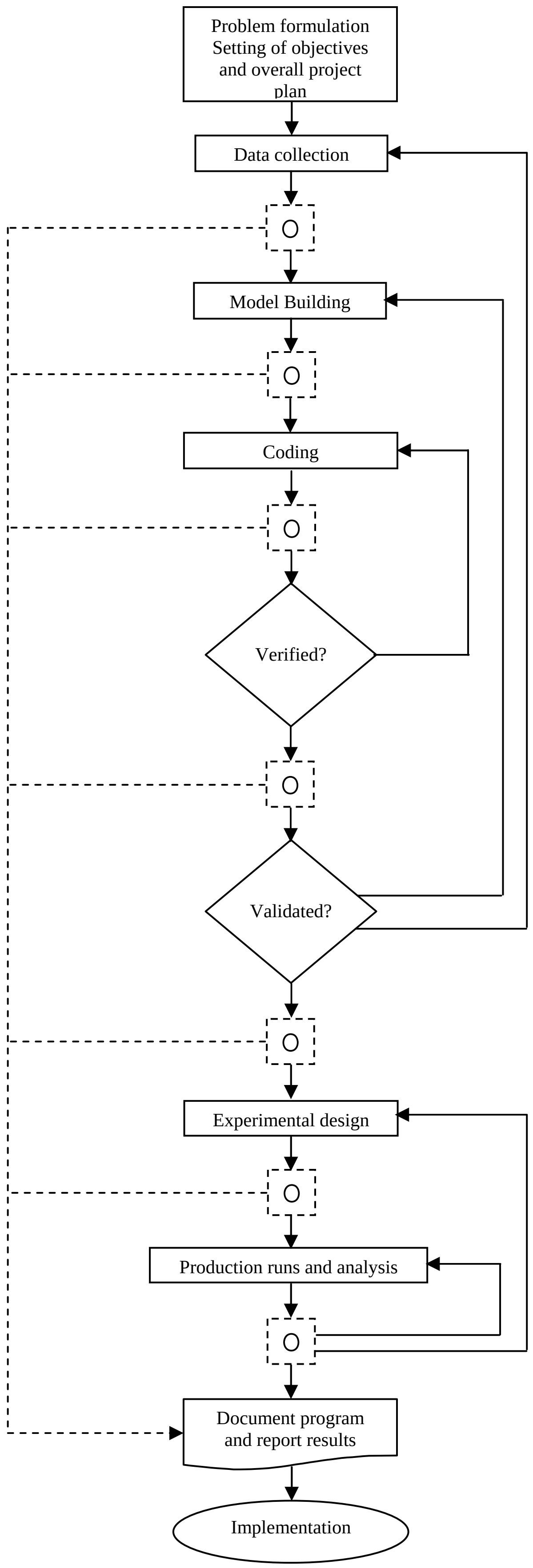


Figure 18. Steps in the revised simulation study (Johansson and Grünberg 2001, Paper 2)

5.4 DES Softwares – Paper 3

DES softwares were briefly discussed in frame-of-reference section *3.5 Simulation software*, where the present situation was mentioned. In this section, the future of the softwares will be discussed.

If a connection were made between the DES *software* year of accomplishing the integration level, according to frame-of-reference subsection *3.5.1 The History of Simulation Software*, and the enterprise integration evolution from *Figure 16* in section *5.2 Framework – Paper 1*, it would look like *Figure 19*. The actual potential of the software is the *line* in *Figure 19*, but the *usage* of DES in the industry is the *dotted line* in *Figure 19*.

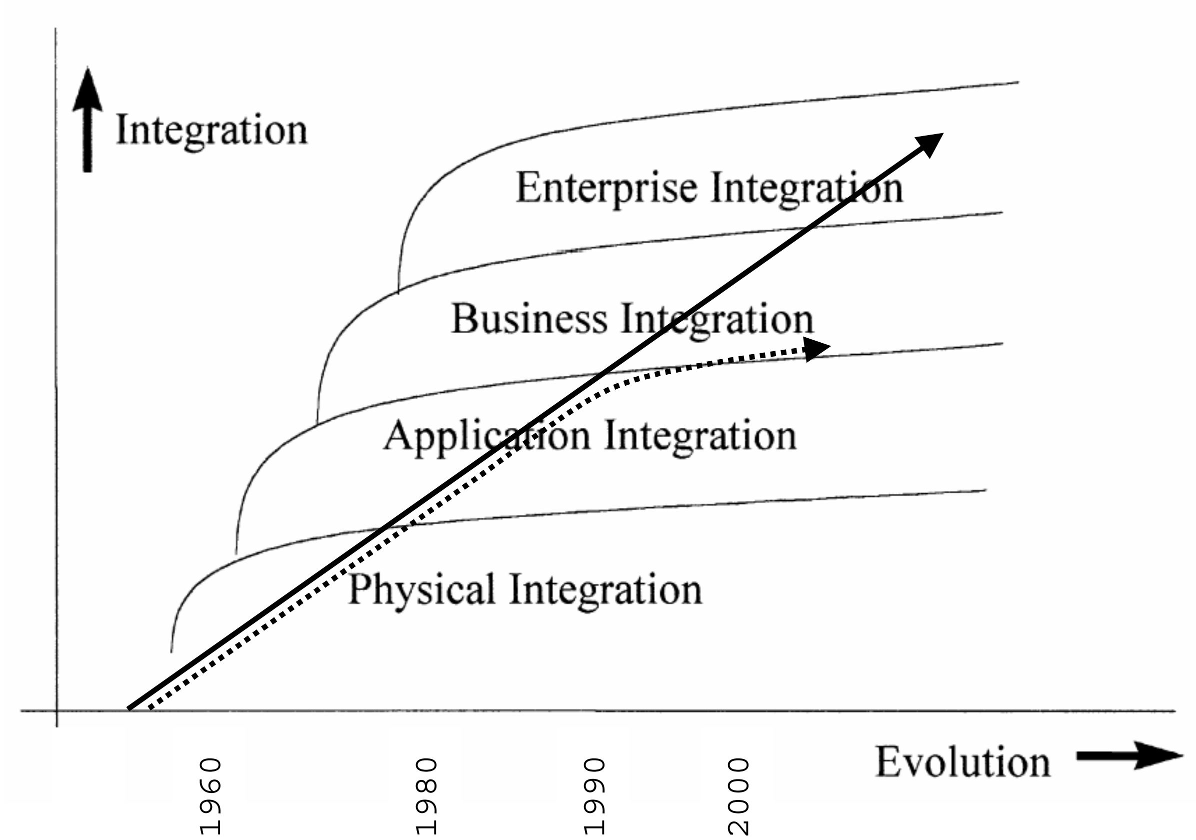


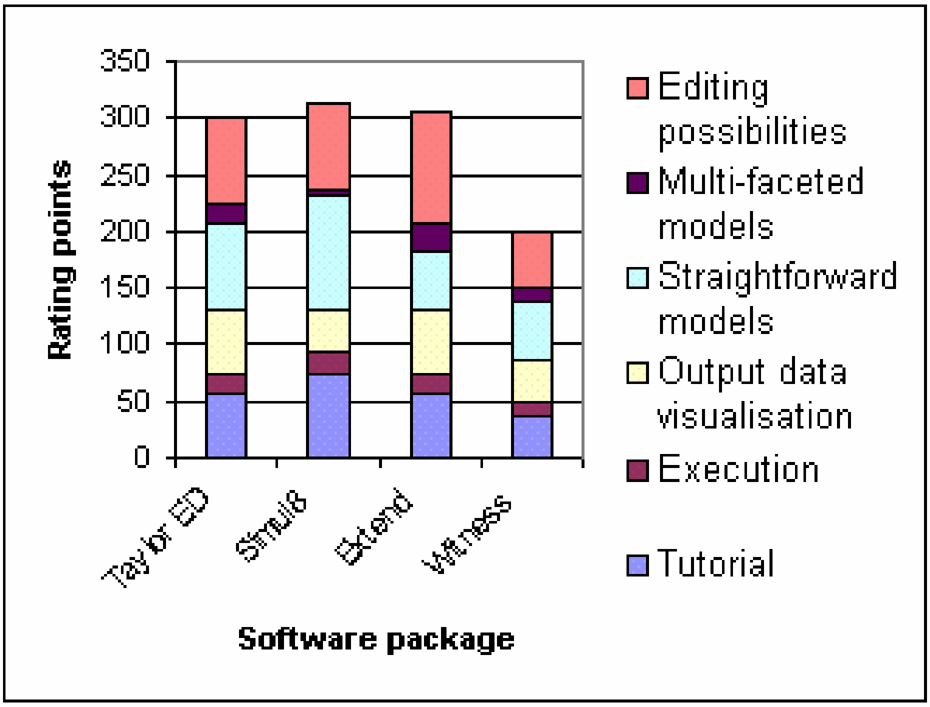
Figure 19. DES software potential versus DES software usage in the Enterprise Integration Evolution context, altered from Ortiz et al (1999).

Figure 19 addresses the problematic setback of the diffusion of DES into the industry. One aspect of this setback will be discussed in the next section *5.5 DES as a Performance Enhancer – Papers 4 and 5*.

There are many application areas for DES softwares, according to frame-of-reference section *3.3 Areas of application for Discrete Event Simulation*. In some areas, the software needs to be used in different ways in order to achieve the desired results. Larger DES projects, with many details, have other demands on the software compared

to shorter projects with less complexity. That is why the evolution of DES software probably will diverge in many directions. Some software vendors will try to focus on fast model-building and fast response-time from the modelling in order to decrease the ramp-up times and introduction of the findings from the project, while others will try to focus on details and larger scale models for follow-up and continuous improvements.
Some of the main results from Paper 3 Johansson et al (2002) are shown in *Figure 20*. These softwares are suitable for "Dynamic Rough-cut Analysis", which is short and fast DES projects to be used mostly for stop-or-go decisions.

Figure 20. Evaluation results divided according to each



criteria group for the software packages (Johansson and Johnsson et al 2002, Paper 3).

During a panel discussion on *Simulation in the future* (Banks et al 2000) at the Winter Simulation Conference, Mabrouk said: "I have a dream…". He continued to name all the positive factors needed for a successful simulation project such as:

- Perfect input data
- Easy to interpret output
- Models that can be built in a second
- Software without bugs
- Free software packages
- Etc.

While this is not yet the case today, this thesis shows that efforts are being made in the direction Mabrouk mentioned. The DES software of today tends to be developed for everyday use and is focusing on larger companies with simulation experts. DES software also tends to grow in complexity with each new release because users need new functions, which makes the programs increasingly expert-associated. This negatively affects new users who must develop *knowledge* in the software, since the level of knowledge that must be achieved, before being able to use the software fully, continually is being raised. It is also important for the developer of the software not to make excessively great changes in the interface. If they are done, even experienced users will not recognise the software interface in new releases.

Another interesting integration aspect will soon be on hand for the industry to use, the PPR softwares. PPR stands for Product, Process, and Resource. This software enables different viewpoints for different users in the system (Myung et al 2002), including connections and cooperation between other softwares such as PDM, ERP, and MRP systems. However, it is not certain that the industry is mature enough to use this software yet. Some issues have to be solved before a successful implementation can be made. These issues will be discussed in the next section *5.5 DES as a Performance Enhancer – Papers 4 and 5*.

5.5 DES as a Performance Enhancer – Papers 4 and 5

To achieve the true potential from DES there are certain issues that needs to be tackled before DES is able to enhance the overall performance. If they are not attained, the results will not be as good as they could be, in fact they could even come out negative. Except the already mentioned requirements such as framework, methodology, and software, the following activities are also required:

1. The *knowledge* of the system to be simulated has to be on hand and correct. I.e., the logical couplings, the structure, and the organisation between interrelations have to be made transparent, and formulated into *information* and *data* in order to be able to put them into a model. See *List of Definitions* for the definitions of Knowledge, Information, and Data.

2. *Correct data* is needed to enable a virtual model to be built. The data needed has to be formulated and measured, preferably according to the frame-of-reference chapter *2 Performance* in order to facilitate verification, validation, and accreditation of the DES model.

3. The *organisational structure* needs to support DES activities, in order to furnish the DES practitioners with information of the system to be modelled.

The employees not actively participating in the DES projects might not need such deep knowledge in DES. Still, a *familiarity* with DES is necessary to enable supportive actions according to the third point.

Figure 21 shows the effort needed in order to introduce different parts to efficient use of DES according to Östman (1998).

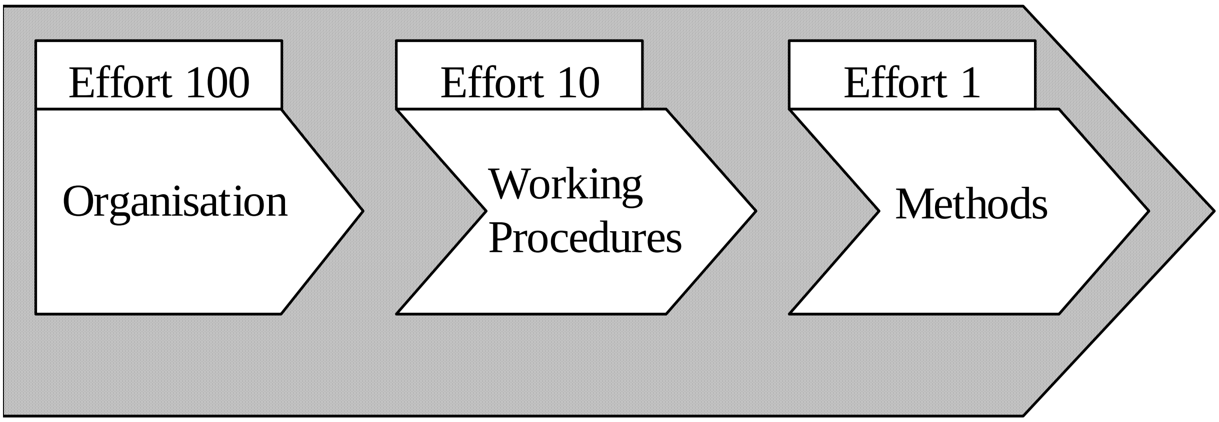


Figure 21. Efforts of implement DES at different levels of a company, Östman (1998)

Figure 21 is a good example of how complex it is to introduce DES into the enterprise integration level described in section *5.2 Framework – Paper 1*. It can also be seen as an explanation of why the use of DES did not follow the straight line in *Figure 19*, described in section *5.4 DES Softwares – Paper 3* above.

In order to maintain the quality of the *data* in the second point, *knowledge* of the process from the first point is of vital importance. These two issues will summarise the main point of this thesis. By gaining *knowledge* of the system and processes, the *data* will become updated and correct, which results in ORDER. This was CHAOS in the other spiral in section *1.3 Problem description*. Thus, the trend is about to change.
To connect this idea to the frame-of-reference in chapter *2 Performance* and chapter *3 Discrete Event Simulation*, it can be concluded that DES is pointing out which direction for actions to take in order to enhance the four performance factors:

- **Dependability** by creating order in the process, and increasing the overall understanding of the process, etc.
- **Speed** by decreasing the lead-times in all phases of a process and/or product lifecycle, etc.
- **Flexibility** by enabling "offline" programming and development of new or modified processes, etc.
- **Quality** by increasing the understanding and maintenance of failures and breakdowns, etc.

In turn, according to *Figure 6* in section *2.2 Performance factors.* It will affect the cost of the operation. This was the case in Paper 4 (Johansson and Kaiser 2002), where

DES was used to create *knowledge* and *order* in the resetting process of a manufacturing system. The DES project itself forced the organisation to take control of the needed performance measurements. This enabled the building of a complex DES model, which in turn enhanced the knowledge of the process in the organisation.

However, the problem concerning the low utilising of DES in Swedish industry is the lack of relevant, structured data and information about the production process. Paper 5 (Johnsson et al 2002) shows that only 6 % of the companies do have enough "ORDER" to enable a DES model to be built on existing data and information, while the other 94% needed an extensive data collection procedure in order to be able to build a DES model of the desired system (Johnsson et al 2002).

6 Discussion

New opinions often appear first as jokes and fancies,
then as blasphemies and treason,
then as questions open to discussion,
and finally as established truths.

George Bernard Shaw

In this chapter, the results from the research conducted will be discussed and compared with other researchers' results.

6.1 ORDER and CHAOS

The research on DES during the last decades has been large, based on the number of published papers in conferences, such as WSC (Winter Simulation Conference), ASIM (Arbeitsgemeinschaft Simulation), SCS (Society for Computer Simulation), etc.
The usage of DES in Sweden generally has been low, according to some surveys made in the past years, 17% 1997 (Jackson 1998) and 7% 1999 (Eriksson 2002).

Why does the use of DES not increase, while there are so many positive features in utilising it?

Randell (2000) states that the lack of use of DES probably has the following two reasons:

- Lack of theoretical knowledge of DES
- Lack of DES integration with other softwares

Randell (2000) finalises his licentiate thesis with a statement in the chapter on future research:

> It has been noticed during the case studies performed that input data collection requires vast resources. Not only are resources required for the first edition of the simulation model, the problem remains when the model is to be maintained. By integrating software containing the needed information with the simulation environment, time could be saved (Randell 2000).

However, the results from papers 4 and 5 (Johansson and Kaiser 2002, and Johnsson et al 2002) show that the main reason for this setback of DES utilisation in Swedish industry is not the lack of theoretical knowledge on DES or lack of integration with other softwares. Rather, it is the chaos and lack of genuine production engineering thinking that makes the effective usage of DES technology impossible, according to paper 5 (Johnsson et al 2002).

Another important aspect is the increasing number of tools and methods implemented in industry. There have been too many softwares, and they have been implemented too fast, yet the adoption of many tools and methods did not prove successfully. Some companies did not have enough patience and will power to succeed with the implementations of them all. In section *5.5 DES as a Performance Enhancer – Papers 4 and 5*, *Figure 21* shows the relation between method-, working procedure-, and organisational effort to change the operation. This means that if *one part* is devoted to learning the software, the times needed for learning the working procedure is *ten times* longer. *Even more effort* is needed for the organisational restructuring. In addition, since DES projects are depending on various sources of information to become successful, they are vulnerable, and demand order and structure throughout all operations to be modelled, which makes the task even more difficult.

6.2 DES software utilisation

It is well known that *early* changes in a development of new processes and products are cheaper and have more effect on the outcome, than *late* changes. See *Figure 22*. However, it is a major task to make the early decisions sustainable and correct. This is mainly caused by the lack of data and information in early phases of the development. The data and information can be inaccurate or missing, which complicates the decision-making. To build a DES model requires assumptions in early stages of the development, in most cases.

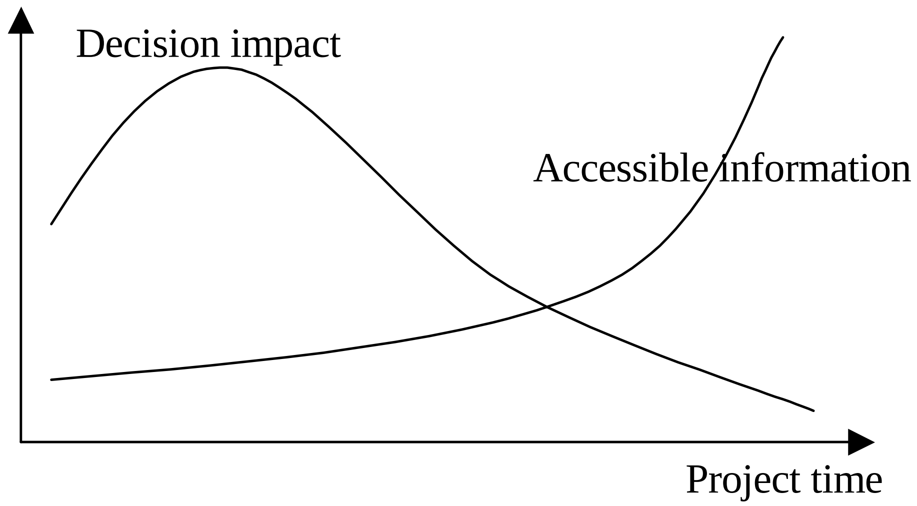


Figure 22. The impact of the decision and the amount of information during the project time (Christensen and Kreiner 1991)

However, during the early period of development of new processes, DES can be used with advantage, since the model can be continuously updated with increasingly accurate data and information, as described in paper 3 (Johansson and Johnsson 2002). The model-building and simulation will not become very time-consuming and expensive either, as mentioned in frame-of-reference section *3.1 Introduction to Discrete Event Simulation*, Terwiesch and Bohn (2001), and Banks et al (1996), if the project is using one of the three recommended softwares from paper 3 (Johansson and Johnsson 2002).

6.3 Effective DES model-building techniques

The model-building will become even better supported and focused early on if a consideration about the performance factors and measurements described in frame-of-reference chapter *2, Performance,* is made in correlation with the data collection and model-building. Because of the performance factors and measurement considerations, the overall goal with the DES model will be determined and can be formulated in an objective form. This will enable usage of the DES project methodology presented in Paper 2 (Johansson and Grünberg 2001).

It is also of great importance to understand that *knowledge* about the process to be modelled is vital for a successful DES project. Using a methodology for DES projects as a cookbook is not recommended, since all projects are different. Some important aspects, which are correlating with paper 2 (Johansson and Grünberg), are stated by Karjalainen (2000):

> Simulation is a powerful tool, but there is a tendency to want to model everything without stopping to consider exactly what is necessary. This may cause the cost of simulation to increase and the results not being available in time. Problem and model definition stages are vitally important to the success of a simulation project.

6.4 Framework for DES activities

Finally, in the context of the life-cycle of a process, the DES project needs to be set into a framework, such as the one presented in paper 1 (Klingstam and Johansson 2000). This approach will enable recycling of the information, data, and models to be used in future projects, as well as facilitate the acceptance of DES usage throughout the organisation. This is partly to keep the DES model up-to-date and partly to decrease the effort to conduct new DES projects later on in the life-cycle of the processes. Today, most DES projects are conducted as one-of-a-kind projects (Klingstam 2001, and Johnsson and Johansson 2002), which does not enable recycling of DES models, data, and information. Nor does it assist in the diffusion of DES into the organisational structures of industrial companies in Sweden.

6.5 Correspondence to research questions and objectives

Here the research questions stated in section *1.4 Research questions* will be answered in correlation to the conducted research described in this thesis.

RQ 1: How can DES be integrated into the life-cycle of a process in an efficient way?

Many aspects of this question are of importance. Some of them are easier to perform than others but the main issues are found in paper 1 (Klingstam and Johansson 2000):

- *A framework* for simulation is needed to assist and guide the relatively new technology into the use of the industry.
- *A standard*, such as GERAM, CIMOSA, or the like is needed to unite the industrial approach in an effective way.
- This approach furthermore will reassure the use of DES throughout the life-cycle of the process.

RQ 2: How should a DES project be conducted to suit the unique present prerequisites of each process?

There are no two DES projects with the same prerequisites, which in turn means that there is no recipe to use that is a systematic instruction. However, a methodology *guideline*, such as the one presented in paper 2 (Johansson and Grünberg 2001) is valuable in the hunt for successful DES modelling.

RQ 3: What kind of DES software is suitable to use in early life-cycle stages?

In paper 3 (Johansson et al 2002), the "Dynamic Rough-Cut Analysis" approach is described as a tool for fast model-building to achieve understanding and guidance in early life-cycle phases. The evaluation of the softwares shows that Simul8, Extend, and Taylor ED are suitable for these activities; see *Figure 20* in section *5.4 DES Softwares – Paper 3*.

RQ 4: How can DES increasing the contribution to the overall performance of a company?

DES can contribute to increasing the overall performance of companies in many aspects, as shown in e.g. subsection *3.2.3, Advantages of DES*. However, the new ones described in this thesis, papers 4 and 5 (Johansson and Kaiser 2002, Johnsson et al 2002), are:

- DES projects *force* the organisation to structure information and data concerning the processes, which enables the spiral in *Figure 2* to turn to the one with ORDER as guidance for successful processes.
- DES projects are multidisciplinary and connect many actors with various perspectives on the same problems, which enables knowledge-sharing and enhancement in competence levels.

7 Conclusions

All truth passes through three stages.
First, it is ridiculed.
Second, it is violently opposed.
Third, it is accepted as being self-evident.

Arthur Schopenhauer

Discrete Event Simulation is merely a tool to *support* production-engineering activities. However, DES cannot serve as a substitute for decreased order- and decreased genuine production-engineering *knowledge* in Swedish industry. This knowledge is essential for successful competition in the global market, and cannot unnoticed slip out of our hands. It will require multiple actions in many forms to stop the left spiral in *Figure 2* from continuing to drag down the Swedish economy, and turn it into the right spiral of *Figure 2*, with increasing prosperity.

This thesis has shown that DES can support the Swedish industry in the striving for increased performance of the operations in the following manner:

Firstly, a *framework* (paper 1) describing *when* to use DES needs to become accepted by the industry. I.e., in the same manner as CAD drawings have a framework.

Secondly, a *methodology* (paper 2) describing *how* to perform a DES project needs to become *accepted* in the organisational structure of companies.

Thirdly, *softwares* (paper 3) for effective use of DES need to become more frequently used and accepted in early development phases.

Fourthly, DES can be used to create *structure* and *ORDER* in a process (papers 4 and 5), since a DES project forces the organisation to deal with its own processes in order to find data and information about how things are connected in the processes.

The production engineering process is a potential area for DES where it can expand and perhaps, be just as important for the operations as the CAD model is for the products. However, we are not even close to fulfilling the criteria for this to come true.

Genuine production-engineering needs to become assimilated into the Swedish industry again in order to recreate the source of competence and knowledge once possessed. Then, perhaps, will the time for effective use of DES come in to its true potential.

8 Future research

The future influences the present just as much as the past.

Friedrich Nietzsche

A main challenge and probably a very difficult one is to use of DES to recover lost ground and catch up with the software development. This would enable entrance to the level of Enterprise Integration in a successful way; see *Figure 23*.
However, the requirements concerning knowledge of the system and the quality of input data is not even closely achieved, according to Johnsson et al (2002, Paper 5).

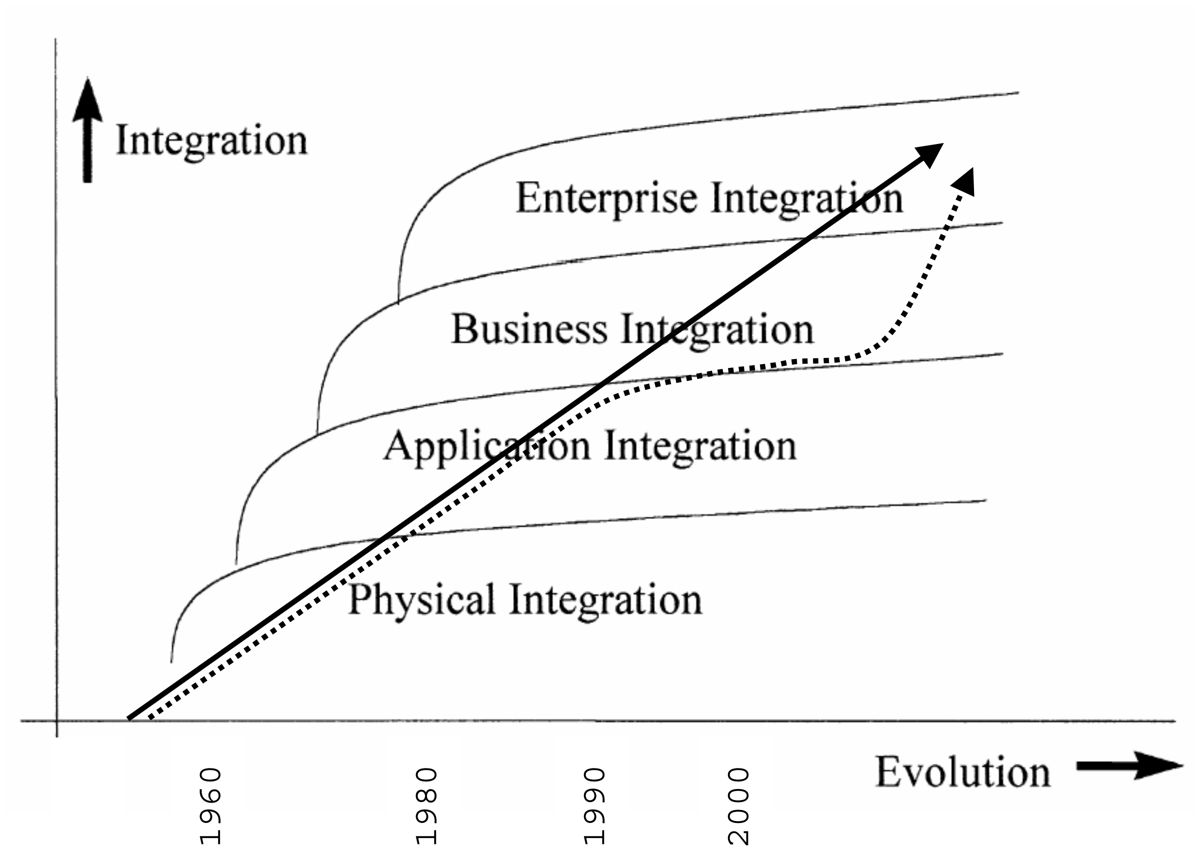


Figure 23. DES software potential, vs. DES software future usage in the Enterprise Integration Evolution context, altered from Ortiz et al (1999).

There is a chance that PPR software can become a useful resource in the striving for order, knowledge, and data quality. This is a potential area for DES to expand into, and perhaps it will become as important for the operations as the CAD models are for the products.
As Östman (1998) states, there is 1 part tool, 10 parts working procedures, and 100 parts organisational acceptance. Now, with the tool on hand and the 10 parts working procedures on its way, the industry is beginning to realise its potential. We can only do as always in life and research: AVANCEZ!

List of acronyms

ABC	Activity Based Costing
AD	Axiomatic Design
AGV	Automated Guided Vehicle
ASIM	Arbeitsgemeinschaft Simulation
BPR	Business Process Re-engineering
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPE	Computer Aided Production Engineering
CIMOSA	Computer Integrated Manufacturing-Open System Architecture
DES	Discrete Event Simulation
DFA	Design For Assembly
DFM	Design For Manufacturing
DRCA	Dynamic Rough-Cut Analysis
ERP	Enterprise Resource Planning
FEM	Finite Element Analysis
FMEA	Failure Mode and Effect Analysis
FORTRAN	FORmula TRANslation
GASP	General Activity Simulation Program
GERAM	Generalised Enterprise Reference Architecture and Methodology
GPSS	General Purpose Simulation System
HLA	High Level Architecture
IDEF	I-CAM DEFinition
ISO	International Organisation for Standardisation
JIT	Just In Time
MPRII	Manufacturing Resource Planning
MPS	Master Production Schedule
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NIST	National Institute of Standards and Technology
OEE	Overall Equipment Effectiveness
OLP	Off-Line Programming
PDCA	Plan-Do-Check-Act
PDM	Product Data Management
PM	Preventive Maintenance
PPR	Product Process Resource
PROPER	Programme for Production Engineering Education and Research
QFD	Quality Function Deployment
SADT	Structured Analysis and Design Technique
SCM	Software Configuration Management
SCS	Society for Computer Simulation
SIMAN	SIMulation ANalysis
SLAM	Simulation Language for Alternative Modeling
SMED	Single Minute Exchange of Die
TPM	Total Productive Maintenance
WIP	Work In Process
WSC	Winter Simulation Conference, www.wintersim.org

VM	Virtual Manufacturing
VR	Virtual Reality

List of definitions

Definition 1. Case Study

An empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident. (Yin 1994)

Definition 2. Productivity

Productivity means how much and how well we produce from the resources used. If we produce more or better goods from the same resources, we increase productivity. Or if we produce the same goods from lesser resources, we also increase productivity. By 'resources', we mean all human and physical resources, i.e. the people who produce the goods or provide the services, and the assets with which the people can produce the goods or provide the services. The resources that people use include the land and buildings, fixed and moving machines and equipment, tools, raw materials, inventories and other current assets. (Bernolak 1997)

Definition 3. Profitability

Profitability is seen as the relation between output and input but includes the influences of prices (i.e. price recovery). (Tangen 2002a)

Definition 4. Performance

Performance is the umbrella term of manufacturing excellence and includes profitability but also non-cost factors such as quality, speed, delivery, and flexibility. (Tangen 2002a)

Definition 5. Effectiveness

Effectiveness is a term to be used when the output of the manufacturing transformation process is focused. (Tangen 2002a)

Definition 6. Efficiency

Efficiency represents how well the input of the transformation process (i.e. resources) is utilised. (Tangen 2002a).

Definition 7. Simulation

1. The reproduction of the essential features of something, for example, as an aid to studies or training
2. The imitation or feigning of something
3. An artificial or imitation object
4. The construction of a mathematical model to reproduce the characteristics of a phenomenon, system, or process, often using a computer, in order to infer information or solve problems (Encarta).

Definition 8. Discrete

1. Completely separate and unconnected
2. Used to describe elements or variables that are distinct, unrelated, and have a finite number of values (Encarta).

Definition 9. Event

1. An occurrence, especially one that is particularly significant, interesting, exciting, or unusual
4. A happening or occurrence.
5. An occurrence defined in the theory of relativity as a single point in space-time.
6. An occurrence or happening of significance to a computer program, for example, the clicking of a mouse button or the completion of a write operation to a disk (Encarta).

Definition 10. System

A group of interacting, interrelated, or interdependent elements forming a complex whole. (The American Heritage 1996).

Definition 11. Data

Data on its own has no meaning, only when interpreted by some kind of data processing system does it take on meaning and become information. (The American Heritage 1996)

1234567.89 is data.

Definition 12. Information

Data on its own has no meaning. Only when interpreted by some kind of data-processing system does it take on meaning and become *information.* (The American Heritage 1996).

"Your bank balance has jumped 8087% to $1234567.89" is information.

Definition 13. Knowledge

Knowledge differs from data or information in that new *knowledge* may be created from existing knowledge using logical inference. If information is data plus meaning then knowledge is information plus processing. (The American Heritage 1996)

"Nobody owes me that much money" is knowledge.

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References

AMICE, E.C., Ed., 1993, CIMOSA: Open System Architecture for CIM, Berlin, Springer-Verlag

Anderson, J.E., 1994, The Management of Manufacturing: Models and Analysis, Addison Wesley Publishers Ltd. England

Arne, B., Nilsson, M., 2000, Flow Simulation of a New Layout for the Assembly of Chassis and Axles at Volvo Truck Corporation (In Swedish), M.Sc. Thesis, PTX 00:09, Department of Production Engineering, Chalmers University of Technology, Gothenburg, Sweden

Axelsson, E., Hjelte, M., 2002, DES used for Evaluation and Improvement of Resetting Processes in Manufacturing Systems (In Swedish), M.Sc. Thesis, ISSN 1651-1875, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, Sweden

Banks, J., 1996, Interpreting software checklists, OR/MS Today, June

Banks, J., Carson, J. S., Nelson, B. L., 1996, Discrete Event System Simulation, 2nd Ed., Upper Saddle River, New Jersey: Prentice-Hall

Banks, J., Gibson, R. R., 1997, Don't simulate when: 10 rules for determining when simulation is not appropriate, IIE Solution, September

Banks, J., 2000, Simulation in the future, panel discussion, Proceedings of the Winter Simulation Conference, pp. 1568-1576

Barnes, M. R., 1997, An Introduction to QUEST, Proceedings of the 1997 Winter Simulation Conference, ed. S. Andradottir, K. J. Helay, D. H. Withers, and B. L., Nelson

Baudin, M., 1990, Manufacturing systems Analysis: With application to production scheduling, Prentice Hall, Inc. New Jersey, USA

Bernolak, I., 1997, Effective measurement and successful elements of company productivity: The basis of competitiveness and world prosperity, Int.

Journal of Production Economic, Vol.52, pp. 203-213

Bititci, U. S., Carrie, A.S., 1998, Integrated Performance Measurement Systems: Structures and Relationships, EPSRC Final Research Report, Research Grant No. Gr/K 48174, Swindon

Bititci, U. S., Turner, T., 2000, Dynamics of Performance Measurement Systems, International Journal of Operations & Production Management, Vol. 20, No. 6, pp. 692-704

Britsman, C., Lönnqvist, Å., 1993, Handbok I FMEA: failure mode and effect analysis: Stockholm, Sveriges Verkstadsindustrier

Christensen, S., Kreiner, K., 1991, Projektledning –Att leda och lära i en ofullkomlig värld (In Swedish), Academia Adacta, Sweden

Cornford, T., Doukidis, G. I., 1991, An Investigation of the Use of Computers within Operational Research, European Journal of Information Systems, 1, 2, pp. 131-140

Cross, K.F., Lynch, R.L., 1998-1999, The SMART way to define and sustain success, National Productivity Review, Vol. 9 No. 1, pp. 23-33

Darwin, C.R., 1859, On the origin of species

Davies, R., 1992, Operational Research in Health Service Planning, Department of Accounting and Management Science Discussion paper, no 92-44, University of Southampton

Dixon, J.R., Nanni, A.J., Vollmann, T.E., 1990, The New Performance Challenge: Measuring Operations for World Class Competition, Dow Jones/Irwin, Homewood, IL

Doumeingts, G., Vallespir, B., Chen, D., 1995, Methodologies for Designing Computer Integrated Manufacturing Systems: A Survey, Computers in Industry, Vol. 25, pp. 263-280

Driva, H., Pawar K. S., Menon, U., 2000, Measuring product development performance in manufacturing organisations, International Journal of Production Economics, Volume 63, Issue 2, 15 Pages 147-159

Einstein, A., 1916, Relativity: The Special and the General Theory. Trans. Robert W. Lawson, 1916; reprint New York: Bonanza Books, 1952. An attempt at a nontechnical account

Encarta® Encyclopedia 2002, © 1993-2001 Microsoft Corporation

Eriksson, U., 2002, Discrete Event Simulation: The truth (in preparation), Doctorial dissertation, Department of Production Engineering, Chalmers University of Technology, Sweden

Forgionne, G. A., 1983, Corporate Management Sciences Update, Interfaces, Vol. 13, No. 3, pp. 20-23, June

Grünberg, T., Johansen, K., Johansson, B., Nordell, P., Tangen, S., 2002a, Productivity Improvement work at ABB Robotics, Västerås, Woxénrapport, KTH, Stockholm, Sweden (Accepted for Publication)

Grünberg, T., Johansson, B., Nordell, P., 2002b, Identifiering av Produktivitetshöjande åtgärder – En fallstudie, Posten Malmö (In Swedish), Internrapport, ISSN: 1651-0984 Rapport nr. 4, Chalmers University of Technology, Sweden.

Grünberg, T., Karlsson, A., 2002, Operations Process Mapping, A Model For Process Mapping and an Application, Proceedings of MIM 2002: 5th International Conference on Managing Innovations in Manufacturing (MIM) Milwaukee, Wisconsin, USA September 9-11

Hollocks, B. W., 1995, The Impact of Simulation in Manufacturing Decision Making, Control Eng Practise, Vol. 3, No. 1, pp. 105-112, Elsevier, Great Britain

Holst, L., 2001, Integrating Discrete-Event Simulation into the Manufacturing System Development Process –A Methodological Framework, Licentiate in Engineering Thesis, Division of Robotics, Department of Mechanical Engineering, Lund University, Sweden

Hover, R. W., Wagner, H., 1958, A Sample Survey of Industrial Operations Research Activities, Operational Research, Vol. 6, No. 4, pp. 876-881

IFIP-IFAC Task Force, 1998, Requirements for Enterprise-Reference Architectures and Methodologies ISO WD 15704, National Electrical Manufacturers Association

IVA, 2000, Rapport från Teknisk Framsyn Panel 4 – Produktionssystem, Kungliga Ingenjörs-vetenskapsakademin, In Swedish, ISBN 91 7082-657-9, Stockholm

Jackson, M., 1998, Discrete Event Simulation – A Tool to Increase Agility in Production Systems, Licentiate Thesis, Linköping University, Sweden, Division of Assembly Technology, Department of Mechanical Engineering, LiU-Tek-Lic-1998:56

Johansen, K., Björkman, M., 2002, Product introduction within extended enterprises, IEEE International Symposium on Consumer Electronics 2002 (ISCE02)

Johansson B., Grünberg T., 2001, *"An Enhanced Methodology for Reducing Time Consumption in Discrete Event Simulation Projects",* In The 13th European Simulation Symposium: Simulation in Industry, Eds. Giambiasi and Frydman, SCS Europe Bvba, Marseille, France, pp. 61-64

Johansson B., Johnsson J., Eriksson U., 2002, *"An Evaluation of Discrete Event Simulation Software for "Dynamic Rough-Cut Analysis""*, In Proceedings of The 35th CIRP International Seminar on Manufacturing Systems "Manufacturing Technology in the Information age", Seoul, Korea, pp. 348-355

Johansson B., Kaiser, J., 2002, Turn Lost Production into Profit. -Discrete Event Simulation Applied on Resetting Performance in Manufacturing Systems, Proceedings of the 2002 Winter Simulation Conference, ed. E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, San Diego, California, Dec 8-11 (Accepted for publication).

Johnsson J., Johansson B., Kinnander A., 2002, Information structure to support Discrete Event Simulation projects, (working paper).

Kaplan, R.S., Norton, D.P., 1996, Translating Strategy into Action: The Balanced Scorecard, Harvard Business School Press, Boston, MA

Karlsson, Å., 2001, Development of a Handling System. Transports of Gears at Saab Automobile's Gearbox Factory (In Swedish), M.Sc. Thesis, PTX 01:05, Department of Production Engineering, Chalmers University of Technology, Gothenburg, Sweden

Karjalainen, J., Blomqvist, M., Suolanen, O, 2000, Simulation as a Method to Support Knowledge Creation in Supply Chain Management, In The New Simulation in Production and Logistics: Prospects, Views and Attitudes, Eds. Mertins and Rabe, IPK Berlin, Eigenverlag, Berlin, Germany, pp. 155-163

Kaiser, J., Nordell, P., Kinnander, A., 2002, Profitability development through resetting reduction in manufacturing systems, 35th CIRP International Seminar on Manufacturing Systems, Seoul, Korea

Kinnander, A., Gröndahl, P., 1999, www.proper.sunet.se/pub_e/research/research_projects/proddev/Prod_dev.pdf (accessed 18:th of September 2002)

Klingstam, P., 2001, Integrating Discrete Event Simulation into the Engineering Process, Doctorial Dissertation, Department of Production Engineering, Chalmers Univ. of Technology, Sweden

Klingstam, P., Gullander, P., 1999, Overview of simulation tools for Computer-Aided Production Engineering, Computers in Industry, Vol. 38, No. 3, pp. 173-186

Klingstam P., Johansson B., 2000, *"Towards a Strategic Framework for Logistic and Production Flow Simulation"*, In The New Simulation in Production and Logistics: Prospects, Views and Attitudes, Eds. Mertins and Rabe, IPK Berlin, Eigenverlag, Berlin, Germany, pp. 45-54

Kreutzer, W., 1986, Systems Simulation – Programming styles & languages, Addison Wesley

Law, A.M., Kelton, W.D., 1991, Simulation Modelling and Analysis, 2nd Ed., New York: McGraw-Hill

Loch, C. H., Terwiesch C., 1999, Accelerating the process of engineering change orders: capacity and congestion effects, J. of Product Innovation Management, Vol.16, Issue2, p.145-159

Mansurov, N., Probert, R., 2001, Improving time-to-marketing using SDL tools and techniques, Computer Networks, Volume 35, Issue 6, Pages 667-691

Marca, D.A., McGowan, C.L., 1988, SADT: Structures analysis and design technique, New York, McGraw-Hill

Maskel, B.H., 1992, Performance Measurement for World Class Manufacturing, A model for American Companies, Productivity Press, Cambridge, MA

Maslow, A. H., 1943, A Theory of Human Motivation, Psychological Review, v50, pp. 370-396

Myung, S., Song, K., Lee, J., 2002, Integration of DFM and virtual NC manufacturing process, 35th CIRP International Seminar on Manufacturing Systems, Seoul, Korea

Nance, R. E., 1995, "Simulation programming languages: An Abridged History", Proceedings of the 1995 Winter Simulation Conference, ed. C. Alexopoulos, K. Kang, W. R. Lilegdon, and D. Goldsman, Arlington, VA, Dec 13-16, pp. 1307-1313

Nakajima, S., 1988, Introduction to TPM: Total Productive Maintenance. Cambridge, Productivity Press, Inc.

Nakajima, S., Ed. 1989, TPM Development Program: Implementing Total Productive Maintenance, Cambridge, Productivity Press, Inc.

Narasimhan, R., Jayaram J., 1998, Reengineering service operations: a longitudinal case study, Journal of Operations Management, Volume 17, Issue 1, Dec 1998, pp. 7-22

Neely, A., 1993, Performance Measurement System Design – Theory and Practise, Manufacturing Engineering Group, Cambridge University

Nikoukaran, J., Hlupic, V., Paul, R. J., 1999, a hierarchical framework for evaluating simulation software, Simulation Practise and Theory Volume 7 pp. 219-231

NIST, 1993, Integration Definition for function modelling (IDEF-0), National Institute of Standards and Technology (U.S.)

Olhager, J., 2000, Produktionsekonomi, Studentlitteratur, Lund

Ortiz, A., Lario, F., Ros, L., 1999, Enterprise Integration—Business Processes Integrated Management, Computers in Industry, Volume 40, Issues 2-3, pp. 155-171

Patel, R., Tebelius, U., 1987, Grundbok I forskningsmetodik, studentlitteratur, Lund, (In Swedish)

Pegden, C.D., Shannon, R.E., Sadowski, R.P., 1995. *Introduction to simulation Using SIMAN*, 2nd Ed., New York: McGraw-Hill.

Randell, L., 2000, A Methodology to Reduce Time Consumption in Discrete-Event Simulation Projects, Licentiate in Engineering Thesis, Division of Robotics, Department of Mechanical Engineering, Lund University, Sweden

Randell, L., 2002, On Discrete-Event Simulation and Integration in the Manufacturing System Development Process, PhD Thesis, Division of Robotics, Department of Mechanical Engineering, Lund University, Sweden

Pritsker, A. A. B., Pegden, C. D., 1979, Introduction to simulation and SLAM, John Wiley, New York

Rivera, J., Diamond, P., 1997, "Extend User's Manual", Version 4, Imagine That, Inc.

Rohrer, M., 1999, Automod Product Suite Tutorial, Proceedings of the Winter Simulation Conference, P. A. Farrington, H. B. Nembhard, D. T. Sturrock, and G. W. Evans, eds, pp. 220-226

Sargent, R. G., 2000, Verification, Validation, and Accreditation of simulation model, Proceedings of the Winter Simulation Conference, pp. 50-59

Schumacher, T., Wallin, S., 1998, "Planning and simulation of a new production system for electronic equipment at SAAB Ericsson Space AB", Institutionen för Transportteknik 1998:8

Seila, A. F., 1995,"Introduction to Simulation", In Proceedings of the 1995 Winter Simulation Conference, pp. 7-14

Slack, N., Chambers, S., Johnston, R., 2001, Operations Management, Third edition, Pearson Education, Essex, England

Smith, A., 1776, Wealth of Nations

Sparkes, P., 1989, Simulation in the Finance, Retail, and Service Sectors, Management Services, September

Stevrin, P., 1991, Utvärdering för förändring, Lund, Studentlitteratur

Suzuki, T., 1992, New direction for TPM, Cambridge, Massachusetts, USA, Productivity Press

Tangen, S., 2002a, A Theoretical Foundation for Productivity Measurement and Improvement of Automatic Assembly Systems, Licentiate Thesis, Department of Production Engineering, The Royal Institute of Technology, Stockholm, TRITA-IIP-02-11, ISSN 1650-1888

Tangen, S., 2002b, "RATOC - a simple method for productivity improvement in robot workcells based on the theory of constraints", Proceedings of the International Symposium on Robot-based Automation (ISR2002), October 7-10, Stockholm, Sweden

Terwiesch, C., Bohn, R. E., 2001, Learning and process improvement during production ramp-up, International Journal of Production Economics, Volume 70, Issue 1, Pages 1-19

The American Heritage, 1996, Dictionary of the English language, 3rd edition, Houghton Mifflin Company, at www.dictionary.com

Tocher, K. D., Owen, D. G., 1960, The Automatic Programming of Simulations, Proceedings of the Second International Conference on Operational Research, J. Banbury, J. Maitland, eds., pp. 50-68

Vernadat, F., 1996, Enterprise Modeling and Integration, 1 ed. Chapman & Hall, London, U.K.

Visionary manufacturing Challenges for 2020, 2002, www.nap.edu/html/visionary (Accessed 18th of September 2002)

Wild, R., 1972, Mass Production Management, John Wiley

Williams, E. J., Darwactor, D., Shorkey, L., 2001, Evaluation of Machine Shop Logistic Alternatives using Simulation, In The 13th European Simulation Symposium: Simulation in Industry, Eds. Giambiasi and Frydman, SCS Europe Bvba, Marseille, France, pp. 255-259

Wilson, R. L., 1994, An Improved Goal-oriented Method for Measuring Productivity, International Journal of Operations & Production Management, Vol. 14, No. 1, pp. 50-59

WITNESS™ USER MANUAL, 1994, WITNESS™ User Manual, AT&T ISTEL Visual Interactive Systems Ltd, Redditch, UK.

Yin, R. K., 1994, Case study research: Design and Methods, Sage Publications, Thousand Oaks, CA

Östman, J., 1998, Virtual Reality och Virtual Prototyping - tillämpningar i amerikansk fordonsindustri (In Swedish), Utlandsrapport USA 9806, Swedish Office of Science and Technology, Sweden

Appended Papers

Paper 1:

Klingstam P., Johansson B.: *"Towards a Strategic Framework for Logistic and Production Flow Simulation"*, In The New Simulation in Production and Logistics: Prospects, Views and Attitudes, Eds. Mertins and Rabe, IPK Berlin, Eigenverlag, Berlin, Germany, pp. 45-54, 2000.

Paper 2:

Johansson B., Grünberg T.: *"An Enhanced Methodology for Reducing Time Consumption in Discrete Event Simulation Projects",* In the 13th European Simulation Symposium: Simulation in Industry, Eds. Giambiasi and Frydman, SCS Europe Bvba, Marseille, France, pp. 61-64, 2001.

Paper 3:

Johansson B., Johnsson J., Eriksson U.: *”An Evaluation of Discrete Event Simulation Software for ”Dynamic Rough-Cut Analysis”*, In Proceedings of The 35th CIRP International Seminar on Manufacturing Systems ”Manufacturing Technology in the Information age”, Seoul, Korea, pp. 348-355, 2002.

Paper 4:

Johansson B., Kaiser, J.: Turn Lost Production into Profit. -Discrete Event Simulation Applied on Resetting Performance in Manufacturing Systems, Proceedings of the 2002 Winter Simulation Conference, ed. E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, San Diego, California, Dec 8-11, 2002 (Accepted for publication).

Paper 5:

Johnsson J., Johansson B., Kinnander A.: Information structure to support Discrete Event Simulation projects, (working paper).