THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

On Virtual Development of Manufacturing Systems

-Proposal for a Modular Discrete Event Simulation Methodology

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To my loved ones: Louise, Felicia and Alice

Abstract

Today's production is characterized by frequent changes and uncertainty due to short product life cycles. Outsourcing to low-cost countries is a common way to solve flexibility and cost problems. Swedish manufacturing companies need to use knowledge as an advantage in order to compete successfully. This thesis formulates one approach on how to reuse and take advantage of knowledge and data for discrete event simulation of manufacturing systems. The approach uses modularity and division of knowledge in order to present a methodology for modular discrete event simulation.

The objective of the research building this thesis is to formulate the demands on a methodology for modular discrete event simulation, which is increasing the reuse of data and knowledge-intensive tasks. This in turn enables sharper focus on the value-adding performance improvement, for which a discrete event simulation study can generate a firm basis. In order to meet this objective, research has been conducted in the following steps:

- *Prerequisite* studies in order to find the research gap in case studies and papers
- *Confirmation* of the research gap and its current status in case studies and papers
- *Management* of the research gap by formulation of a methodology in this thesis
- *Validation* of the methodology in four case studies

The proposed methodology covers activities for *simulation specialists*, in terms of module building, *simulation users* in terms of model building and decision support, and *simulation observers*, in terms of decision support and visualization. The methodology is based on traditional discrete event simulation methodologies, with additional effort put into division of knowledge-intensive tasks in order to streamline the model building and the reuse of data and knowledge. This is achieved through modularization and parameterization of the building blocks used in discrete event simulation model building with module boundaries similar to those in the real-world manufacturing system.

It is concluded that the modular discrete event simulation methodology can provide profitable advantages for OEM suppliers of manufacturing systems and their nearby interactors. Important parts of the methodology have been validated in industrial case studies; however, general benefits for any manufacturing system were not found, only for OEM suppliers of manufacturing equipment and those with direct relations to these kinds of systems.

Keywords: Discrete Event Simulation, Manufacturing Systems, Knowledge, Productivity Development

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Göteborg, May 2006

Björn Johansson

List of publications

Appended Papers

Paper 1 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

Paper 2 Johansson, B., Johnsson J., Ericsson 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

Paper 3 Johansson, B., Kaiser, J., 2002, Turn Lost Production into Profit. -Discrete Event Simulation Applied on Resetting Performance in Manufacturing Systems, in Proceedings of the 2002 Winter Simulation Conference, ed. E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, San Diego, California, U.S.A, Dec 8-11

Paper 4 Johansson, B., Johnsson, J., Kinnander A., 2003, Information structure to support Discrete Event Simulation projects, in Proceedings of the 2003 Winter Simulation Conference, ed. S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, New Orleans, Louisiana, Dec 7-10 (Invited Paper).

Paper 5 Johansson, B., Johnsson, J., Bagiu, J., 2004, Modular Assembly Systems Simulation for Lead Time Reduction, The 2nd International Precision Assembly Seminar IPAS2004, Bad Hofgastein, Austria, February.

Paper 6 Bagiu, J., Johansson, B., 2004, Profitable Intelligent Manufacturing Systems for the Future, The 35th International Symposium of Robotics ISR 2004, Paris, France, March.

Paper 7 Johansson, B., Williams, E. J., Alenljung, T., 2004, Using Autonomous Modular Material Handling Equipment for Manufacturing Flexibility, in Proceedings of the 2004 Winter Simulation Conference, ed. R .G. Ingalls, M. D. Rossetti, J. S. Smith, and B. A. Peters, Washington DC, U.S.A, 5-8 December (Invited Paper).

Licentiate thesis

Johansson, B., 2002, Discrete Event Simulation -Present situation and future potential. A strategic approach to performance enhancement in manufacturing systems. Lic. Eng. Thesis, Product and Production Development, Chalmers University of Technology, Göteborg, Sweden ISSN 1651-0984 Report No. 7

Additional Papers

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

Johnsson, J., Johansson, B., 2003, Discrete Event Simulation in a Virtual Enterprise Environment: a Case Study Reflection of Multiple Developers, 15th European Simulation Symposium and Exhibition, Delft, the Netherlands, October 26-29

Johnsson, J., Johansson, B., 2004, Managing Strategic, Tactical and Operational Performance in Manufacturing Collaboration, IGLS2004, Innsbruck, Austria, February.

Murgau, A., Johansson, B., Pejryd, L., 2005, A Case Study on the Interaction between Physical and Knowledge Flows in Manufacturing Systems, the 38th CIRP International seminar on Manufacturing Systems, Florianópolis, Brazil May 16-18.

Standridge, C. R., Centeno, M. A., Johansson, B., Ståhl, I., 2005, Introducing Simulation Across The Disciplines, in Proceedings of the 2005 Winter Simulation Conference ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, Orlando, U.S.A., 5-8 December.

Stillström, C., Johansson, B., 2006, Mobile Manufacturing System Characteristics, 17th Annual Conference of POMS, Boston, MA, U.S.A, 28 April – 1 May.

Johansson, B., 2006, A Modular Discrete Event Simulation Methodology, 12th IFAC Symposium on Information Control Problems in Manufacturing, Saint-Etienne, France, 17-19 May.

Johansson, B. Ottosson, S., Persson, L., 2006, Virtual Reality in Design for Manufacturing and Assembly, Journal of Engineering Design, (Invited Paper, in preparation).

Additional publications and reports

Johansson, B., Allander, M., 1999, Flödessimulering och 3D-animering av en monteringsfabrik – En simuleringsstudie i QUEST, Institutionen för Produktionsteknik Examensarbete PTX 99:13. (In Swedish)

Johansson, B., Tangen, S., 2000, Produktivitet –Undersökning på sex företag, Chalmers tekniska högskola, Institutionen för Produktionsteknik internrapport. (In Swedish)

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

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

Johansson, B., Tangen, S., 2003, Produktiviteten i fokus - del 6, Produktionssimulering som arbetssätt för ökad produktivitet, Bättre Produktivitet del 6, 2003. (In Swedish)

Tangen, S., Grünberg, T., Johansson, B., Nordell, P., Johansen, K., 2004, “Produktiviteten i fokus (English title: Productivity in focus)”, Woxénreport no 38, WoxénCentrum, The Royal Institute of Technology, Stockholm, TRITA-IIP-04-04, ISSN 1650-1888. (In Swedish)

Johansson, B., 2004, Produktiviteten i fokus - del 9, Kompetensutveckling för framtidens tillverkningssystem, ett måste för svensk industri, Bättre Produktivitet del 1. (In Swedish)

Grünberg, T., Johansen, K., Johansson, B., Nordell, P., Tangen, S., 2004, Produktiviteten i fokus - del 10, Produktivitet - Hot och Möjligheter, Bättre Produktivitet del 2. (In Swedish)

Johansson, B., Kinnander, A., 2004, Produktivitetsförbättring av manuella monteringsoperationer – Sekvensbaserad Aktivitets och Metodanalys (SAM) vid sex nordiska företag, Chalmers Tekniska Högskola, Produkt och Produktionsutveckling, internrapport ISSN: 1651-0984 Rapport Nr: 25. (In Swedish)

Johansson, B., 2005, An effort to create modular discrete event simulation support for a lathe workshop, Chalmers Tekniska Högskola, Produkt och Produktionsutveckling, internal report ISSN: 1652-9243 Report No. 8.

Table of Contents

1. Introduction

The world is changing, and the manufacturing companies have to adjust to that (Peter Almström 2005)

1.1. Initial reflection

Simulations are practiced by all humans everyday, as we in our minds plan and predict future events. We try to measure how our behavior will affect the outcome of different actions in our dynamic world. We try to find the best possible output of our actions in relation to the required input. The author believes that this is what makes the human being intellectual and superior to other life-forms on our planet: the ability to abstract and predict the future in terms of actions taken.

Simulating a manufacturing site where products, machines and personnel interact in an ever-changing environment is very complex for the human brain. This is why discrete event simulation is used in some cases.

This thesis will focus on how OEM suppliers of Manufacturing Systems can use virtual development for lead-time reduction benefits through using the presented methodology "Modular Discrete Event Simulation".

1.2. Background

Today's production is characterized by frequent changes and uncertainty due to short product life cycles. Outsourcing to low-cost countries is a common way to solve flexibility and cost problems. One way for industrialized countries to compete with lower wages in other countries is to use automation, which decreases the percentage of cost on wages and increases the cost for technology, knowledge and equipment. The future trends in manufacturing, as described in Manufuture (2003), IVA (2000), and NRC (1998), present a number of challenges that companies will have to meet in order to be competitive in the future.

All of the three major reports presented above are in agreement, even though they were done separately with different companies and in different countries, see Table 1.

Table 1 Reports on Future trends in manufacturing and their main country-origin.

Report	**Base country**
Manufuture 2003	The Netherlands
IVA 2000	Sweden
NRC 1998	USA

The report from IVA (2000) can be summarized in five main areas for manufacturing companies to be competitive in the future:

- Individuals and companies can live locally and act globally.
- Production and product development are made on a project basis.
- The intellectual capital will be the most important mean for competition.
- The customer wants individualized products.
- Circular business systems, closed resource loops, and functional sales will be utilized.

The Manufuture conference focuses on how European companies should try to develop the manufacturing technologies in order to be competitive. The result can be divided into five areas of importance for competitiveness of the European manufacturing companies in the future (Manufuture 2003):

- Increased research and technical development
- International cooperation on manufacturing research
- Education and training
- A stimulating operative environment for industrial innovations
- Increased competitiveness of European research

The National Research Council (NRC) wrote *Visionary Manufacturing Challenges for 2020* in 1998. This report put forward grand challenges for the future of manufacturing industry. Out of these grand challenges, the most important technical, political, and economic forces for the development of manufacturing were listed (National Research Council 1998):

- The competitive climate, enhanced by communication and knowledge sharing, will require rapid responses to market forces.
- Sophisticated customers, many in newly developed countries, will demand products that are customized to meet their needs.
- The basis of competition will be creativity and innovation in all aspects of the manufacturing enterprise.
- The development of innovative process technologies will change both the scope and scale of manufacturing.

- Environmental protection will be essential as the global ecosystem is strained by growing populations and the emergence of new high-technology economies.
- The global distribution of highly competitive production resources, including skilled workforces, will be a critical factor in the organization of manufacturing enterprises.
- 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.

The last bullet from the list made by NRC (1998) is concretely addressed in this thesis while developing the methodology for modular discrete event simulation. The main conclusion from the Manufuture conference 2003 (Manufuture 2003) was that the manufacturing industries need to evolve from *resource based manufacturing* to *knowledge based manufacturing* in order to survive on the competitive market in the future. As knowledge is the key to utilize the presented methodology for modular discrete event simulation, it also correlates with Manufuture (2003). IVA (2000) does also bring up the intellectual capital which can be seen as knowledge.

1.2.1. Motivation

The overall motive for this research can be understood by using the three reports (NRC 1998, IVA 2000, Manufuture 2003) on future manufacturing and the requirements upon competitive solutions. Industrialized countries do have a setback when competing with the wages for manual labor. Knowledge and technology requiring less manual labor must therefore be used as competitive advantages. The reports repeatedly stress that knowledge, innovations, short product lifecycles, batch sizes of one, reconfiguration, research, education and training, etc. are vital factors for future manufacturing competitiveness. Since discrete event simulation is a tool used for predicting the effects of changes on a production system, it is with good reason this thesis focuses on utilizing discrete event simulation more productively, especially since global competition increases demands on shorter development phases, quicker ramp-up of production, shorter product market windows, and individualized products.

Development of discrete event simulation software is an ongoing process. However, the *user-friendliness* (enables increased use) and *advanced features* (enables flexibility during model building) in discrete event simulation software are more or less contradicting each other (More on this is found in chapter 8.3 Flexibility vs modularity and user-friendliness, and Appendix Case 9). Some software vendors are developing their platforms towards user-friendliness in order to reach more users, and others aim at the advanced features in order to achieve more powerful and flexible applications.

Discrete event simulation awareness in industry is growing and more industrial companies wish to use discrete event simulation. Since discrete event simulation traditionally is an expert tool and not easy to learn and it also requires a lot of time spent with the tool continuously in order to maintain high level for performance, there is ample motivation to search for an easier way to build discrete event simulation without expert knowledge on the specific tool, i.e. user-friendliness is requested by industrial companies. As far as fulfilling user friendliness it will not prove to be as hard a task, compared to maintaining the advanced features and flexibility of the tool at the same time, which is a more problematic area to combine since they are contradicting each other. Modularization is a proven technology frequently used while designing products (Erixon et al 1994). Erixon et al (1994) states that the effects of modularizing the product is:

- Shorter development times
- Faster implementation of product changes
- Lower risk when developing new products
- Shorter production lead-times
- Increased quality during the production phase
- Fewer product parts to manage and administrate

The modularization is then enabling product flexibility on a user-friendly basis. Since the *product* in this thesis is the *manufacturing system*, a similar approach will be used.

The target of this thesis is to combine both *user-friendliness* and *advanced features* in a controlled manner in order to reach *many users* with *power* and *flexibility* through modularization of the model-building phase in discrete event simulation tools.

1.2.2. Purpose

The purpose of this thesis is to present a methodology for modular discrete event simulation, which can be used to increase the benefits in terms of cost, lead-times, investments, and knowledge when designing, implementing, and using reconfigurable modular manufacturing systems. The thesis focuses mainly on how discrete event simulation can be utilized by companies which are OEM suppliers of manufacturing equipment. However, the presented methodology in general is generic and can be used on any system. But it will lack the advantages gained from modularity in other business areas, and in these cases become more equal to the traditional discrete event simulation methodology.

The overall purpose of this thesis is to increase productivity by using modularity and discrete event simulation with a knowledge aspect as support functions during the lifecycles of manufacturing systems. Focus is set on three fields to achieve this:

- Discrete Event Simulation
- Manufacturing Systems
- Knowledge

These three fields are used synergistically to form a methodology, which can be used for productivity enhancement of modular manufacturing systems.

Discrete event simulation is not a new invention; it has been used for many decades. Even though it has been around for a long time, the use of this technology has not reached further than a few percent. Table 2 contains data from studies dealing with the use of simulation in industry.

Table 2 Studies conducted on the use of discrete event simulation in industry.

Usage measured	Replies	Response rate	Main country studied	Study conducted year	Reference
9%	431	NA	UK	1991	SSG (1991) referred to in Ericsson (2005)
4%	95	42%	Sweden	1992-1993	Savén (1994)
7%	140	20%	Sweden	1999	Ericsson (2005)

Some of the reasons for the low utilization of simulation can be found in Ericsson (2005), who concludes that:

> "Regarding the current level of use, as obtained in present thesis, and taking in consideration existing theory, the user base will probably continue on an *enthusiastic level*. According to the theory, to speed up the diffusion – to increase the user base, with a *discontinuous innovation* hallmark, it has to be developed in such a way that the use of it does not influence an adopter's behaviour."

Other sources (Ball and Love 1992, Bley et al 2000) also point out that building discrete event simulation models requires expert knowledge and significant experience, not only in discrete event simulation but also in understanding the system to be modeled, and in project management (Klingstam 2001).

Modularization of discrete event simulation model-building has been desired for many years; authors like Ball and Love (1992), Bhuskute et al (1992), Meinert et al (1999), Son et al (2000), Valentin and Verbraeck (2002), Randell (2002), Heilala (2005) has been putting a lot of effort into this subject. These research and contribution from these authors will firstly be explained in chapter 3.6 Previous work on modular discrete event simulation, and secondly be compared to the research conducted within this thesis in chapter 8.2 Comparison with other discrete event simulation methodologies.

One way to speed up the diffusion and increase the user base of discrete event simulation is to make it more accessible for everyone to use. In order to get the accessibility the simulation *software* (and a computer) firstly needs to be present at the manufacturing company. Secondly the users need to have necessary *skills* in order to use it. Thirdly, the *willpower* to use it needs to be present for each user (Ericsson 2005). And last but not least support from the organizational point of view needs to be present, such as routines and *methodologies* on *how*, *by whom,* and *when* to use discrete event simulation. This thesis focuses on the *skill*, *software* and *methodologies* by addressing modular discrete event simulation.

In order to make an effort to increase the use of DES in Swedish industry, this thesis will focus on how to ease the use of DES through utilizing a modular discrete event simulation methodology.

1.3. Research objectives

The primary research objective in this thesis is to develop a *modular discrete event simulation methodology* suitable for *OEM suppliers of manufacturing systems*. The methodology should be *easy to use*, support *reuse of data* and *increase productivity development* both for the *simulation* and *real world* manufacturing system, i.e. be a modular discrete event simulation methodology for manufacturing systems.

The secondary research objective is to show numerous examples utilizing discrete event simulation for *manufacturing systems* as a *productivity enhancer* in order to *highlight* the *potentials* of the technology, as well as *setbacks* and *difficulties* while using discrete event simulation.

1.4. Research questions

The purpose and motives presented serve as a background to the following statement:

The complexity of using discrete event simulation needs to be lessened, the utilization of the discrete event simulation technology needs to increase, and the methodology need to be improved to support reconfigurable, reusable discrete event simulation models for present, and future, manufacturing systems in line with the visions of NRC (1998), IVA (2000), and Manufuture (2003).

This statement can be broken down into the following research questions:

RQ1. How could lead-times for development and analysis of manufacturing systems be affected by the use of discrete event simulation?

RQ2. How should a methodology for conducting a simulation project with modular discrete event simulation be outlined in order to be effective and user-friendly?

RQ3. In what way does modular discrete event simulation methodology affect the knowledge requirements on the practitioners compared to traditional discrete event simulation methodology?

1.5. Delimitations

The proposed methodology for modular discrete event simulation is mainly suited for OEM suppliers of manufacturing systems where the modularization is part of and beneficial for the real world system. The initial approach was wide and tried to incorporate manufacturing systems in general, however the methodology turned out to be most profitable for OEM suppliers of manufacturing equipment, and that fact is quite trivial. Other discrete event simulation practitioners may also partly benefit from the methodology presented, but effects that these practitioners may obtain are not part of the main purpose of the present thesis and therefore only one case study on this issue is presented, where the benefits are limited to a few (see appendix, Case 9 Modular Discrete Event Simulation of a mechanical workshop).

Standardization such as GERAM (IFIP-IFAC Task Force 1998) and CIMOSA (AMICE 1993, and CIMOSA 1994) are not addressed in the present thesis. Excessive efforts are needed in this field in order to enable implementation within the scope of this thesis. The effort is focused on modularity for now; however, standardization is also an important issue, which needs to be thoroughly investigated and implemented for increased and more productive use of discrete event simulation in industry. Work on the progression of standards in the field of discrete event simulation is already taking place (e.g. McLean and Leong 2002, Qiao et al 2003, and McLean et al 2003). Standardization is however addressed in an ongoing research project called Conceptual factory development, in which NIST is participating in parallel with the VINNOVA project. This makes the standardization issue a subject for future research in terms of this thesis.

The thesis main aspects cover *discrete event simulation* of manufacturing systems, but not *real world* systems.

Module interfaces and boundaries is not part of the present thesis, but it might be a subject for future research, since it will be needed in order to construct standardized module libraries. In fact this is the next step needed to be clarified in parallel with the standardization.

Version handling of the discrete event simulation models and modules is not included in this thesis, but it might be a subject for future research, since it will be needed for proper documentation and maintenance of for example a factory model. The reason for not treating it in this thesis is that the standardization issue has to be solved first, then there is a greater purpose and increased benefits from handle versions of the standardized models. Before that it is also a much harder task to perform version handling of the models since there is no standardized way of documenting them.

1.6. Outline of the thesis

Chapter one puts the research in its context and describes the motive for it. This is followed by a description of the problem area. The chapter ends with research questions and objectives.

Chapter two consists of a description of scientific procedures, followed by the specific procedures used for each contribution founding this thesis.

Chapter three consists of a frame-of-reference on Discrete Event Simulation, mainly describing questions concerning how, what, when and why, with DES in focus. It ends with a definition of modular discrete event simulation and a review of other research on this specific topic.

Chapter four consists of a frame-of-reference on manufacturing systems.

Chapter five consists of a frame-of-reference on knowledge.

Chapter six summarizes each of the appended papers and their main contribution. Additionally, chapter six also summarizes some of the case studies, which are further described in Appendix.

Chapter seven describes the proposed modular discrete event simulation methodology. An outline of the methodology is given. Furthermore, competence aspects including discrete event simulation expertise and simulation user perspectives are described. Lead-time benefits while using the modular discrete event simulation methodology are explained. Knowledge prerequisites are clarified, and additional issues for using modular discrete event simulation on manufacturing systems are presented.

Chapter eight discusses future use of discrete event simulation. It compares the proposed methodology with other recent research within the field of discrete event simulation, and ends with a validation of the research results.

Chapter nine concludes the thesis by addressing the fulfillment of purpose, motives and research questions.

Chapter ten discusses future research on the efforts of this thesis, and also generally in the area of discrete event simulation.

2. Research Method and Procedure

The purpose of the science theory and methods descriptions in this operations research thesis is to form a context for the researcher that enables the researcher to describe how the research has been conducted for validation and method considerations (Thomas Grünberg 2003)

2.1. Introduction to research procedures

The results described in this thesis are the outcome of research conducted through utilizing different research methodologies. The research methodologies will firstly be described and thereafter connected to the case studies and papers which the present thesis is based on.

While working with this thesis the author had many contacts with companies in Sweden (e.g. ABB, SKF, Posten AB, Scania, Ericsson, FlexLink, Flextronics, Volvo Cars, Volvo Trucks, SAAB, ABS Pump, etc.) and some abroad. In-depth analyses were conducted in the form of case studies at these companies (see *Definition 1. Case Study* in List of Definitions). Extensive literature studies have also contributed to the foundation of this thesis. The most relevant parts of the literature studies are presented in chapters 3 Discrete Event Simulation, 4 Manufacturing Systems and 5 Knowledge. Some of the case studies are presented in Appendix, and also partly in the papers appended.

At the beginning of the research base for this thesis, and also during the start-up of some of the subprojects during the last years, explorative studies were made in line with Yin's description (Yin 1994):

> "In this type of case study, fieldwork and data collection are undertaken prior to the final definition of study questions and hypotheses. Research may follow intuitive paths, perceived by others as sloppy. However, you may be genuinely trying to discover theory by directly observing a social phenomenon in its "raw"

> form (Glaser & Strauss, 1967). Moreover, when the final study questions and hypotheses are settled, your final study may not necessarily be a case study but may assume some other form."

The explorative studies were done in order to establish a base to form research questions from. This chapter will describe research characteristics in general and also what research methods were used for each of the contributing parts towards modular discrete event simulation for manufacturing systems.

2.1.1. Quantitative – Qualitative research

The description of the research problem decides if the research is to be qualitative or quantitative. Quantitative research *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. The main tool for the researcher in qualitative research is *comprehension*, which is why one must have a wide understanding of the problem. (Patel and Tebelius 1987).

2.1.2. 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 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 is therefore responsible for the quality of the research. The researcher should almost always try to stay objective, in order not to place preconceptions on the outcome of the studied object. The word *almost* in front of *always* in the previous sentence indicates that there is an exception on this rule. The exception is IAR (Insider Action Research), which will be described below in 2.1.5 Insider action research.

2.1.3. Participant - Observation

In the participant-role, 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 of studying events in their context at the time they actually happen. The main disadvantage is that the participant-role requires more attention, and is more expensive than the simple observing approach (Patel and Tebelius 1987, Yin 1994).

2.1.4. 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 blurred, and in which multiple sources of evidence are used.

2.1.5. Insider action research

During the later part of the research described in this thesis Insider Action Research (IAR) methodology, as described by Ottosson and Björk (2003), was used.

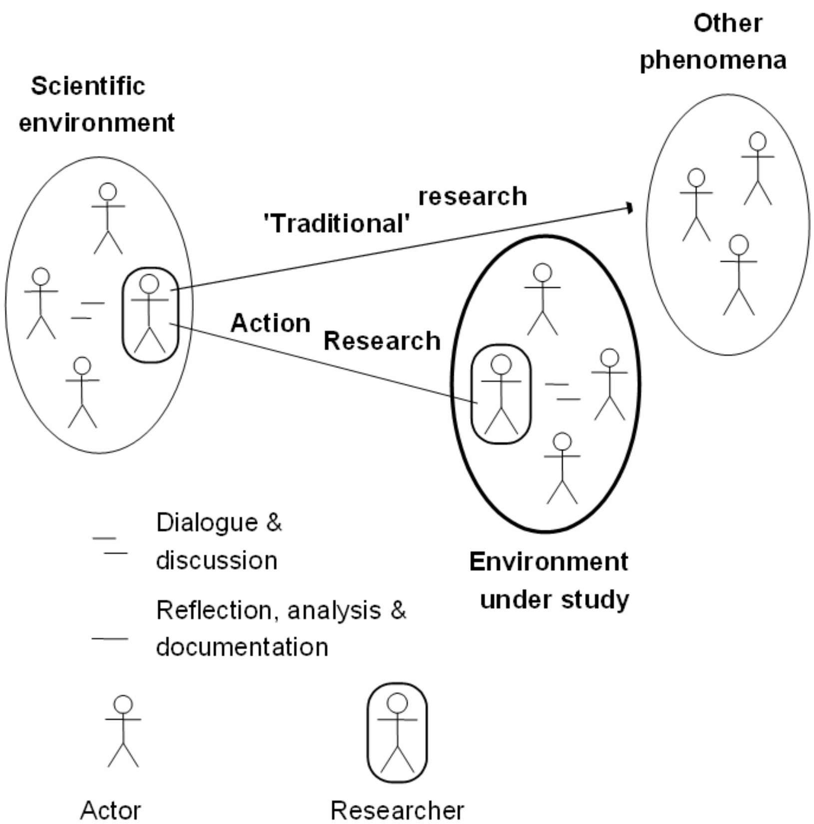

Figure 1 Illustration on relationships involved in an action research approach (Björk 1999).

IAR is traditional Action Research (AR) wherein the researcher is not only an observer but also a team member acting within the observed group. According to Ottosson and Björk (2003), the following advantages can be obtained by performing AR instead of being outside the process of interest (see also Figure 1).

1. A minimum risk of losing valuable information/data due to forgetfulness or incorrect reconstruction. When reconstructing past events, there are risks of misunderstandings. The researcher has no opportunity to consider the circumstances outside or inside the studied process that may have influenced the result.
2. First-hand information eliminates the influence of other people's understanding of the situation and their ways of expressing it.
3. Opportunities exist to rapidly correct interview notes or to clarify misunderstandings between the interviewer and the respondent(s).

The author has been involved in some of the research efforts as a *team member*, see Table 3 below.

2.2. Research methods used

During the research conducted when building this thesis, all of the above-described research methods have been used. Table 3 below shows what kinds of main research methods were used for the different papers, which the thesis is built upon, and Table 4 shows the main research methods used for the different case studies.

Table 3 Research methods used during the research building papers 1-7.

PAPER	QUANTITATIVE	QUALITATIVE	PARTICIPATED	OBSERVED	IAR (*Team Member*)	LITERATURE STUDIES	CASE STUDY METHODOLOGY
1		X	X			X	X
2	X			X		X	
3	X		X		X	X	X
4	X			X		X	
5	X		X		X	X	
6		X	X		X	X	X
7		X	X		X	X	

Table 4 Research methods used during the research building case 1-9.

CASE	QUANTITATIVE	QUALITATIVE	PARTICIPATED	OBSERVED	IAR (*Team Member*)	LITERATURE STUDIES	CASE STUDY METHODOLOGY
1	**X**			**X**	**X**	**X**	**X**
2	**X**			**X**		**X**	**X**
3	**X**			**X**		**X**	**X**
4	**X**			**X**		**X**	**X**
5	**X**			**X**	**X**	**X**	**X**
6		**X**		**X**	**X**		**X**
7		**X**		**X**	**X**		**X**
8		**X**		**X**	**X**		**X**
9		**X**		**X**	**X**		**X**

Figure 2 shows the logical order in which the theoretical and practical studies are situated in order to enable the development of modular discrete event simulation for manufacturing systems.

The present thesis is composed of two types of research. First of all, research building the *base showing the current status of the gap of discrete event simulation practice* (Prerequisites and Confirmations in Figure 2)*, and* secondly, research conducted showing *how to fill the gap and thus make manufacturing systems more profitable* (Management, Result, and Validation in Figure 2).

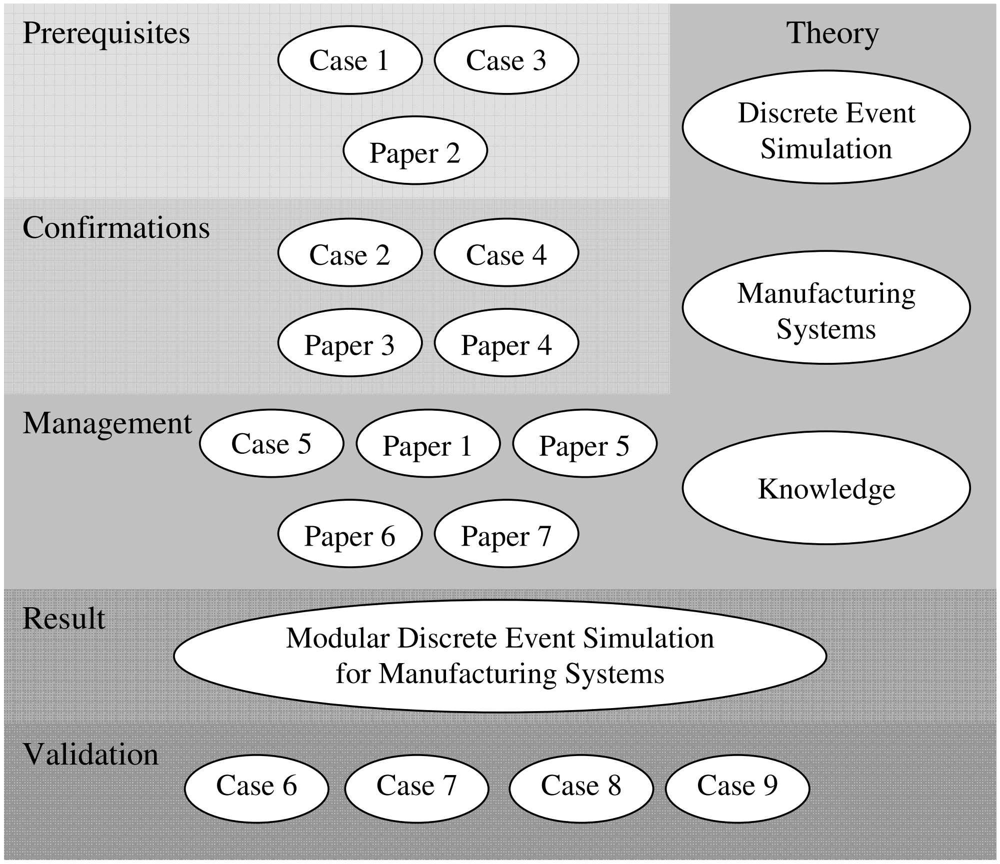

Figure 2 Research procedure conducted to propose modular Discrete Event Simulation for Manufacturing Systems.

2.2.1. Prerequisites and Confirmation of research gap

The main sources used to confirm that discrete event simulation has great potential and is an underused tool are literature studies. Some of its potential and the low use are discussed in this thesis. Numerous examples can be found where researchers around our globe provide evidence on discrete event simulation potentials. Case studies (e.g. Karlsson 2001, Axelsson and Bengtsson 2002, Sandman and Wallström 2003, Andersson 2003, Cato and Rosenström 2003, and Andersson and Åström 2004), and surveys (Ericsson 2005) conducted during the past five years at Chalmers University of Technology also provide a wide basis for the utilization gap. In this thesis a summary of four case studies on the gap are described: case studies 1, 2, 3 and 4. Papers 2, 3 and 4 give contain further discussion of the research gap.

2.2.2. Managing the research gap

The main contribution from this thesis, which aims to address the gap in the utilization of the potentials of discrete event simulation, is the methodology for modular discrete event simulation described in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems. Additional contributions to enable the formulation of this methodology and additional benefits of utilizing discrete event simulation for manufacturing systems are given by case study 5, and papers 1, 5, 6 and 7.

2.2.3. Validation of the modular DES methodology

In order to validate that the presented methodology for modular discrete event simulation actually is applicable is shown by presenting four examples, all case studies which use the methodology as a base; see Appendix case studies 6, 7, 8 and 9. Further validation aspects are presented in chapter 8.5 Validation of research results.

2.2.4. Research procedure summary

The whole research procedure can be described in four steps, where the first two steps aim to confirm the research gap as described in section 2.2.1. Prerequisites and Confirmation of research gap and the last two create and describe a solution to the research gap as described in section 2.2.2 Managing the research gap:

- Firstly *explorative* in order to find the research gap.
- Secondly, *quantitative* in order to verify that the gap actually exists.
- Thirdly, utilizing *IAR* to find and form a possible solution for the gap.
- Finally, utilizing *case study methodology* for validation of the research, described later on in 8.5 Validation of research results.

3. Discrete Event Simulation

Discrete event simulation is a subgroup of the simulation family, which is one of the most powerful tools available to decision-makers responsible for the design and operation of complex process and systems (Joacim Johnsson 2004)

3.1. Introduction to Discrete Event Simulation

Discrete Event Simulation (DES) techniques have been available for many decades, but the demand for the technique was low for a long time, and the technology-support supplied to users of the DES technique was weak. There were two main reasons for the low demand on DES. First of all, computers were not as powerful as today, and secondly, the competition on the market was not strong enough. In contrast, computers are powerful today and their development is still extremely fast. Moreover, the competition between companies is global. This leads to competition that is tougher than ever before.

For many years, the industry has been focusing on shortening time-to-market, including development times for products and processes (Driva et al 2000, Mansurov and Probert 2001, Terwiesch and Bohn 2001). Therefore, the need for a powerful decision-supporting tool is high in today’s global market (Driva et al 2000, Terwiesch and Bohn 2001). At the same time, DES has been regarded as one of the potential rescuers of these higher needs for fast decision-supporting tools (Law and Kelton 2000, Banks et al 2004, Klingstam 2001), even though simulation modeling and analysis has been classified as a time-consuming and expensive activity (Banks et al 2004, Terwiesch and Bohn 2001). Although DES is a very powerful tool, the diffusion in industries of this innovation is slow (Ericsson 2005). This is the case in Sweden, which experts describe as a country where information technology is used extensively in industry. Although simulation is in good standing among industries, only about 50 % of the simulation projects started have been successful (Mansurov and Probert

2001). DES is rated among the top three tools used in management science (Ericsson 2005).

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 life cycles it is nowadays even more important to do the *right* thing the first time, since there will be less time for 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 clarify what discrete event simulation is and how it is used in terms of both industrial sectors and project methodology. A historical perspective on the software development, including pros and cons with discrete event simulation, will also be addressed. The chapter ends with a survey of previous research on modular discrete event simulation.

3.2. Discrete event simulation description

This section will define and describe the characteristics of discrete event simulation, and identify the advantages and disadvantages of using 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*, for example, the way a snake can become brightly colored just to look poisonous, even though 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 *List of Definitions*, 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 modeled as imitations into the model (Banks 2000).

3.2.2. The characteristics of discrete event simulation

Discrete event simulation means that the model is updated only when 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 5*.

Table 5 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 driven through time ("run") by a mechanism that moves the simulated time forward, according to *Figure 3*. The system state is updated at each event along with the capturing and freeing of resources that may occur at that time. *Figure 3* also shows the other related input parameters needed to generate the output from a DES model.

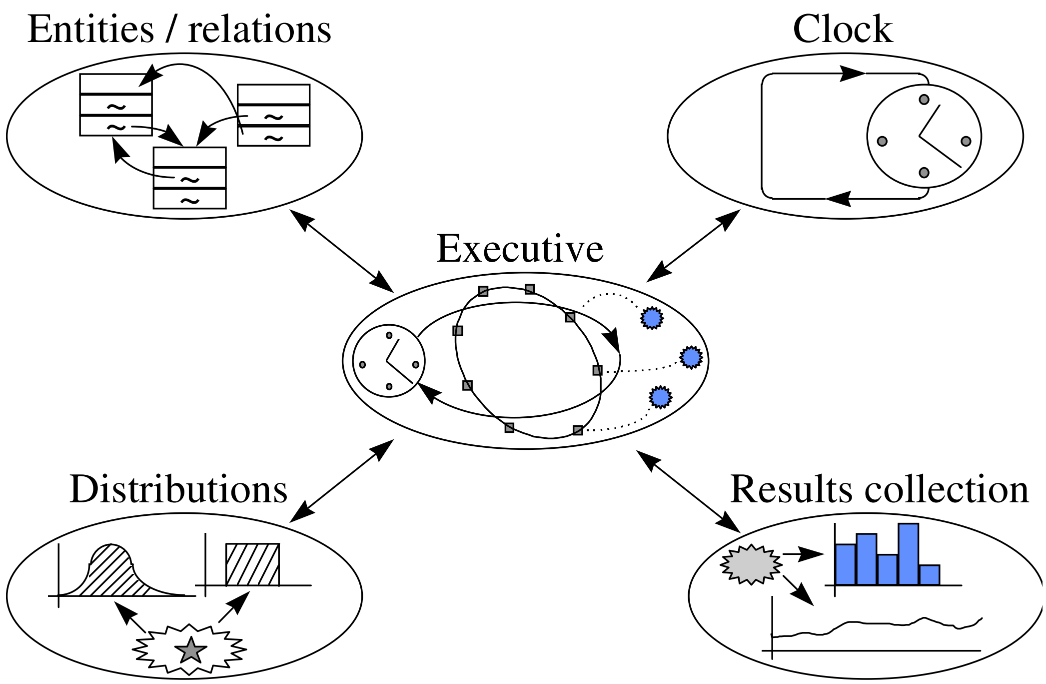

Figure 3 Structure of a discrete event simulation system, adapted from Kreutzer (1986).

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

3.2.3. Advantages of DES

Discrete event simulation has many advantages, mostly because of the ability 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 the advantages of DES are listed in Pegden et al (1995):

- New policies, operating procedures, decision rules, information flows, organizational 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 contribute to the understanding of how the system actually operates, and avoid a situation where individuals merely believe that they know how the system operates.
- "What-if" questions can be answered. This is particularly useful in the design of new systems.

Additional advantages related to the results of the present thesis will be described in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems. However, DES is not a one-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 do not become apparent before it is too late. Some examples from Pegden et al (1995) are shown below:

- Simulation is used in some cases even though an analytical solution is possible and perhaps 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 modeling and analysis can be time-consuming and expensive. Skimping on resources for modeling and analysis may result in a simulation model or analysis that is insufficient 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 exactly 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 analyses.
- 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 solutions are limited to *static* analyses, 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 modeled with discrete event simulation as long as it consists of events with some logical couplings over a specified time. Sections 3.3.1-3.3.7 lists the most frequent applications for DES identified by 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. One of the areas where DES technology is most frequently used is manufacturing (Cornford and Doukidis 1991, Forgionne 1983, and Hover and Wagner 1958). DES used for manufacturing problem solving can be for example:

- Analyses of assembly operations
- Optimization of cycle time and utilization
- Investigations of the dynamics in a supply chain

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

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 is likely to be an effective tool for the investigation of various dynamic 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

3.3.4. Military applications

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

- Modeling leadership effects and recruit types 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

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 modeling in rail-capacity planning
- Analysis of passenger flows in airport terminals

3.3.6. Business Process simulation

The potential of DES in this category is high, but at present it is far from being used optimally. Some banks, restaurants, and other business centers 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 long-running annual Winter Simulation Conference, such as:

- Product development programmed planning
- Reconciliation of business and systems modeling
- Personnel forecasting and strategic workforce planning

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 human behavior in a dynamic model. It has been done in, for example:

- Modeling human performance in complex systems
- Studying the human element in air traffic control
- Computer simulation as a tool for studying human-centered systems

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 less common. However, Davies (1992) discusses the use of simulation in the health sector, and Davies, and Sparkes (1989) discusses it in relation to the retail finance and service sectors. These fields will probably use simulation more frequently in the future when the manufacturing market becomes more saturated and the software vendors look for more and other types of customers (Hollocks 1995).

3.4. Classical Discrete event simulation Project Methodology

Many methodologies have been developed during the last decades to facilitate DES projects. This section will discuss the most commonly used methodologies. Methodologies such as the ones outlined by Law and Kelton (2000), Banks et al (2004), and Pegden et al (1995) have much in common. Several steps in these approaches are similar, e.g. problem definition, data collection, model building, comparison, and analysis. *Figure 4* 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 (2004). The descriptions in the following subsections are related to *Figure 4*.

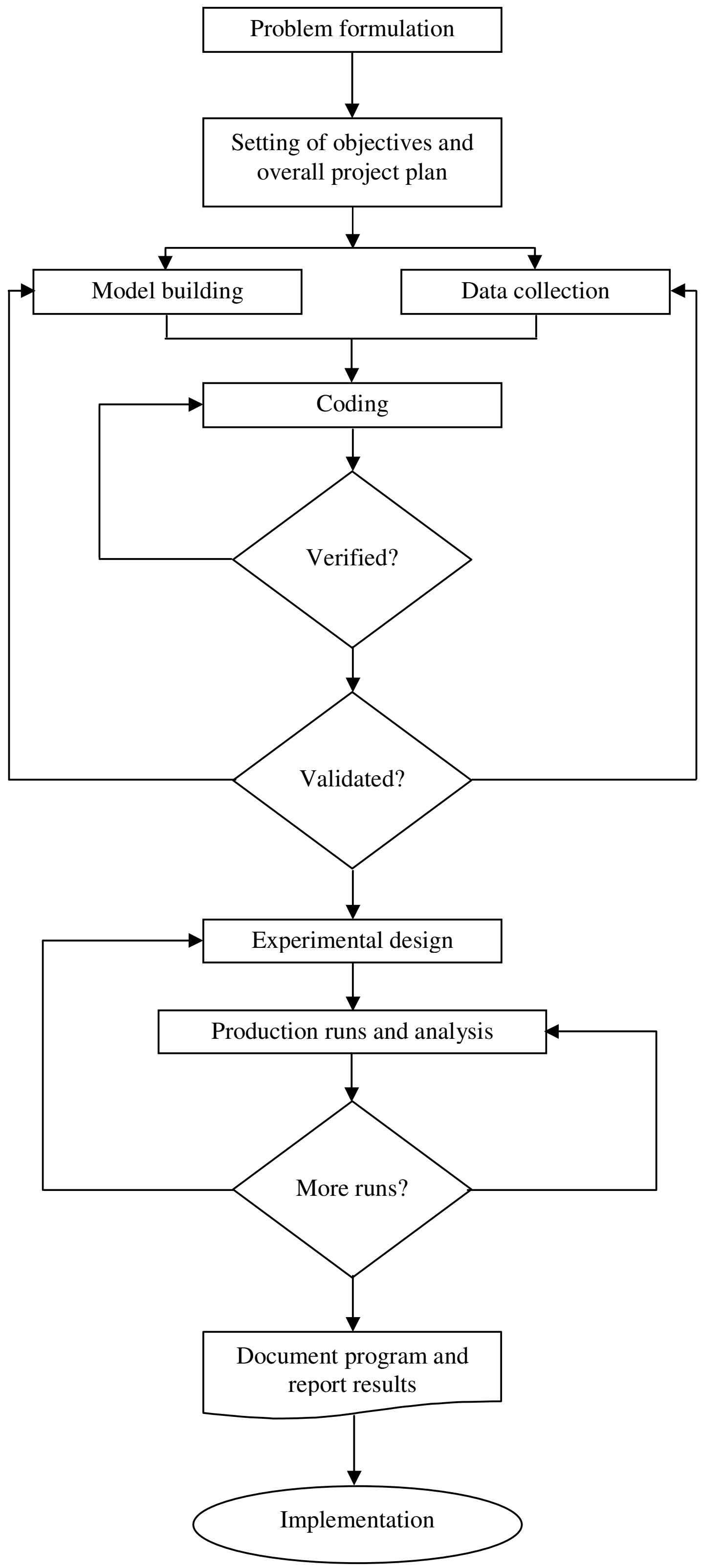

Figure 4 Steps in a simulation study (Banks et al 2004).

3.4.1. Problem formulation

DES projects are conducted mostly by specialists and bought by a customer who has a problem that has to be analyzed (Banks et al 2004). 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 ensure that the problem is clearly understood. In the opposite scenario, when the simulation analyst prepares the problem statements, it is important that the client understands and agrees with the formulation. Banks et al (2004) suggest that a set of assumptions should be prepared by the simulation analyst and agreed upon by the client. Despite these preparations, it is possible that the formulation of the problem will have to be reformulated as the simulation study progresses.

It should also be pointed out that before any other activity is conducted, it has to be made clear that DES is the appropriate tool for the specified problem (Schumacher and Wallin 1998). In Banks et al (2004), based on Banks and Gibson (1997), a number of criteria to ascertain whether a DES project is the appropriate solution or not are discussed. According to the authors, 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 chances for launching a successful DES project are higher. Nevertheless, many other issues influence the result. The next issue to be addressed is the setting of objectives and an 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 analyzed. Resources needed for the simulation study at large should be included, such as personnel who will be involved, hardware and software requirements, stages in the investigation, and the 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 steps described in this chapter (Banks et al 2004).

3.4.3. Data collection

In the best circumstances, the client has collected the data needed in the format required. If this is the case, it saves a lot of time and increases the chance of success for the simulation project. In many projects, the client indicates that the data required is available. However, when the time comes to implement the data it often turns out that the data is different from what was expected. As shown in *Figure 4*, 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. Details such as failures, shift scheduling, and material-handling capabilities should be added later. Towards the end, special features for the most complex parts of the model may be added.

Maintaining the client's involvement in the model building is vital for success. It is also vital for the constructor not to make an unduly complex model, since this increases the cost of the project, without necessarily adding value to the results.

3.4.5. Coding

The conceptual model from subsection 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 that is accurate enough.
Verification of the model includes securing that the model behavior is the desired behavior according to the previously made conceptual model. This includes comparing the functionality of the computer-coded image of the system with the conceptual model. Verification answers the question: *"Is the model built correctly?"*

A definition of verification in a DES context is done by Brade (2004):

"Model verification is the demonstration that a model is correctly represented and was transformed correctly from one representation form into another, according to all transformation and representation rules, requirements, and constraints."

3.4.7. Validation

Validation is the determination of whether the model is a correct translation of reality according to the previously made decisions concerning the level of detail. Validation answers the question: *"Has the correct model – relative to the real-world system under study – been built?"*
According to Law and Kelton (2000), one of the surest ways to validate a model of an existing system is to compare the model output (using historical data as input) with the real output from the same time span. This method is called "The correlated inspection approach" (see *Figure 5*). This method can be used with another twist 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).

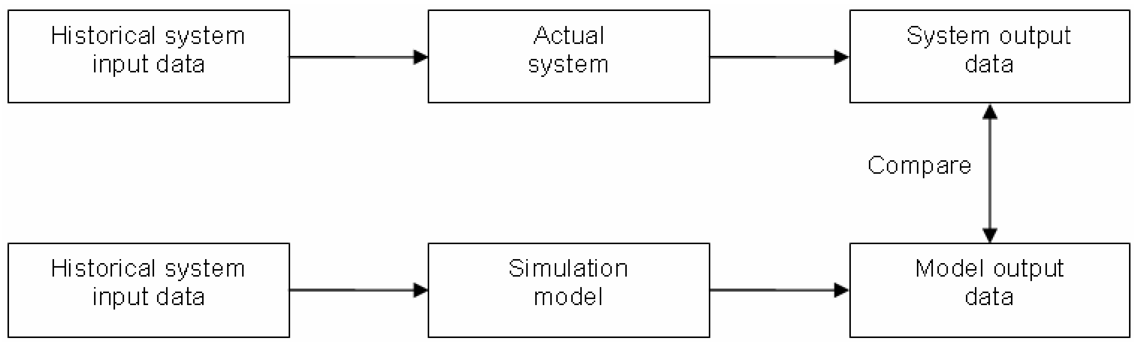

Figure 5 The correlated inspection approach (Law and Kelton 2000).

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 fulfill 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 6*.

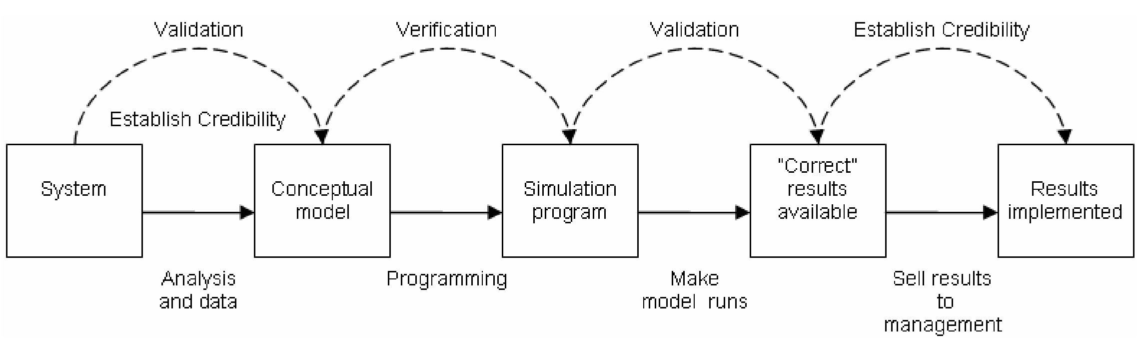

Figure 6 Timing and relationship of validation, verification, and establishing credibility (Law and Kelton 2000).

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 modeler agree on the model quality.

3.4.8. Experimental design

To obtain a steady basis for analyzing 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 number of replications 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 design a factorial experiment, if one is interested in more than one parameter (Law and Kelton 2000). A reduced factorial design such as the one used in Karlsson (2001) will reduce the simulation runs needed to half in comparison with a full experiment, and it will also show what factor/factors have the highest influence on the outcome of the system (see *Figure 7* in section 3.4.9). Strong factorial designs can also evaluate interactions, especially two-way ones. Table 6 shows a factorial experiment with four factors influencing the output of the system.

Table 6 Experimental factors and their max and min values to be tested (Karlsson 2001).

Factor	Factor description	Low level	High level
A	Time between resetting	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

At this stage of a simulation project the computer model is used to simulate scenarios. One example, using factorial design of experiments, is shown in *Figure 7*. The simulated scenarios are then evaluated and analyzed to estimate measures of performance for each of the different solutions.

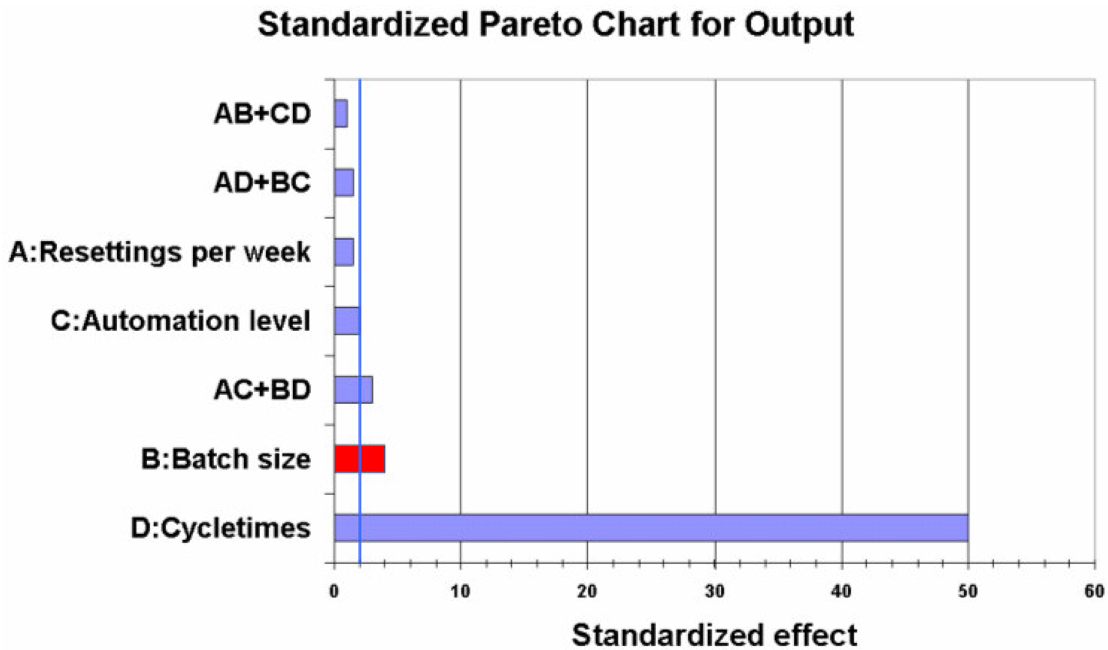

Figure 7 Standardized Pareto Chart for Output of gears from Table 6, 99% confidence interval (Karlsson 2001).

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 and Kelton 2000, Banks et al 2004).

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 for why documentation is so important is that it is necessary 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 reasons for doing the DES project.

3.4.12. Implementation

The implementation of the results depends on all the above steps. If the simulation project was a success, the task that remains is to implement these findings within the real system. It may, however, be necessary to conduct further investigations on the findings in order to strengthen the system before it is implemented. A successful simulation project is not only one with good results concerning the organization. It can be of even greater importance to decide to withdraw from building a plant that from a simulation perspective presents a *good* result, but which from an economic perspective turns out to be a bad investment.

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 increases.

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 tools. The methodology outlined in the manual is shown in Figure 8. The methodology used in the WITNESS™ manual is of the same kind as the one described in section 3.4 Classical Discrete event simulation Project Methodology (see *Figure 4*). 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 (2000), Banks et al (2004), and Pegden et al (1995). This is the case with WITNESS™ DES project methodology. Figure 8 shows the flowchart over WITNESS™ DES project methodology, in which some steps of DES contain the same actions as Banks et al's (1996) project methodology.

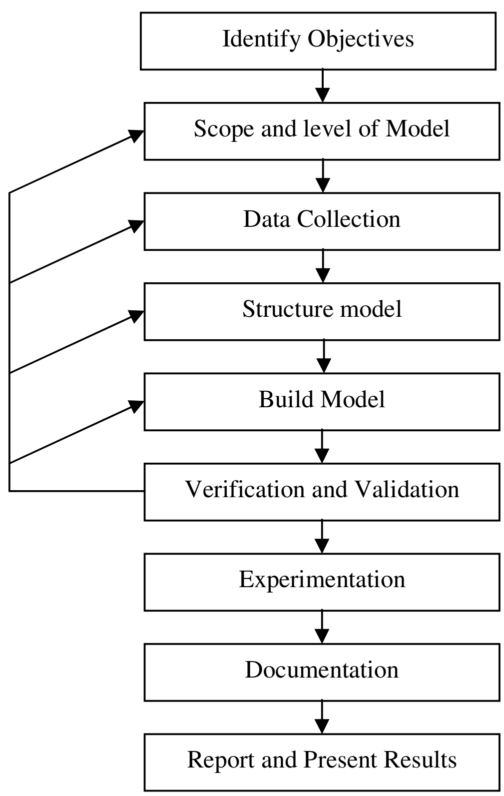

Figure 8 Steps in a simulation study (WITNESS™ user manual 1994).

3.4.14. Law and Kelton (2000) DES project methodology

The DES methodologies described in Law and Kelton (2000), shown in Figure 9 below, use another structure in terms of verification and validation than the other methodologies mentioned. The importance of pilot runs in DES methodology is emphasized in Law and Kelton (2000). 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 (2000) are the same as those presented in Banks et al (2004), and in the WITNESS™ user manual (1994).

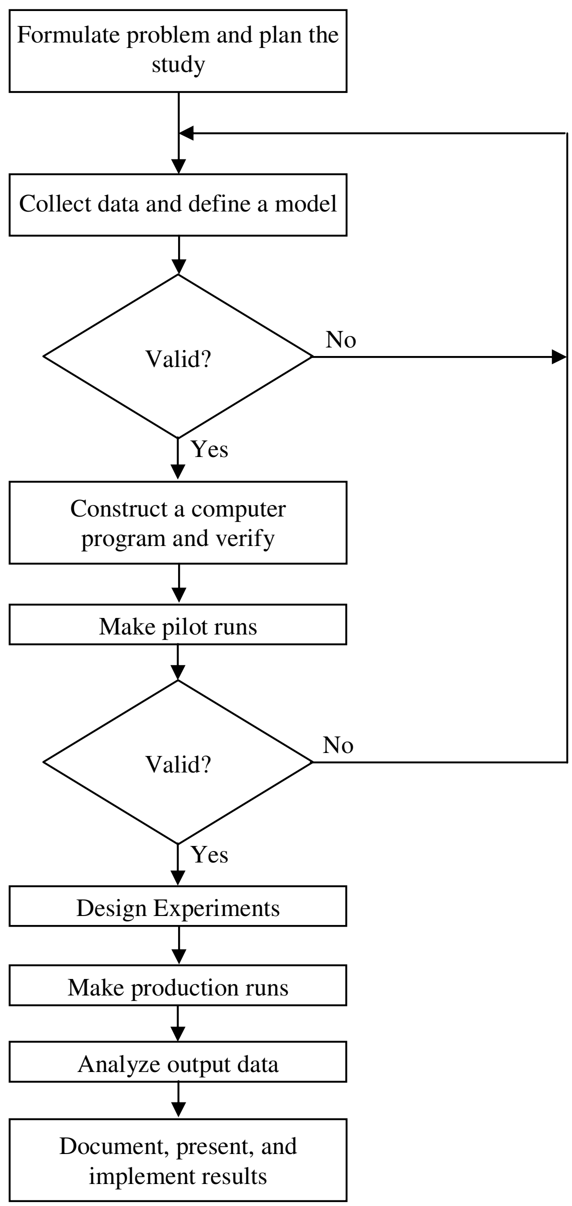

Figure 9 Steps in a simulation study (Law and Kelton 2000).

3.5. Discrete event simulation software

The software used to conduct DES projects is of vital importance for the outcome of the project. There is much tailor-made software suited for different kinds of DES projects on the market today (Klingstam and Gullander 1999, Nikoukaran et al 1999, Johansson et al 2002 paper 2, Rivera and Diamond 1997, Banks et al 2004, Rohrer 1999). It is also possible to use a common general purpose programming language to conduct a DES project, even though this is not recommended.

3.5.1. The History of Simulation Software

Along with increasingly powerful computers, simulation software has developed apace. In the early age of the modern computer, 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 ones to identify and develop routines that could be reused in subsequent simulation projects were 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 around 1961. GASP and GPSS used flow-chart symbols familiar to engineers, which made them more user-friendly than FORTRAN, which was frequently used in the preceding period.

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

1971-1978 The Expansion Period
Efforts during this period mainly concerned attempts to simplify the modeling process. Another significant step was the gradual development of GPSS and GASP. GPSS/H was released with compilation speeds that were 5 to 30 times faster than those of the standard version. GASP incorporated state events in addition to time events, interactive debuggers were implemented, and efforts towards automatic programming were tested, but turned out to be somewhat overoptimistic.

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

In the book *Discrete Event System Simulation* by Banks et al (2004) 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 visualization tools. Some packages use the "fill in the blank" procedure 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 the appended Paper No. 2 (Johansson et al 2002). The years from 1996 and further on will be discussed later on in chapters 7 Discrete Event Simulation for Modular Manufacturing Systems and 8 Discussion.

3.5.2. Selecting simulation software

When selecting appropriate simulation software there are some important issues to keep in mind. Banks et al (2004) give the following advice:

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 for its impact on 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 varies considerably.
5. The possibility to link 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 program supports graphical model building, instead of only a simulation language. This feature will shorten the learning curve. However, beware of the phrase "no programming needed" which will lock the software into 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; 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), in Paper No. 2 (Johansson et al 2002), and in paper No. 5 (Johansson et al. 2004).

3.6. Previous work on modular discrete event simulation

Previous research in the field of modular discrete event simulation is limited. The next section will show examples from previous research and explain their approach, after introducing the definition of modularity used in this thesis. Later on in chapter 8.2 Comparison with other discrete event simulation methodologies, these approaches will be compared to the research in this thesis; similarities and dissimilarities will be discussed.

3.6.1. Definition of modularity

Before addressing the previous research on modular discrete event simulation a definition of the word "modular" in this context is needed
Modularity is hard to define as 1 or 0, i.e. modular or not modular. The modularity in discrete event simulation software can actually be seen as early as in the formative period (1966-1970) (see chapter 3.5.1 The History of Simulation Software). It can be argued that modularity in its simplest form is carried out as soon as something is reused. This is done in the simulation languages or programming software, such as C++, Pascal or Python. In the present thesis, however, the modularity of discrete event simulation is discussed in terms of modularity support by the architecture in the discrete event simulation software. Regarding the definition of what level of modularity this thesis is considering, Bauer et al (1991) presents two definitions, one of which will be used. The definitions are definitions of the hierarchical control model for automated systems; one is defined by NIST, and the other by ISO. The hierarchical control model for automated systems developed by NIST consists of five levels, which are Facility, Shop, Cell Workstation and Equipment; see Table 7.

Table 7 The NIST hierarchical control model for automated systems (Bauer et al 1991).

Level	Description
Facility	Manufacturing engineering and management of information and production
Shop	Real-time management of jobs and resources
Cell	Management of batch sequencing and material-handling facilities
Workstation	Coordination of a set of equipment on the shop floor
Equipment	Control of individual equipment, e.g. a robot or a machine tool

The ISO definition consists of one additional level, i.e. six levels in total and the levels are: enterprise, facility/plant, section/area, cell, station, and equipment; see Table 8.

Table 8 The factory automation model developed by ISO (Bauer et al 1991).

Level	**Description**
Enterprise	Achievement of the enterprise mission
Facility/Plant	Implementation of the enterprise functions
Section/Area	Provision and allocation of resources and the coordination of the shop floor activities
Cell	Sequencing of jobs through stations
Station	Control and coordination of small workstations
Equipment	Realizes the physical task execution

The definition by ISO is used in this thesis. Additionally this factory automation model is used to define the modularity addressed when dealing with modular discrete event simulation. The main addressed modularity issue in this thesis aims at using the *station level* in Table 8, where each workstation can be modeled as a module. The station can be a single machine, a robot, a conveyor, a buffer etc.

The internal definition of what is inside such a module can be referred to as a simulation building block as defined by Valentin and Verbraeck (2002); see the next section, section 3.6.2 Simulation building blocks.

This *level of modularity*, the *definition* in itself, and its *internal structure* is used due to OEM companies' actual definition of their real world modules, which is defined in a similar manner. Figure 10 shows the internal structure characteristics of a discrete event simulation module as defined in this thesis with attribute examples. The module structure from Figure 10 is specified with attribute examples of logics, data, interfaces, and graphics. A three module is shown in Figure 11, Table 9 and Table 10.

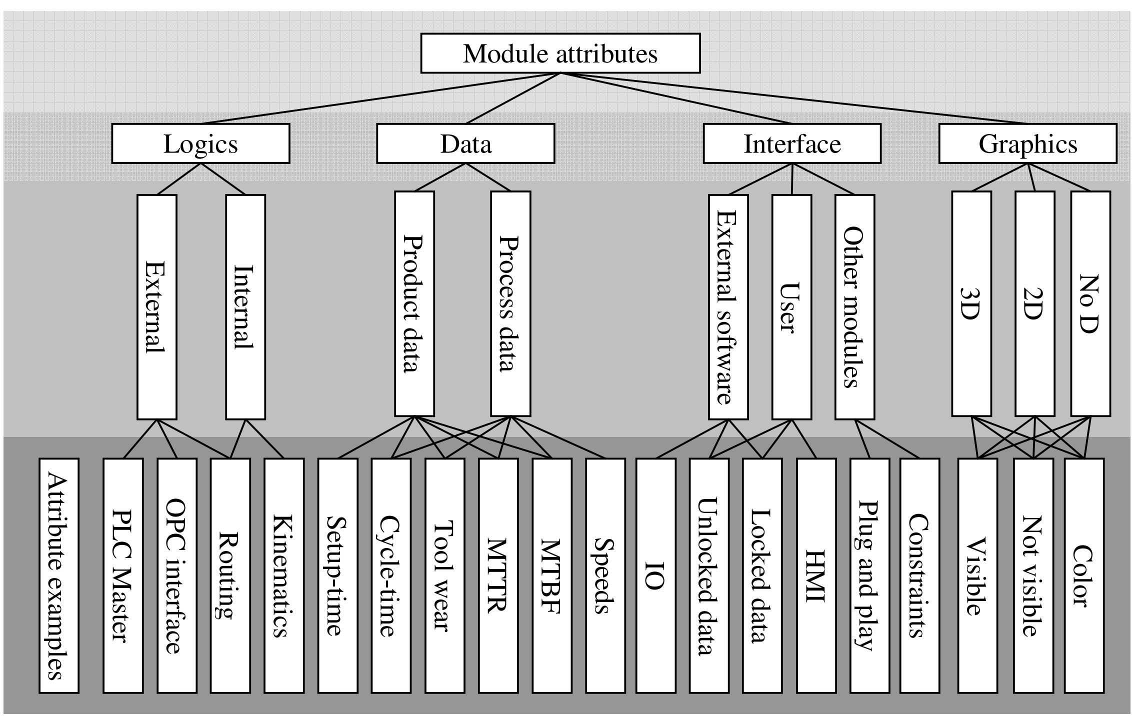

Figure 10 DES Module and its internal structure as defined in this thesis.

Logic in Figure 10 includes the functionality and rules internally within a module, as well as the communication with upper-level software and other software outside of the module boundaries through the interfaces specified in "Interface" in Figure 10. The interfaces are either to other modules, to external software, to the model builder or a combination. The graphical representation of a module is made either in 2D, 3D or no D. The data representation in a module can be either internally specified in the process itself, or as a combination of product specific data. For example a setup time may vary depending on which type of product the process is preparing for, i.e. product specific data.

Some modules are combined to form a small example of a manufacturing system in Figure 11. The figure shows one identical conveyor on each end of a manual workstation. The conveyor module specifications are shown in Table 9 and the manual workstation in Table 10.

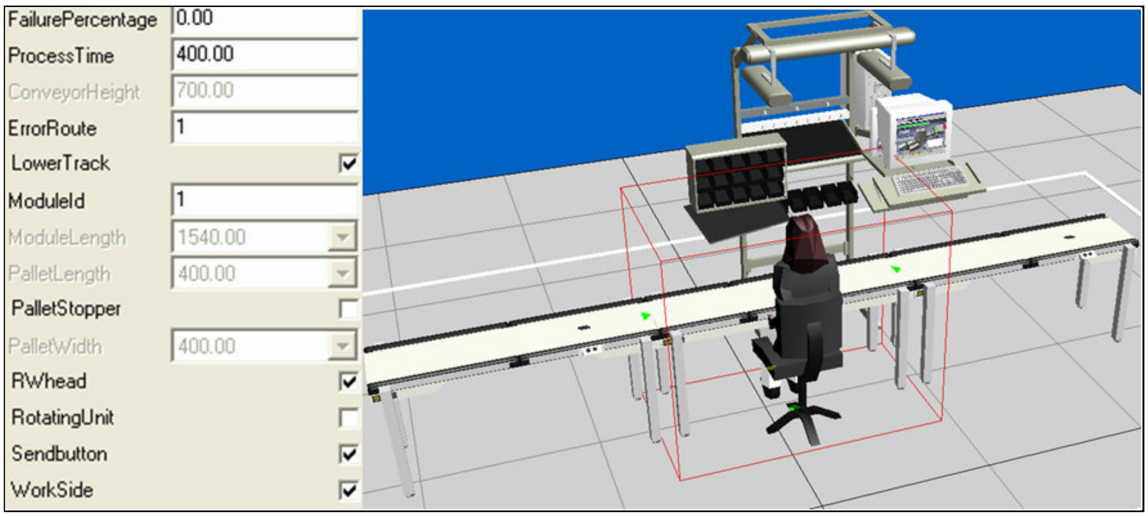

Figure 11 An example of a modularized manufacturing system with two conveyor modules and a manual workstation.

Table 9 A conveyor DES module characteristics.

Module	Conveyor
Logics	Product movement
Data	Length, width, height, acceleration, speed, MTTR, MTBF
Interface	Conveyor, manual workstation
Graphics	BOM : Motors, chains, legs, aluminum profiles, cables

Table 10 A manual workstation DES module characteristics.

Module	Manual workstation
Logics	Assembly, quality control, process, product movement,
Data	Module Length, Pallet Length, Pallet width, Conveyor height, speed, Failure percentage, Process time etc…
Interface	Conveyor, manual workstation, human
Graphics	BOM : Motors, chains, legs, aluminum profiles, cables

3.6.2. Simulation building blocks

Almost all simulation software uses simulation building blocks. These blocks can be classified as modules, depending on the definition employed. Valentin and Verbraeck (2002) consider simulation building blocks as:

- Self Contained (Nearly independent)
- Interoperable (Independent of underlying technology)
- Reusable and replaceable
- Encapsulating in their internal structure
- Providing useful services or functionality to their environment through precisely defined interfaces
- Customizable in order to match any specific requirements of the environment in which they are used (plugged)

Valentin and Verbraeck (2002) also state that simulation building blocks can be used with good results to shorten the lead-time when conducting discrete event simulation projects. However, there are only a limited number of project examples using simulation building blocks, which show improved results attributable to the use of building blocks.

While carrying out the investigations that are the basis for the present thesis, interesting findings were made. For instance, simulation experts in large companies have begun to create libraries with simulation building blocks. Large automotive and large telecom companies in Scandinavia are examples of companies where more or less structured libraries of simulation building blocks exist. These simulation building blocks are then used by the simulation experts themselves in order to shorten the lead-time for their model building, also increasing the accuracy of the models through already verified and validated building blocks, which improves the simulation expert's work.

3.6.3. Object-oriented simulation

Ball and Love (1992) discusses an approach where discrete event simulation practice is divided into two separate tasks. The first task is for the developer and focuses on the development of new functionality for the simulation tool. The second task is for the manufacturing engineer and focuses on using the created functionality to build simulation models. Ball and Love (1992) aims at separating the user and the developer. Using object oriented techniques for developing simulation software results in the creation of library classes. These library classes can be found on most simulation software packages, such as Automod, Extend, Quest, and others. The use of libraries allows greater flexibility for modeling according to Ball and Love (1992).

Bhuskute et al (1992) presents such a library in an article from the winter simulation conference. The article describes a highly reusable modeling and simulation framework for discrete parts manufacturing. The framework uses classes to structure the simulation model into modular and reusable parts. The modeling environment structure is shown in Figure 12.

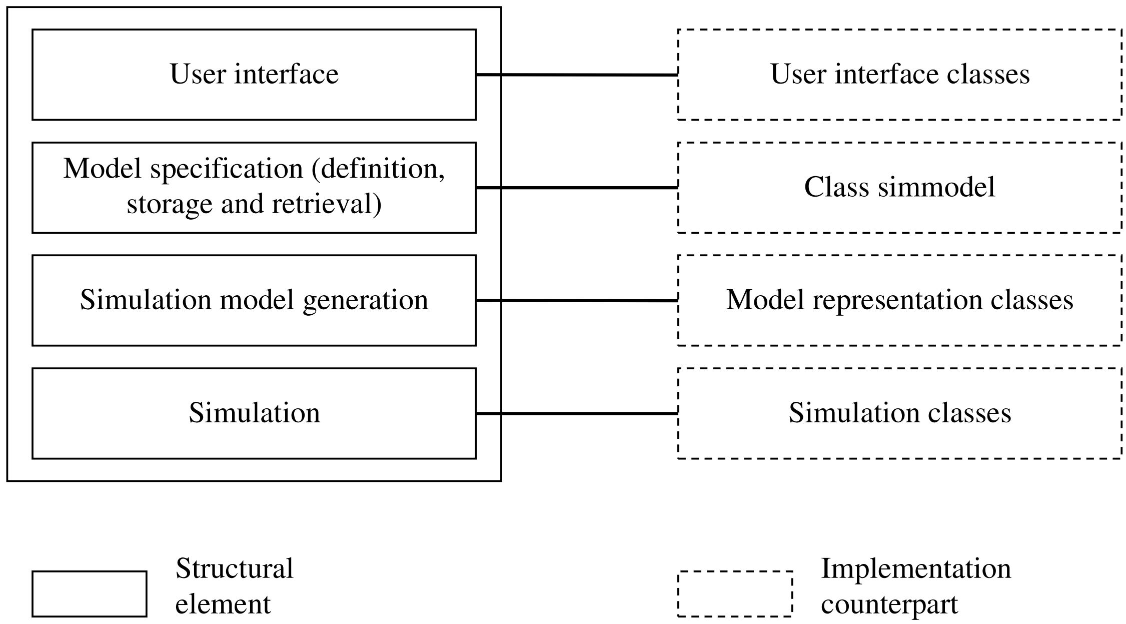

Figure 12 Modeling Environment Structure (Bhuskute et al 1992).

Cochran and Chen (2005) present an evaluation of object oriented-simulation software where SIMAN C++, and Simple ++ are evaluated. Their approach aims at comparing the trade-offs between ease of use, flexibility, reusability, and other desired characteristics. The conclusion from Cochran and Chen (2005) is a model used to evaluate comparatively the three general categories (Mackulak et al 1994) of simulation software: general programming languages, simulation languages, and simulators. The evaluation result is presented in Figure 13.

3.6.4. Modular simulation of manufacturing systems

Since automated material handling systems (AMHS) is one of the system types which are most suitable for modular simulation, the obvious conclusion to make is that there is a lot of modular simulation of AMHS, but in reality it is not as frequent as one may think. Meinert et al (1999) argue, "simulation is one of the best tools available for examining complex system behavior in dynamic environments". Moreover, Meinert et al (1999) argue that there is a need for a generic, modular simulation solution system. They also refer to a case study where the simulation software Automod (Rohrer 1999) was used as a base for constricting functional modularity for designing at a system level. The modules represented were material handling systems, processes and control logic. However the modularity addressed in Meinert et al's paper is on an expert level. The use of Automod as the engine for building discrete event simulation models is modularized in nature, but expert knowledge is still needed because of the coding, the multi-menu user interface and the art of engineering required when building the system.

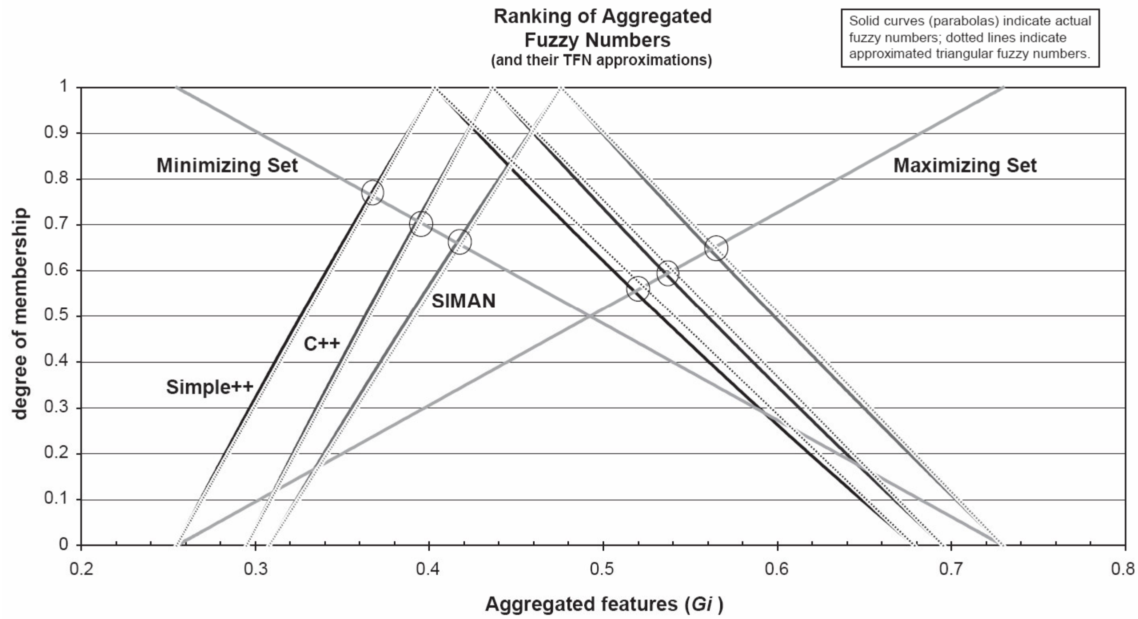

Figure 13 Ranking of aggregated fuzzy numbers from the evaluation of simulation software (Cochran and Chen 2005).

Few publications can be found with focus on the modularity and reusability of DES modules. One researcher who deals with this is Heilala (Heilala and Voho 2001). He discusses the reuse and modularity of discrete event simulation modules (Heilala 2005), and Heilala and Montonen (1998) show an example of a modular library in QUEST (see Figure 14). However, since QUEST is a simulation package, which is classed as an "expert" tool by many, it is not likely to become a "public" library of modules, which are available for anyone to use without expert knowledge on DES.

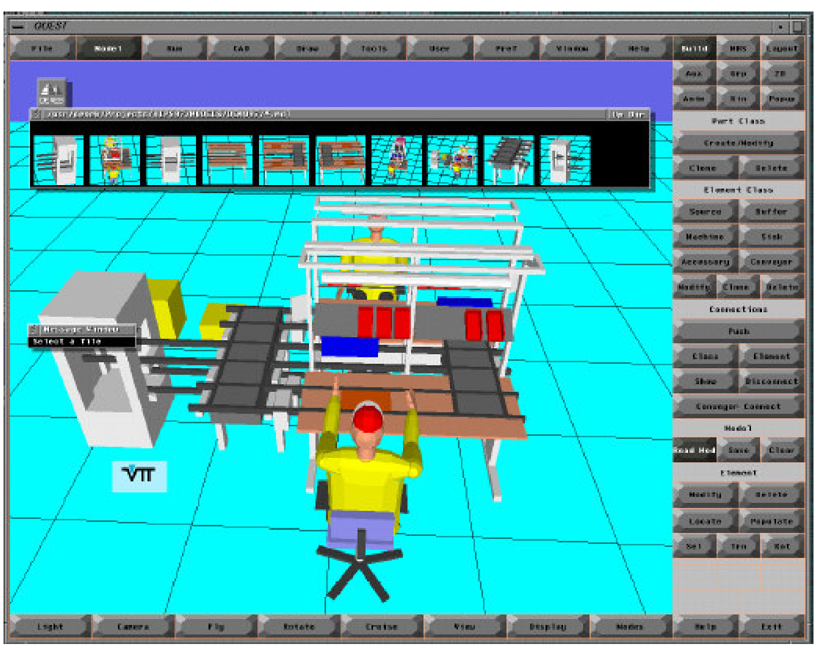

Figure 14 Example of discrete event simulation library (Heilala and Montonen 1998).

4. Manufacturing Systems

A system is all the time exposed to various of circumstances, which in turn can result in that constrains are frequently created and eliminated (Stefan Tangen 2004)

4.1. Introduction to Manufacturing Systems

This thesis follows the American definition of manufacturing and production, which means that manufacturing is defined as:

> *"The process of making wares by hand, by machinery or by other agency, often with the provision of labor and the use of machinery" (Zoning Ordinance 2005).*

Production will thereby be defined as a part of the manufacturing process.

Manufacturing systems have evolved since the middle of 19th century and are still evolving. The paradigms of manufacturing systems have shifted with major technological innovations, which have contributed to the progress of the evolution of technology. The literature on manufacturing suggests different views of classifying the periods of development in manufacturing (Garro and Martin 1993, Jaikumar 1993, Buzacott 1995, Mehrabi et al 2000, Manufuture 2003). These authors' classifications contain between three and six major epochs of manufacturing development. In this thesis the definition used in Manufuture (2003) will be used. According to Manufuture (2003), there have been three major paradigm transfers since the Craft production started with customized production in the middle of the 19th century. Table 11 below summarizes the paradigms up until year 2000, and gives a forecast on the next paradigm, which is believed to be Sustainable production.

Table 11 Manufacturing Paradigms (Manufuture 2003).

Paradigm	**Craft production**	**Mass Production**	**Flexible Production**	**Mass Customization**	**Sustainable Production**
Paradigm started	~1850	1913	~1980	2000	2020?
Process Enabler	Machine tools	Moving assembly line	FMS Robots	RMS	Increasing manufacturing
Technology Enabler	Electricity	Inter-changeable parts	Computers	Information Technology	Nano / Bio material Technology
Market	Very Small Volume per product	Demand > Supply Steady demand	Supply > Demand Smaller Volume per product	Globalization Fluctuating demand	Environment
Society Needs	Customized products	Low cost products	Variety of products	Customized products	Clean Products
Business model	Pull Sell-design-make-assemble	Push Design-make-assemble-sell	Push-Pull Design-make-sell-assemble	Pull Design-sell-make-assemble	Pull Design for environment-sell-make-assemble

This chapter will focus on the process enabler of the dominant paradigm of today: Reconfigurable Manufacturing Systems (RMS). As seen in Figure 15, the manufacturing paradigm of mass customization includes the previous paradigms on the economic goal perspective (Mehrabi et al 2000).

Chryssolouris (1992) suggests that flexibility is to be determined by the system's sensitivity to change. Lower sensitivity to change equals higher flexibility. Furthermore, if changes result in large penalties, the system will be very inflexible. On the other hand, if change can be implemented without penalty, the system has maximum flexibility. Chryssolouris (1992) also states that manufacturing flexibility is a concept which is complex, multidimensional, difficult to synthesize, and difficult to define quantitatively.

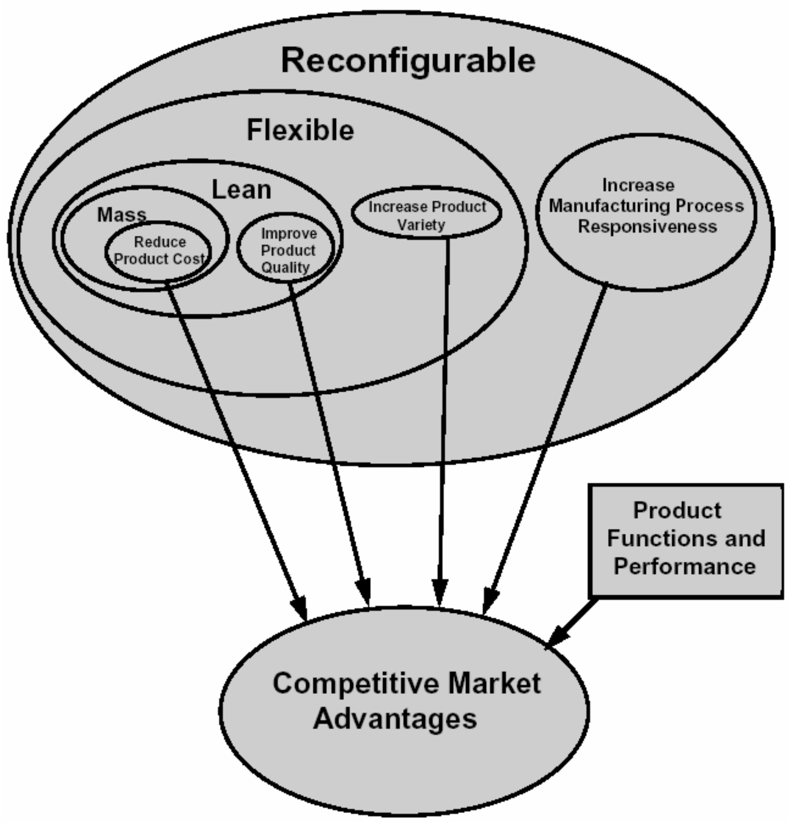

Figure 15 Economic Goals for various manufacturing paradigms (Mehrabi et al 2000).

The great number of taxonomies for flexibility shows that it is a well-known concept with many perspectives and facets. Some of the definitions are shown in this list (Gullander 1999):

- Machine flexibility and material handling flexibility: the ease of making changes in the device required to produce a given set of part types.
- Process flexibility: the ability to produce a given set of part types, possibly using different materials, in different ways.
- Routing flexibility: the ability to use different routings in order to increase manufacturing efficiency or to handle breakdowns, while continuing to produce a given set of part types.
- Operation flexibility: the ability to interchange ordering of several operations for each parts type, possibly using different machines, materials, and operations.
- Product mix flexibility: the ability to manufacture a variety of parts in a mixed manner, each product having different requirements regarding routes and operations.
- Production flexibility: the universe of part types that the manufacturing system can produce.

- Volume flexibility: the ability to operate profitably at different production volumes.
- Expansion flexibility: the ability to expand the system easily and in a modular fashion.
- Inherent flexibility: the ability of the manufacturing system as a whole to be able to add or exchange system components easily, mainly in order to incorporate the use of new technology without losing already invested time, money, and system components.

Above are examples where flexibility is used within a context. The overall definition of flexibility itself in this thesis is the one put forward by Gupta and Goyal (1989) (see also Appendix, List of Definitions, Definition 12. *Flexibility*):

> *"Flexibility is the adaptive response to unpredictable situations." (Gupta and Goyal 1989)*

4.2. Flexible Manufacturing Systems

Flexible Manufacturing Systems (FMS) is defined as a machining system configuration with fixed hardware and fixed software. The software is programmable, which enables flexibility to handle changes in work orders, production schedules, part-programs, and tooling for many part types (Mehrabi et al 2000). As seen in Figure 15, the economic goal of an FMS is to enable cost-effective manufacturing of several types of parts, which can change over time. Shortened changeover time on the same system at the required volume and quality is also an important economic objective (Kaiser 2002).

4.3. Agile Manufacturing Systems

Agile manufacturing systems are characterized by the integration of three primary resources into a coordinated interdependent system. According to Kidd (1994) these three primary resources are:

- An innovative management structure and organization
- A skill base of knowledgeable and empowered people
- Intelligence and flexibility.

According to Goranson (1998, cited in Almström 2005), agile manufacturing systems are more reactive to and concerned with the business opportunity level and appropriate reactions in uncertain environments, hence taking more heed of organizational and management issues than FMS systems do. Agile manufacturing can also be explained as flexible in a non-production manner, for example through virtual enterprises, temporary constellations of companies coming together carrying out projects (Johnsson and Johansson 2004). For example, having a large network of partners ready to handle the outsourcing of production is agility following the above definition.

4.4. Holonic Manufacturing Systems

Koelster (1967) defines the word *Holon* as a combination of *holos*. This is a Greek word for whole combined with the suffix *-on*. As in proton or neutron, this means a particle or part. The holon describes the hybrid nature of sub-wholes/parts in real-life systems, which means that holons are simultaneously self-contained wholes to their subordinated parts and dependent parts of a larger whole that contains it (Tarumarajah et al 1998). According to Tarumarajah et al (1998) two main characteristics are prominent for holonic systems. The holons need to be autonomous, and they have to be cooperative. The definition of *Autonomy* (Appendix, List of Definitions, Definition 15. *Autonomy)* says that:

> "Autonomy is defined as the capability of an entity to create and control the execution of its own plans and or strategies" (Seidel and Mey 1994)

Being autonomous provides the holon with its wholeness and self-regulation, while the cooperation demonstrates its integrability. The Integrated Manufacturing Systems program (IMS) has a consortium for Holonic Manufacturing Systems (HMS), which is based on most of the work that Koelster (1967) did. However, according to Tarumarajah et al (1998), HMS has not yet been proved in manufacturing settings, although there is extensive research in the field. Valckenaers et al (2002) are actively developing a system using holons that is inspired by ant colonies.

4.5. Reconfigurable Manufacturing Systems

Koren and Ulsoy (1997) define a Reconfigurable Manufacturing Systems (RMS) as:

> "A reconfigurable manufacturing system is designed for rapid adjustment of production capacity and functionality, in response to new circumstances, by rearrangement or change of its components."

The components in this definition can be machines, conveyors, mechanisms for an individual machine, sensors, or new algorithms for the control. According to Koren et al (1997), the circumstances for using RMS can be NPI, TPI, integrating new process technology to an existing system, and changing product demand.

Mehrabi et al (2000) identify five key characteristics of a RMS. The five characteristics can partly be found in the previous paradigms, such as *Convertibility* of a FMS system during the *Flexible Production Paradigm*, and *Customization* during the *Craft Production Paradigm*, but the Mass customization paradigm with RMS as the process enabler sets higher demands on the manufacturing system; see Table 12. The five characteristics from Table 12 are similar to Flexible Manufacturing System (FMS) principles on many issues. However the main difference is that RMS is as flexible as needed, not as possible.

Table 12 Key characteristics of a reconfigurable manufacturing system (Mehrabi et al 2000).

Key Characteristics	Definition of the characteristics
Modularity	Design all system components, both software and hardware, to be *modular.*
Integrability	Design systems and components for both *ready integration* and future introduction of new technology.
Convertibility	Allow *quick changeover* between existing products and quick system adaptability for future products.
Diagnosability	*Identify quickly the sources of quality and reliability problems* that occur in large systems.
Customization	Design the system capability and flexibility (hardware controls) to *match the application* (product family).

The main difference towards the dedicated transfer line is that the RMS has a high production rate; at the same time as it can handle changes without large reinvestments. Figure 16 shows the RMS system compared to dedicated lines and FMS.

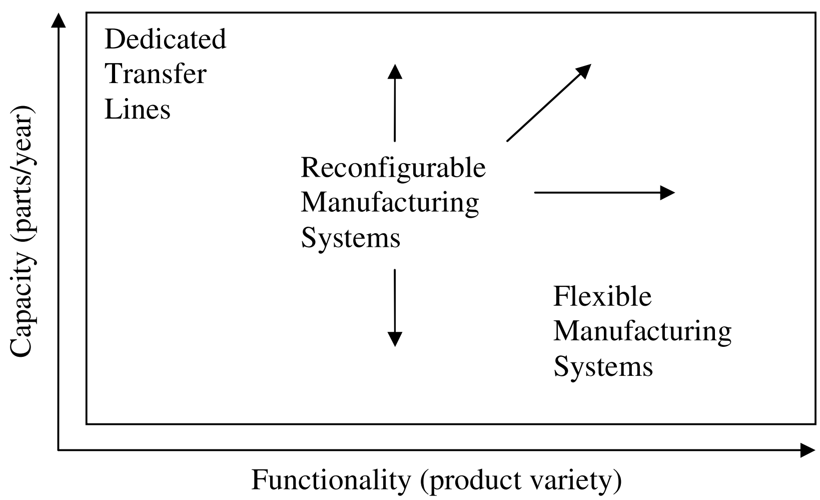

Figure 16 Mapped types of manufacturing systems in capacity-function coordinate (Mehrabi et al 2000).

4.5.1. Modularity

RMS needs the modularity to meet the requirements for changeability (Tönshoff et al 1994). In order to utilize the modularity on machine level, the system structure has to be modular as well (Erixon 1996). The primary goal in developing RMS according to Koren et al (1999) is to develop machine modules, which can quickly be exchanged between different manufacturing systems. This exchangeability can be achieved by defining interfaces between modules in a standardized way, both for the control systems and the machines. In order to guarantee easy reconfiguration of the system, not only the physical system, but also the control and management software has to be considered. Koren et al (1999) state that *supervision of the control systems* is one of the main reasons for early FMS system failures. However, in RMS the supervisory program must be adaptable to different system configurations, which enables a reconfiguration that is generally easier than the FMS one.

4.5.2. Integrability

The internal integrability inside an RMS is vital since machine and control modules need to be designed with interfaces for component integration in order to be reconfigurable. Koren el at (1999) explain that the integrated system's performance is predicted and based on a given performance of its components and the interfaces of both software and machine hardware modules.

4.5.3. Convertibility

In a RMS the optimal operating mode is production in batches, with short converting times to keep WIP low and a steady output from the system, in line with the system modeled in paper 3 (Johansson and Kaiser 2002). Conversion requires changing tools, part-programs and fixtures. Additional conversion might be needed where manual adjustments of passive degrees-of-freedom are required (Koren et al 1999).

4.5.4. Diagnosability

Diagnosability improves the response-time when failures occur. Detecting unacceptable processes or part quality is critical in reducing ramp-up time in RMS. As manufacturing systems are made more reconfigurable and are modified more frequently, it becomes a necessity to tune in the newly reconfigured system rapidly, enabling production of high quality and rate (Koren et al 1999).

4.5.5. Customization

The characteristics of customization are twofold: customized flexibility and customized control. By customized flexibility Koren et al (1999) mean that machines are built around parts of the family that is being manufactured and that they provide only the flexibility necessary for those specific parts, thereby reducing cost. Control customization is achieved through integration of control modules with the aid of open-architecture technology, and in that it way provides the control functions required.

4.6. Material Handling Systems

Material handling systems are characterized by the handling of products. For example, it may concern:

- Moving products between machines (Bearings between polishing machines)
- Sorting products (Letters in a letter sorting terminal)
- Buffering products (Bottles in a filling factory)

While conducting this handling of products, there are many interesting aspects of productivity, efficiency and manufacturing logistics, which can have major influence on the number of parts produced per time unit from a factory. Hence, it will most definitely also influence the profitability and lead-time of the manufacturing system.

4.6.1. History of material handling systems

Henry Ford used a simple variant of a material handling system while producing cars in the early 20th century. A more advanced material handling system was developed in the late 1960's by Molins Company Ltd. They presented "Molins System 24", which is a flexible integrated system developed by Mr. Williamson. This system uses products fixed on pallets with an automated handling system in order to move the product between the connected machines (Koren et al 1999). In 1971 the "Shuttle car System" was developed. This is a rail-type pallet transfer system, which means that products move to and from the machining stations on this pallet. Since only one pallet is available, only one product can be handled at a time. This system is therefore suitable for long and variable cycle-times. Later, during the 1970s, the development of FMSs started. For automated material handling systems this allowed more frequent use, for instance group-structured production cells linked with automated material handling systems (Koren et al 1999).

4.6.2. Modularity in material handling systems

Material handling systems suppliers have used a modular approach for a few decades when producing the *parts* for building the material handling systems, aluminum profiles, conveyor chains, cables, sensors, etc. This kind of modularity makes every single manufacturing system unique in the end since tailor-made end-systems are produced, despite the fact that smaller parts are modular and standard components. Since the 1990s, FlexLink has offered a modular assembly system for products up to 30 kg. This system is called DAS (Dynamic Assembly System). The DAS system is characterized by high-scale modularity. For example, a module can be a complete workstation, a turntable, or a conveyor (see Figure 17). Each of these modules has standard interfaces in order to be available for modular purposes, such as reuse at another occasion for another purpose.

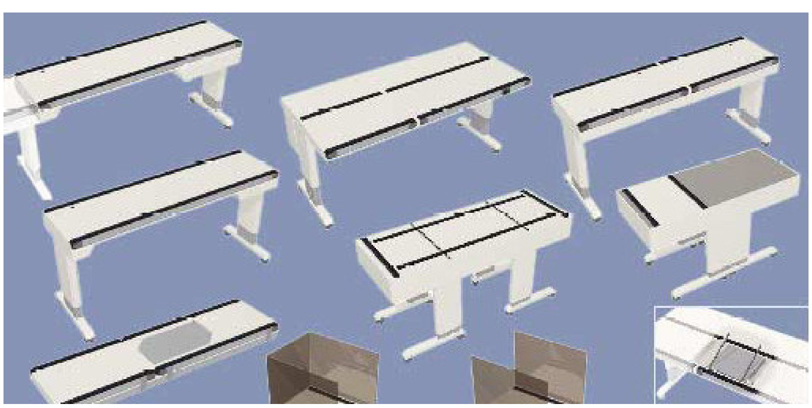

Figure 17 DAS modules from FlexLink.

5. Knowledge

Despite large epistemological progress during the 20th century, the concept of knowledge in too many cases evidently has been connected to theoretical knowledge (Peter Nordell 2003)

5.1. Introduction to knowledge

The foresight (Manufuture 2003, IVA 2000, and NRC 1998) described in chapter 1.2 Background has confidence in and motivates efforts in line with the "knowledge society" which is evolving today. The recognition of the "knowledge society" has been made by many authors (see e.g. Drucker 1968, Bell 1973, and Toffler 1990, cited in Nonaka 1994). This is by many seen as a paradigm shift in line with those described in 4.1 Introduction to Manufacturing Systems.

This part of the thesis will set the frame of reference for knowledge, information, and data and their relation to each other, including how they can be transferred between each other through interfaces and individuals. The main focus of the chapter is knowledge.

5.2. Definition of knowledge related terms

In this thesis, the classification from Figure 18 will be used. Increasing value is added for the subject of matter where data, information, and knowledge are the different forms.

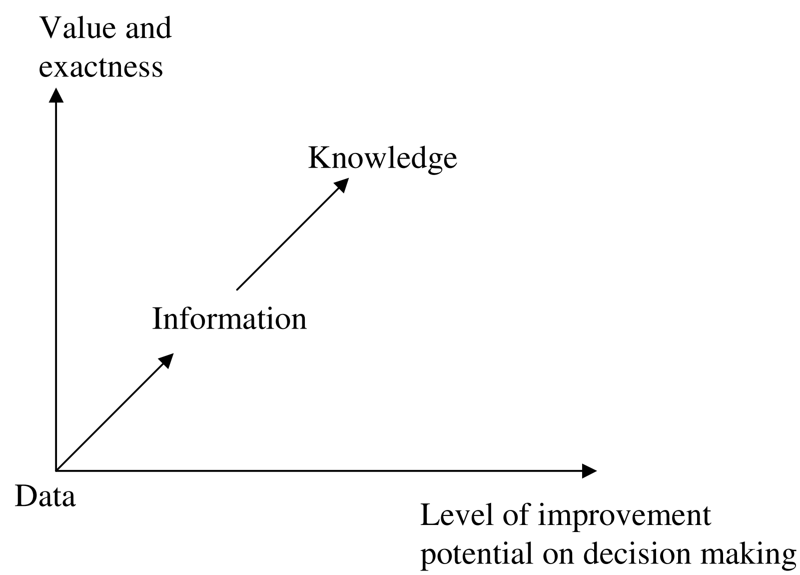

Figure 18 Exactness and value for Data, Information, and Knowledge in an increasing accuracy.

Below the definitions of each of these terms as used in this thesis are described.

5.2.1. Data

The definition of data is (Appendix, List of Definitions, Definition 16. *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" (American Heritage 1996).

5.2.2. Information

The same sentence can be used to describe the definition of information (Appendix, List of Definitions, Definition 17. *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*" (American Heritage 1996).

5.2.3. Knowledge

Knowledge, however, is more difficult to define. The definition of knowledge is widely discussed by many authors, especially within the history of philosophy where the classical Greek period can be seen as an eternal quest for the true meaning of knowledge. For example Plato, in the classical Greek period, and later also Locke and Kant wrote on epistemology discussions (Nonaka 1994).

According to the American Heritage (1996), the difference between knowledge versus data and information can be described as follows (Appendix, List of Definitions, Definition 19. *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.
Nonaka (1994) describes knowledge as created and organized by the very flow of information, anchored in the commitment and beliefs of its beholder. This means that human action is related to understanding. This is one of the key enablers in the proposed methodology of modular discrete event simulation, which is described in Chapter 7 Discrete Event Simulation for Modular Manufacturing Systems.

5.3. Modes of knowledge creation

The knowledge definition defined by Nonaka (1994) will be used throughout this thesis. According to Nonaka (1994) there are two dimensions of knowledge, *explicit* knowledge and *tacit* knowledge. Explicit knowledge can be defined as knowledge which is "digital", such as knowledge which can be stored in books and archives in order to enable other individuals to learn from it (Nonaka 1994). Tacit knowledge can be defined as knowledge, which requires experience plus communication between individuals before it can be mastered, as in the case where apprentices work with mentors to learn craftsmanship through observation, imitation and practice. Table 13 shows the modes of knowledge creation in and between tacit and explicit knowledge.

Table 13 Modes of the Knowledge Creation (Nonaka 1994).

From / *To*	Tacit Knowledge	Explicit Knowledge
Tacit Knowledge	Socialization	Externalization
Explicit Knowledge	Internalization	Combination

5.3.1. Socialization

Nonaka (1994) describes *Socialization* as the interaction between individuals, such as the case in master-apprentice learning environments. This also indicates that the key to this knowledge creation of tacit-tacit type is *experience*. The experience needed to be able to handle tacit knowledge in the context of discrete event simulation is discussed more in chapter 7.5 Modular DES methodology competence aspects.

5.3.2. Combination

The opposite variant is explicit-explicit, which is called *Combination*. This means that information flow is transferred from one individual to another through an interface. The interface can be, for example, a computer screen, a telephone, or a book, according to Nonaka (1994). My reflection on this definition is that explicit-explicit seems to cover the exchange of facts and/or information between individuals.

5.3.3. Externalization

Externalization and *Internalization* of knowledge, tacit-explicit and explicit-tacit, can be described as follows: "These conversion modes capture the idea that tacit and explicit knowledge are complementary and can expand over time through a process of mutual interaction" Nonaka (1994). Nonaka does not really give an explanation of *Externalization* except for the sentence just quoted. My opinion on this is that the kind of knowledge conversion often loses a lot of value during the transformation, since tacit knowledge is hard to formulate in the form of facts and information.

5.3.4. Internalization

The explanation of *Internalization* is the common description of traditional "learning" where an individual learns something out of a "digital" basis, such as books, computers, and other sources (Nonaka 1994). The way the author sees it; this knowledge conversion can be called *knowledge creation* through interpretation of *facts* and *information*.

Tacit and explicit knowledge are used to explain the division of tasks for the simulation expert and the simulation user within the modular discrete event simulation methodology presented in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems.

5.4. Enablers for knowledge creation

Von Krogh et al (2000) define five main enablers for the knowledge creation process. These five enablers work cooperatively in order to enable a working environment, which promotes and assists the knowledge creation and knowledge transfer processes. The five enablers are (Krogh et al 2000):

1. Install a knowledge vision
2. Manage conversations
3. Mobilize knowledge activists
4. Create the right context
5. Globalize local knowledge

A knowledge *vision* includes not only the ideas on future but also the reflection on and continuous reinvestigation of current beliefs (von Krogh et al 2000). *Conversations* are the best way to create and share knowledge according to von Krogh et al (2000); good conversations are the main contributors to increased social knowledge in any organization. To ensure and catalyze social processes of knowledge creation in an organization, an individual or a group needs to take *responsibility* for energizing and coordinating a knowledge creation effort. They can be seen as knowledge activists who actively create space and *context* for knowledge creation (von Krogh et al 1997).

5.5. Division of labor

Scientific Management was a hot topic during the early 20th century. Is it still? Even though it may be similar in shape, we are still talking about the same issues: outsourcing, knowledge, efficiency, effectiveness, productivity, profitability, flexibility etc. All these aspects are addressed by Frederick Winslow Taylor in his book "The principles of scientific management" from 1911. Taylor's scientific management is perhaps somewhat too rough to be adopted directly in the industry today. However similarities are obvious, but the Scientific Management base values have been given other names (e.g. JIT, TPS, QFD, and Six Sigma) and have been adjusted to suit the values of humans and to protect the environment to some extent. Although this adjustment has not been fulfilled all around our globe yet, the base values remain. The outsourcing trend of production facilities from both United States and Europe to Asia and specifically China is well known. Even Taylor discusses similar developments in the introduction to his book (Taylor 1911):

> "President Roosevelt, in his address to the Governors at the White House, prophetically remarked that "The conservation of our national resources is only preliminary to the larger question of national efficiency." The whole country at once recognized the importance of conserving our material resources and a large movement has been started which will be effective in accomplishing this objective. As yet, however, we have but vaguely appreciated the importance of "the larger question of increasing our national efficiency." We can see our forest vanishing, our waterpowers going to waste, our soil being carried by floods into the sea; and the end of our coal and our iron is in sight. But our larger wastes of human effort, which go on every day through such of our acts as are blundering, ill-directed, or inefficient, and which Mr. Roosevelt refers to as a lack of "national efficiency" are less visible, less tangible, and are but vaguely appreciated."

This quotation from Taylor (1911) shows that labor and its precious time and knowledge content is of utmost importance to achieve welfare. This will be further discussed and used to explain the proposed methodology for modular discrete event simulation of manufacturing systems in chapter 7.1.2 Knowledge requirements in the context of DES.

6. Summary of papers and case studies

The research work of this project is conducted in close collaboration between Chalmers University of Technology and an industrial partner company (Jürgen Kaiser 2002)

6.1. Introduction to papers and case studies

The purpose of this chapter is to:

- Show the explorative research conducted in order to find the research gap, Case 1, 3 and Paper 2.
- Show the quantitative research conducted in order to verify that the gap exists, Case 1-5 plus additional ca 30 case studies, Paper 3, and 4.
- Show the requirements for and benefits from the modular discrete event simulation methodology Case 5, Paper 1, 5, 6, and 7.

This chapter starts with a summary of each appended paper, wherein the research contribution is clarified. Each paper is summarized as follows:

- The purpose of the scientific study is clarified.
- The research methodology is described.
- The results and conclusion of the findings are given.

After the paper summary, the connection and contribution towards the modular discrete event simulation methodology from case study 1-5 and papers will be clarified and discussed (See Appended Papers for full paper and case study details.).

6.2. Paper 1: An Enhanced Methodology for Reducing Time Consumption in Discrete Event Simulation Projects (Johansson and Grünberg 2001)

6.2.1. Purpose

The purpose of this paper was to show how increased timesaving could be obtained in discrete event simulation projects mainly by addressing the methodology itself but also by carefully determining the objective of each specific project.

6.2.2. Method

Case Study methodology (Yin 1994) was used as a base for finding the discrete event simulation methodology improvement potential. Two case studies (Johansson and Allander 1999, Jörgensen 2000) are described in Johansson and Grünberg (2001) to exemplify the benefits. Some additional case studies were also available as reference material (e.g. Karlsson 2001, Klingstam 2001).

6.2.3. Result and conclusion

The result includes an improved methodology that builds on traditional discrete event simulation methodology procedures. The study also addresses the objective when forming a discrete event simulation project. All simulation projects can follow the revised methodology described in Johansson and Grünberg (2001), even though all projects that follow the revised methodology are not going to have an early end, since it is determined by the way the objectives are set at the start of the project. If the objectives are based on "as good as possible" (abstract) results, no matter how long a time it takes, then the project will surely go through all stages of the methodology even if the revised methodology is used. In contrast, if the objective is set to "find the solution for this" (concrete), then it is possible to find the solution earlier and save valuable time. Table 14 shows when the revised methodology is likely to have an impact on the project, where "+" means "positive impact" and "0" means "no positive impact".

Table 14 Impact of the objective set in early stages of a simulation project (Johansson and Grünberg 2001).

Objective \ Time	Shortest possible	Set to a date	Infinite
Concrete	+	+	+
Abstract	+	0	0
"Best possible"	0	0	0

6.3. Paper 2: An Evaluation of Discrete Event Simulation Software for "Dynamic Rough-Cut Analysis" (Johansson et al 2002)

6.3.1. Purpose

Many companies view simulation as a complex expert tool, and do therefore not use it as frequently as they could. The purpose of this paper is to assess which Discrete event simulation software packages are suitable for the modeling of Dynamic Rough Cut Analysis (DRCA).

The need for speed during model building addresses the importance of an easy-to-use simulation tool since many simulation packages demand expert knowledge of the user in order to be fully utilized. The focus of this study has been on the concept of "Dynamic Rough Cut Analysis", which means building DES models rapidly and efficiently. A consequence of high speed in the building of a model is that the modeled system will be rougher, but it will still give enough details to make it possible to take strategic decisions.

6.3.2. Method

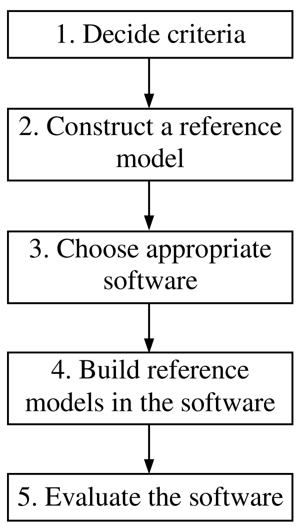

Figure 19 Methodology used in the evaluation of DRCA software.

The method and procedure to evaluate discrete event simulation software suitable for DRCA was made according to Figure 19.

1. Decide what criteria are of importance. By using Nikoukaran et al (1999), a conclusion on six criteria to be evaluated was decided:

    a. Tutorial
    b. Execution
    c. Output data visualisation
    d. Straightforward models
    e. Multi-faceted models
    f. Editing possibilities

2. Construct a reference model fitted to be evaluated with the DRCA software.

3. Search and choose appropriate DES software for conducting projects using the DRCA concept.

4. 24 students made the reference model building in the evaluation study during their final year of the Master of Science education.

5. After building the reference model, the students filled in an evaluation form considering the different evaluation criteria.

6.3.3. Result and conclusion

The evaluation results are presented in Figure 20. The DES software of today tends to be developed for an everyday use that normally focuses on fairly large companies with simulation experts. DES software also tends to grow in complexity with each new release as a result of users' needs of new functions, which makes the programs increasingly expert-oriented. This is negative for new users as they must learn to how to use the software, since the level of knowledge that must be achieved before the software can be fully used is fairly high. It is also important for the developer of the software not to make major changes in the interface. If this is done, not even experienced users will recognize the software interface in new releases (Johansson et al 2002).

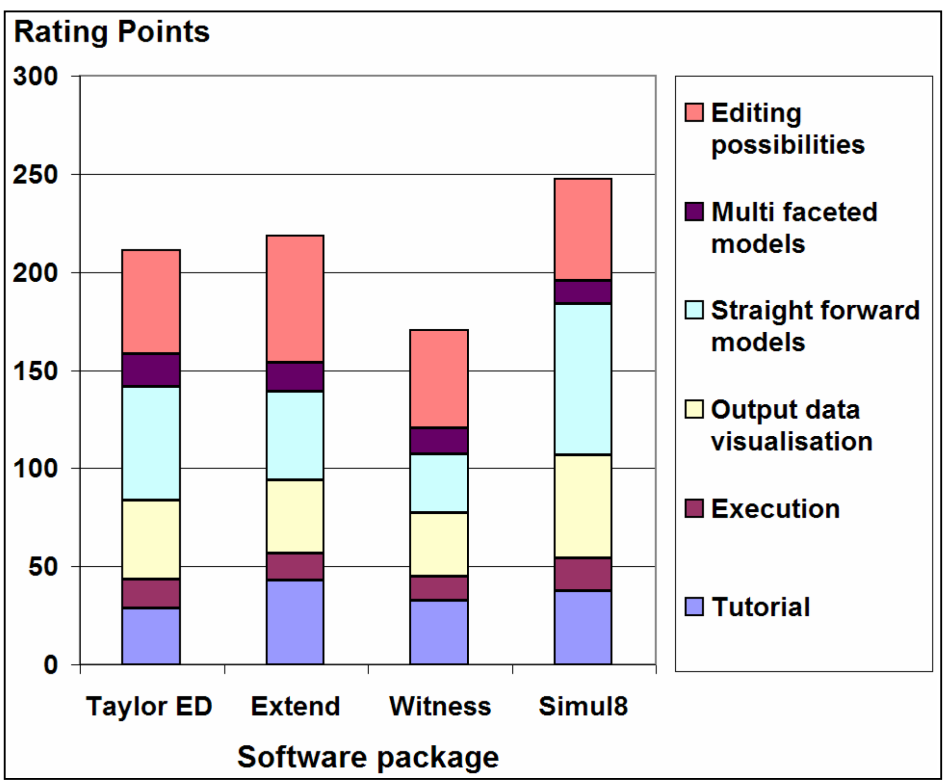

Figure 20 Evaluation results for the software packages.

6.4. Paper 3: Turn Lost Production into Profit. -Discrete Event Simulation Applied on Resetting Performance in Manufacturing Systems (Johansson and Kaiser 2002)

6.4.1. Purpose

The purpose of this paper was to investigate to what extent DES can be utilized for the evaluation and improvement of resetting processes in manufacturing systems.

6.4.2. Method

The paper presents a case study, using DES as the tool for finding and quantifying improvement potential for resetting time reductions. During the case study the methodology described in Chapter 3.4 Classical Discrete event simulation Project Methodology was used (see also Banks et al 2004). Part of the case study is also well described in Axelsson and Hjelte (2002).

6.4.3. Result and conclusion

With the DES model of a manufacturing system including the resetting process of the manufacturing system and the related simulation runs, it was shown that DES can be used for the evaluation of resetting processes in manufacturing systems. 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 simulations provided valuable information for the ongoing improvement work in the manufacturing system, in terms of facts and figures. Moreover, the simulations were a means of visualizing the outcome for the improvement team. The 3-D simulation model could be used to visualize the different scenarios of a parallel resetting organization. The results also indicate that there is a large potential for increasing the productivity in the manufacturing unit by implementing the findings from the DES model into the manufacturing system.

The general conclusions from the case study populating this paper can be summarized 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.

The main contribution form this paper to the thesis is that this kind of manufacturing system would yield large benefits from the methodology proposed in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems, however since it was not yet developed by then, this case study and paper lacks the benefits from it.

6.5. Paper 4: Information structure to support Discrete Event Simulation projects (Johansson et al 2003)

6.5.1. Purpose

Discrete event simulation is ranked among the top three tools for management support. However, it has not yet become as successful a tool in industry as many experts have predicted. The purpose of this paper was to examine the reason for this delay of diffusion into industry. The purpose was also to find out if there is enough information and knowledge available in manufacturing companies in order to utilize the tool discrete event simulation profitably.

6.5.2. Method

In this paper a quantitative survey was made in line with the definition used by Patel and Tebelius (1987). This survey comprised analyses of sixteen DES projects undertaken from 1995 to 2001 in Sweden, England, and Singapore.

6.5.3. Result and conclusion

The results of the paper show that one clear conclusion can be drawn, namely that if there is no data on how the manufacturing system works, there is no chance to improve the system in a sound manner, neither with DES nor with any other tool. The study shows that only 6% of the companies (One company out of sixteen) do have enough data available for a DES model to be built easily. Additional reflections are:

- To be able to utilize DES at its full capacity there is a great need for data-handling systems that automatically generate and present the appropriate data from real-world raw data.
- The system has to follow an accepted standard such as GERAM and CIMOSA (Vernadat 1996) to diffuse into the daily work in industry and to be compatible with supplier and customer requirements.
- The organization and the working procedures have to correlate with the DES project-methodologies.

The results of the survey are shown in Table 15.

Table 15 Summary of the Survey, Describing the Percentage Available Data in Each Category of the 16 Projects.

DOMAIN	SECTOR	DATA TYPES	Projects with available data
Production data available	Logistics	Logistics service provider, supplier data, part data	31%
	Plans	Product production plans, production schedules, flexibility needs/capabilities	88%
	Equipment	Machines, tools, jigs, fixtures, infrastructure, buildings, material transport, storage equipment	56%
	Processes	Process plans, instruction sheet, numeric control programs	44%
	Organization	Shop-floor status, inspection data, tractability data	75%
All production data available		Summarizing the above five categories	6%
Project Performance	Project satisfaction	Fulfillment of the project goal	81%
	Assumptions made	Forced to use assumptions in project caused by lack of documented data	100%
	Model sensibility	Model sensibility analysis performed	75%
	Model reliability	Warm-up period used, multiple runs used	75%
	Validation problems	Validation problems of the model because of inaccurate data use	44%

6.6. Paper 5: Modular Assembly Systems Simulation for Lead Time Reduction (Johansson et al. 2004)

6.6.1. Purpose

In this paper an extensive review is made in order to find the right DES software approach to use with reconfigurable modular manufacturing systems. The software must be able to handle "offline" experiments reconfigurations of the system. The aim was to sort out the effects and various important factors for successful use of DES software applied to reconfigurable modular manufacturing systems.

6.6.2. Method

The market of available software used to conduct DES projects was analyzed in order to find the most suitable software combinable with reconfigurable modular manufacturing systems technology. The main source used to find the appropriate software packages was the Internet, but also *OR/MS Today,* August 2003, in which most available DES software packages are listed (about one hundred), was valuable. After testing demos and talking to many of the software vendors, there was a total of twelve software packages selected for further analysis. These twelve software packages where then all tested and evaluated for each of the eight criteria:

- Application price
- Easy to learn
- Global spread
- Advanced features
- Graphical representation
- Interface
- Modularity
- AutoCAD connection

6.6.3. Result and conclusion

The conclusion of the evaluation study indicates that no software supports RMMS technology completely, but it indicates that 3Drealize is the most appropriate software to choose for the purpose of RMMS. Other software, such as Automod and Simul8, is not far from 3Drealize when it comes to providing the capabilities wanted in RMMS. The overall conclusion is therefore to continue evaluation on the top three software of the survey in order to find out which the most appropriate solution is.

It is sound to mention that a RMMS system should have gained profits from being simulated using the modular discrete event simulation methodology. However, since it was not available at this time, it was not used.

6.7. Paper 6: Profitable Intelligent Manufacturing Systems for the Future (Bagiu and Johansson 2004)

6.7.1. Purpose

The purpose of this paper is to enlighten the possibilities with intelligent manufacturing systems, especially from the perspective of material handling, and to show benefits that can be gained by keeping the production facilities instead of outsourcing the production to other companies and/or countries.

6.7.2. Method

A descriptive literature survey combined with case study material from real manufacturing systems with implemented material handling systems make up the base for formulating three key industrial enablers for future intelligent manufacturing systems with material handling systems as the driving force for productivity.

6.7.3. Result and conclusion

The three keys areas, followed by facilitating effects, are listed below:

1. flexibility
    a. autonomous intelligent modular equipment
    b. standardized product carrier system handling different product types
    c. human beings

2. process efficiency effects
    a. A batch size of one product can be reached by taking away all non value-adding work and buffering.
    b. The lead-time will be shortened to half or less.
    c. The cost and work in progress needed drops dramatically.
    d. The line utilization can reach levels above 95%, compared with 50-70% utilization today, resulting in far higher utilization possibilities for the core processes.

3. volume increase/decrease
    a. Step-by-Step automation
    b. Modularized software and hardware
    c. Functional sales

The system characteristics described in this paper is one, which would yield benefits from utilizing the proposed modular methodology when conducting discrete event simulation activities. Mainly due to the real world modularization and the list above, which is in line with the structure for the proposed modular discrete event simulation methodology.

Paper 7: Using Autonomous Modular Material Handling Equipment for Manufacturing Flexibility (Johansson et al 2004)

6.7.4. Purpose

The purpose of this paper is to describe how reconfigurable modular manufacturing systems can be used in combination with discrete event simulation in order to increase the productivity of a manufacturing system.

6.7.5. Method

IAR as described by Ottosson and Björk (2003) is mainly used as most of the impressions and results presented in this paper stem from cooperative work inside a company.

6.7.6. Result and conclusion

The presented technology using reconfigurable modular manufacturing systems in combination with modular discrete event simulation has the following benefits:

1. It simplifies the model building of DES models by modularization.

2. It increases the accuracy and availability of manufacturing lead-time data by pre-built modules, including pre-validation and pre-verification of the modules.

3. It increases the insight into a dynamic manufacturing environment by knowledge division of simulation and system knowledge, enabling personnel with system knowledge to build a DES model.

4. It reduces lead-times by reusing work already done and by intensifying the knowledge content in the:

    a. Sales process
    b. Manufacturing line design process
    c. Implementation process
    d. Operational process
    e. Reconfiguration process
    f. New manufacturing equipment design and testing
    g. Education on and understanding of dynamics in manufacturing systems

This paper in combination with Johansson (2006) forms the modular discrete event methodology outline. Further efforts are needed in order to specify the details in each stage of the proposed methodology (See chapter 10 Future Research). However, for now the proposed methodology at large is validated (See case studies 6-9), and partly used by some OEM companies who sells manufacturing equipment and systems.

6.8. Case study and paper contribution towards modular discrete event simulation of manufacturing systems

This subchapter summarizes the main research findings from the papers and case studies that are used as a base to formulate chapter 7 Discrete Event Simulation for Modular Manufacturing Systems.

6.8.1. Case study contributions

Case 1 (See appendix) describes the current trends of reconfigurable manufacturing systems. This base is used to understand what demands will be set on the discrete event simulation within the context of reconfigurable manufacturing systems. The result from case one indicates that:

- Modular and reconfigurable manufacturing systems will be demanded more often in the future than today.
- Future manufacturing systems will be characterized by openness and therefore several standards will have to be developed.
- The manufacturing system control will become more decentralized in the future.
- Industrial and automated manufacturing systems will be based on digital networks.
- Ethernet will be implemented in many industrial systems which will make the systems more rapid.
- Product tracking technologies will be more important in the future and the literature means that RFID will become the most common technique in this field.
- Modeling and simulation tools will be developed and used for more functions than they are today.

Case 2 and 3 (See appendix) are similar in nature and both have the same scientific message to contribute with in this thesis. They show that discrete event simulation is an efficient tool that is helpful for finding solutions to complex problems. These two cases also show that the interfaces to the discrete event simulation software packages are too complex to be used by personnel working with the actual manufacturing system. The need for expert knowledge on discrete event simulation is evident. Hence, cases 2 and 3 clearly indicate that a modular discrete event simulation methodology as the one described in this thesis is needed. Several other sources point in the same direction (see e.g. Axelsson and Hjelte 2002, Ström and Turesson 2005, Bertilsson and Holmberg 2005).

Case 4 (See appendix) shows that there are many places in industry where discrete event simulation can be used in order to find large productivity potentials. DES will provide a sound base of support that can be used when companies are to decide on future improvements. DES can therefore be a good investment even in a short-term perspective. However, since the discrete event simulation models today require expert knowledge in order to be kept up to date there are even more potentials to be utilized. The simulation expert will always be needed as a part of the working procedure. This is almost never done, and the models are therefore put away and not updated properly. Later on, when there is time for another improvement round, the model is rebuilt again from scratch.

Case 5 (See appendix), discrete event simulation and PLC-Emulation shows that it is possible to control a discrete event simulation model with a soft-PLC. This also indicates that it is possible to conduct offline programming of complete manufacturing systems by using emulation in combination with discrete event simulation.

The market survey shows that emulation activities are rarely used in industry. Those who use it the most are system suppliers, and they are also the ones who can profit the most from using it since they use it frequently and have the knowledge required (Walfridsson and Wertheimer 2005). The conclusion from this part is that the discrete event simulation of manufacturing systems will not include discrete event simulation of emulated PLCs within the near future, although the technology is promising.

Case 6, 7, 8, and 9 (See appendix) are used in order to validate the methodology presented in 7 Discrete Event Simulation for Modular Manufacturing Systems. Validation is discussed further in chapter 8.5 Validation of research results.

6.8.2. Paper contributions

The contribution from paper 1 is first of all that it improves the traditional discrete event simulation methodology by making frequent checks on the current status of the project. The checks are constantly compared with the objectives of the project. Moreover, it clarifies how the goals with a simulation study should be set in order to meet the objectives more efficiently.

Paper 2 focuses on finding discrete event simulation software enabling models to be built quickly. Four software packages were evaluated, where the total time of conducting a discrete event simulation project in each software package was analyzed. The analysis indicates that there is a need for more user-friendly discrete event simulation software in order to enable the specific manufacturing system experts to build and use their own models. At present, discrete event simulation experts are needed to build the models with tailor-made user interfaces.

Paper 3 exemplifies the use of DES for manufacturing systems through the utilization of DES both by the simulation of the material flow and the resetting process. The paper also shows the need for a modular discrete event simulation methodology, since the manufacturing system itself is modular. There are numerous similar facilities at this company, which could have benefited from this model if it had been made with the modular discrete event simulation methodology instead of the traditional one.

Paper 4 shows that the presumed lack of data in order to construct discrete event simulation models is true; only one out of sixteen cases had enough data available to construct a discrete event simulation model. This lack of data will be ameliorated if the proposed modular discrete event simulation methodology is used, since the methodology supports the reuse of data from one module to another.

Paper 5 shows that the current status of discrete event simulation software cannot fully adopt the modular methodology. However, the development trends are clearly moving in the direction where software packages support discrete event simulation of modular manufacturing systems more and more.

Paper 6 points out possible benefits of using modular manufacturing systems enabling profitable production in the western world in the future. The paper outlines the following three characteristics and key features as the features which will make modular manufacturing systems the profitable solution for future manufacturing:

- flexibility
- process efficiency
- volume increase/decrease

Paper 7 combines three fields of interest that are covered by the present thesis: discrete event simulation, manufacturing systems and knowledge. The paper describes how modular discrete event simulation can be used in combination with modular manufacturing systems to reduce lead-times and divide the knowledge content among individuals in a company. This gives lead-time benefits, as well as productivity enhancements, during the different life-cycle phases of a manufacturing system.

7. Discrete Event Simulation for Modular Manufacturing Systems

So What? Will Discrete Event Simulation ever be institutionalized and used by routine? Regarding its potential, the proportion and the way it is used today, has it a future at all? (Ulf Ericsson 2005)

7.1. Introduction to DES for modular manufacturing systems

This chapter describes how manufacturing systems can utilize recent findings on discrete event simulation in order to improve productivity when it comes to real world manufacturing systems through implementing the findings from discrete event simulation, but primarily in the process of *using* discrete event simulation as a tool for productivity improvement. Specific attention will be paid to a methodology for creating discrete event simulation models out of predefined modules. This methodology will be outlined, different competence roles needed when using the methodology will be explained, potential lead-time benefits while using the methodology will be clarified, and explanations connecting to the division of labor and knowledge will be given. Finally, additional advantages of using discrete event simulation for manufacturing systems will be addressed.

7.1.1. Purpose of the modular DES methodology

This methodology has been developed in order to increase the benefits of using virtual development of manufacturing systems. Traditionally reusability of data and information from one system development project to another is very low. The main advantage and contribution with this methodology compared to classical DES methodologies such as Banks et al (2004), Law and Kelton (2000), Pedgen et al (1995) is the "built in" *reuse* of data and information. This feature will make work in additional projects after the first one much easier since data and information has already been verified and pre-packed in modules for reuse from the first one. Since not all industries reconfigure their systems or build similar manufacturing systems over and over again, this methodology is mainly aimed at OEM companies which design manufacturing systems; for example line builders, machine builders, or system integrators.

7.1.2. Knowledge requirements in the context of DES

How are knowledge and division of labor in scientific management related to discrete event simulation? The simple answer is that discrete event simulation is an expert tool that requires experience and knowledge. It is even considered an *engineering art* by many (e.g. Gustafsson 2002). The use of discrete event simulation would be simplified if it was possible to divide the tasks in a simulation project into uncoupled knowledge requirements. It would then be possible for more than one person to work on the discrete event simulation model. In addition, the knowledge division would not set as high expectations on each individual competence in the project, but rather joint expectations on the project group as a whole.

7.1.3. Key characteristics of the modular DES methodology

The modular DES methodology has two main divisions where different skills are needed in order to fulfill the tasks required (see also paper 7, Johansson et al 2004).

Traditionally discrete event simulation *experts* build simulation models for each and every simulation project. This is due to the need for expert knowledge and the nature of building simulation models.

The results of this thesis aim at packaging the knowledge of the simulation expert into modules consisting of logical relations coded for DES, CAD drawings, connection interfaces and parametric variables. The only thing that the customer will be able to modify is the parametric values opened up by the simulation expert. All other information in the module is locked for each version of the modular library. An example of project conduction can be outlined as follows:

Prior to the project a DES expert has coded modules for material handling equipment where each module is like a virtual “Lego” brick consisting of:

- CAD data
- Logical relations
- Connection interfaces to other modules
- Non-public parameters, such as constrictions, constants and unchangeable logic
- Variables for public parameters, such as cycle time, MTBF, MTTR, routing, Capacity, Length, Width, Height, changeable logic etc…

When the project starts anyone can use this "public" library of modules to build a manufacturing system. The knowledge needed to build a system is:

- Knowledge on what task to solve (what the system should accomplish)
- Knowledge of the actual manufacturing system
- Knowledge about how to use the modular library

Different methodologies have been developed for structuring purposes in simulation projects. The methodologies have much in common, (Law and Kelton 2000, Pegden et al 1995, Banks 2000). The approach commonly contains steps such as problem definition, data collection, model building, comparison and analysis. The major difference between these methodologies and the methodology argued for in the present these is that the *simulation expert* is always at the centre in methodologies such as the ones described in Law and Kelton (2000), Pegden et al (1995),and Banks (2000). This person is the most vital person in these simulation projects. The methodology described here does not require a simulation expert to be present in the actual simulation project. Figure 4, Figure 8 and Figure 9 all show the steps in consecutive order during a *classical* simulation study. The following description of the revised methodology contains similar steps, but some steps are completely revised enabling more individuals with system knowledge to build the simulation model.

7.2. Simulation expert tasks in the modular discrete event simulation methodology

The simulation expert will work prior to the launching of the actual simulation project. The task for the simulation expert is to model a module with parameters, which can be reused many times by those who conduct a simulation project. The architecture for simulation modules has to be predefined and standardized, so that upgraded/updated module libraries are compatible with previous versions.

The steps for building simulation modules to be put into the public simulation library are described in subsequent paragraphs and visualized in Figure 21 below.

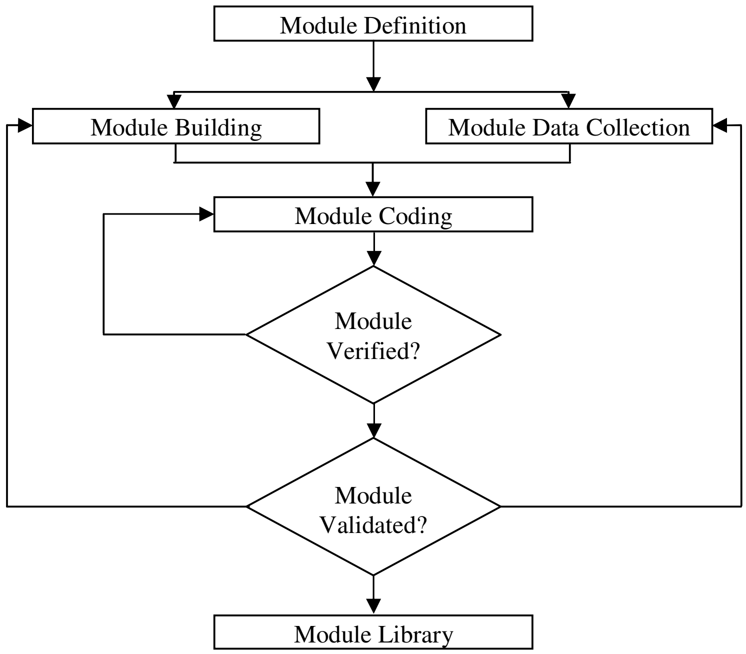

Figure 21 Proposed steps in building modules for modular discrete event simulation models.

7.2.1. Module definition

The module itself must have a real-world counterpart that it is supposed to represent. The goal should cover what is to be included, what the specification for the module is, what the function of it is, the logical meaning, interfaces, and module boundaries for this module. The reason for having this particular module should be clarified and defined.

7.2.2. Module building

The module needs representative CAD-drawing parts as an original source for creating the physical appearance of the module in a 3D-environment (if the specific software supports 3D visualizations.). It also needs specifications for Bill of Materials in order to generate these automatically from the module parametric values.

7.2.3. Module data collection

The module restrictions and real world limitations in terms of size, speed, width, height, times, and other parameters need to be collected and added to the module.

7.2.4. Module coding

The logic of the real world module have to be coded into its virtual representation, covering features such as product moving paths, input and output signals, sensors, and safety signals.

7.2.5. Module verified?

When the module has been given a representation in the virtual world, both logically and in 3D, it is time to ensure that the module behavior is the desired one, considering the previously specified module definition.

7.2.6. Module validated?

Validation is the determination of whether the module is a correct translation of its real world representative as specified in the module definition. The ideal way to validate a simulation module of an existing module is to compare the virtual module characteristics such as output, speeds, buffer capacities, etc., with the same real world module characteristics under the same conditions.

7.2.7. Module library

Finally, when the simulation module is validated it is ready for use. A "public" library of modules needs to be maintained and available. This library has to follow a predefined structure in order to "survive" updates, upgrades, and additions of new modules into it. When the module has come to this point, it is complete in the sense that the discrete event simulation expert has done all the major tasks that are required from him/her. From now on, any simulation user should be able to utilize the module.

7.3. Simulation user tasks in the modular DES methodology

The simulation users need to have a modular simulation library available for use in order to be able to fulfill their tasks. Since the modules have already been created, verified and validated, the knowledge and work needed from people who are not simulation experts are far less complex than was the case when using the classical simulation methodology. Still the tasks for creating a DES model of a system require knowledge, but the knowledge needed is not mainly a matter of DES, but rather of the *system* that is to be modeled. The steps for building simulation models out of the public module library are described in Figure 22:

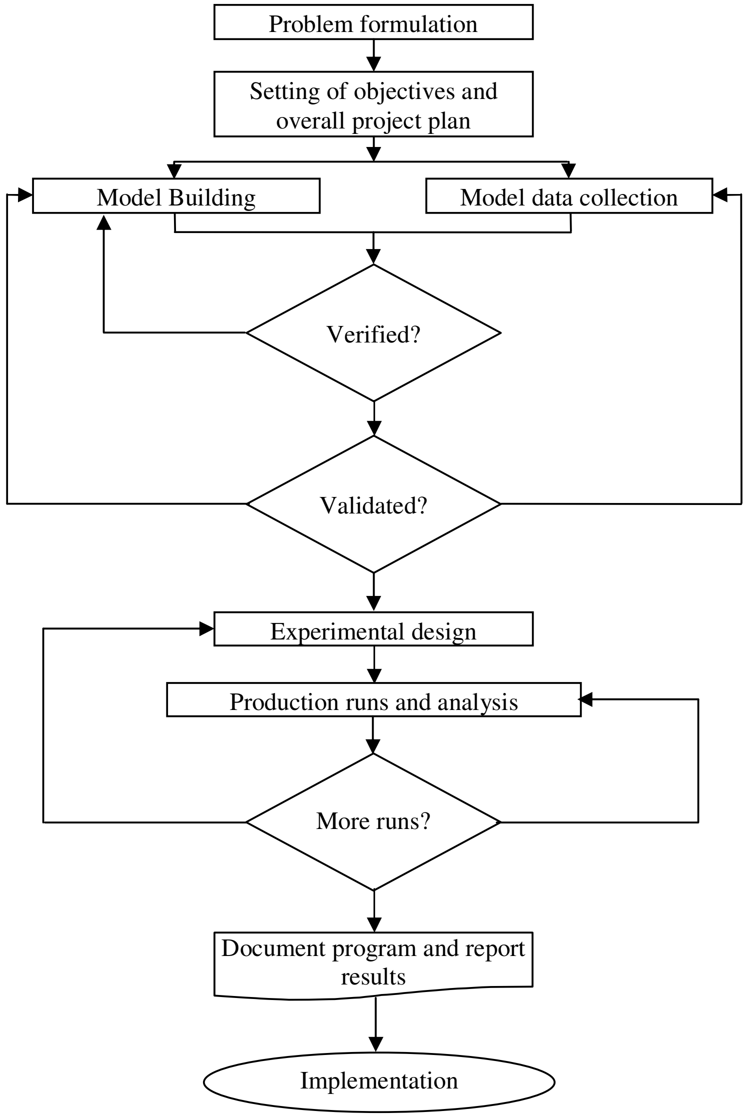

Figure 22 Proposed steps in building models for modular discrete event simulation models.

The steps in Figure 22 will now be described in sections 7.3.1-7.3.11.

7.3.1. Problem formulation

This step has not changed much from the classical DES methodology. The only real change in this feature is that the client of a simulation study can solve his/her own problem by modeling it himself/herself out of the modular library. This decreases the risk for misunderstandings. The statements in the problem formulation still must be very precise and easy to understand, particularly if the statement is provided by those that have the problem, i.e. the clients. The simulation analyst must then take extreme care to ensure that the problem is clearly understood. If the problem instead is formulated by the simulation analyst, it is important that the client understands and agrees with the formulation.

7.3.2. Setting of objectives and overall project plan

The setting of the overall objective and project plan is the same as in the classical methodology. The questions to be answered within the simulation project are indicated by the objectives, which should be stated in a measurable format (see paper 1, Johansson and Grünberg 2001). The project plan should include a statement of the various scenarios to be investigated and analyzed. Resources needed for the simulation study at large should be included, such as personnel who will be involved, hardware and software requirements, stages in the investigation, and the cost of the study (if any). Decisions on who should be responsible for the different areas mentioned above should also be agreed upon at this stage of the simulation study.

7.3.3. Model building

The model building part of the methodology has changed a lot. It is now necessary only for the model builder to "drag and drop" modules from the modular library to connect modules to create the total system. This means that the model builder need not have expert knowledge in the internal parts of each module and its code. It is enough if the person understands the functionality of the system in the real world. The coding part of the model building is eliminated since each module is pre-coded and consists of the necessary logic and physical representations. The similarities with the classical approach are that the real world will be simplified to a series of mathematical and logical relationships. However, the revised methodology uses the components and the structure through the modules to represent the real word system instead of modeling everything from scratch. It is recommended not to make the model too complex at an early stage of the project since the level of detail will increase as the model develops. One should start with the basic features, such as arrivals, queues and servers. Then failures, shift scheduling, and more complex solutions may be added later on. The basic features should already be included in each. For example, a conveyor should have the conveyor-speed assigned to one parameter if it is possible to control the speed in the real word representative. In the end, the special features for the most complex parts of the model should be added. This may require advice from the discrete event simulation expert to the system expert in order to get smaller parts of a module to be tailor-made for a specific purpose.

Maintaining the client involvement in the model building is vital if success is to be attained. Client maintenance is more easily accomplished in this methodology since the client can actually build the model.

Most DES projects generally start the model building by creating a conceptual model of the system (a sketch or a rough drawing is sufficient). However, with the modular DES methodology this is not always necessary as the conceptual model can sometimes be made directly in the software.

7.3.4. Data collection

Since the data structure for each module is set by the simulation expert earlier, most of the data needed in this methodology is already verified, validated and included within each module; it is only the specific data for a particular case that is needed. This kind of data can be, for example, cycle times, MTTR, MTBF, conveyor speeds, the limitation of product handling, and routing rules. In the best of circumstances, the client has collected the data needed in the format required. Unfortunately, this is not usually the case. For instance, it happened in only in 6% of the cases studied by Johansson et al (2003, see Paper 4). However, since most of the data is already built in the modules, the workload in this part of the project is eased considerably. As shown in Figure 22, model building and data collection are simultaneous tasks in most projects, although either of these blocks can be dealt with separately.

7.3.5. Verified?

The verification in this part is mainly needed on a *system* level since each module has already been verified before it is put in the modular library. Verification of the model includes securing that the model behavior is in agreement with the desired behavior, following the previously constructed, or sometimes only imagined, conceptual model.

7.3.6. Validated?

The validation process is not changed a lot by the modular model building; it must still be done very carefully at the *system* level. However, since the comparison of modules with reality has already been made, the system validation process is simplified. Validation is the determination of whether the model is a correct translation of reality concerning the previously made decisions about the level of detail. To validate a model of an existing system, the ideal way is to compare the model output (using historical input data) with the real output from the same time span. Sargent (2000) recommends a procedure that should be carried out as a minimum validation procedure to ensure that the validation is sufficient. See also chapter 3.4.7 for additional validation techniques.

7.3.7. Experimental design

The modular approach facilitates experimental design, since modules can easily be inserted, removed, or changed in the model. Additional features are the parametric values connected to each module. These values can easily be changed and other solutions can be examined and compared with each other.

7.3.8. Production runs and analysis

The modular library enables specified scenarios to be simulated, evaluated and analyzed to estimate measures of performance for each of the different solutions in short time. In addition, the possibility of analyzing PLC logistics with emulation, layout planning and automatically generated Bill of Materials are supported, which increases the usefulness even more.

7.3.9. More runs

With the modular library at hand more runs of a specific model or changes in a model are easily managed and conducted with the new methodology. Based on simulation runs completed, the analyst has to decide whether there is a need for another scenario to be simulated. The analyst also has to determine if more runs of the same scenario are necessary in order to detect variations in the outcome of the simulations made.

7.3.10. Documentation and reporting

Documentation and reporting is still a very important step. The advantages compared to the classical methodology are that the Bill of Material can be generated automatically. Good documentation is important in many ways. Firstly, the documentation will be of great help if the simulation model has to be reused. Secondly, the documentation ensures that the model maintains a high quality in terms of understanding and decision-making.

7.3.11. Implementation

Additional advantages are that the logic in each module and the logical couplings can be used for offline programming of the manufacturing systems real world PLC. There are researches conducting research in this area, such as Emulation of PLC systems (see case 5, Walfridsson and Wertheimer 2005). The implementation process has a short lead-time with the modular approach since it reuses data from work carried out earlier by the DES specialist.

7.4. Setbacks

The revised methodology used for modular discrete event simulation projects does of course have some drawbacks as well. The ones identified are listed and explained below:

- One-of-a-kind projects will need increased effort compared to the traditional methodology, since modules are not reused and the modularization requires extra work.
- The first model built will be at least as time-consuming as with the classical methodology.
- At least one person with expert knowledge on discrete event simulation is needed in order to create the modules.
- Version handling when the modules are updated in the real world is an issue, which requires additional attention. Interesting similarities can be found and

used to develop similar version-handling for modular discrete event simulation as is used in product data management (PDM)

- There are few software packages that support the methodology. Some software packages are under development, but the shortage of software packages supporting the methodology still limits the possibilities of practical use; see Appendix case study 9 for an example
- Simulation experts need to be contacted each time a "non-standard module" is to be implemented as a new module in the model-building phase; see also chapter 7.6.1 Module development.

7.5. Modular DES methodology competence aspects

The tasks for creating a discrete event simulation model of a system require knowledge. However, the knowledge needed is not primarily knowledge about simulation anymore, but rather knowledge about the system that is to be modeled. While utilizing the traditional DES methodologies, described in chapter 3.4 Classical Discrete event simulation Project Methodology, a knowledge creation process is required. Either the DES-expert has to teach the system expert about DES, or the system expert has to teach the DES-expert about the specific system to be modeled in order to be able to create a sound DES model of the specific system. This is also described by Bley et al (2000), where they point out that a problematic situation arises when the simulation expert needs to understand the real world system in order to make a model out of it; see Figure 23. Nonaka (1994) calls this type of knowledge creation socialization. Mastering socialization requires experience. Socialization is further described in chapter 5.3.1 Socialization.

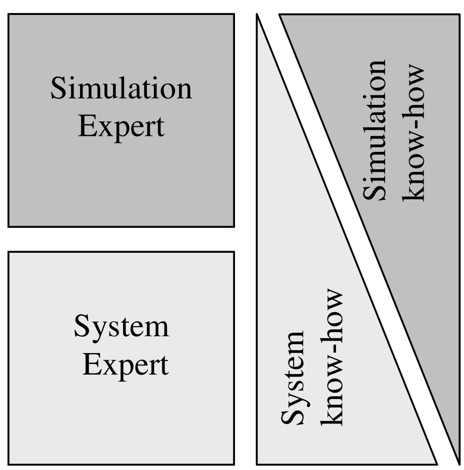

Figure 23 System knowledge versus simulation knowledge, modified from Bley et al (2000).

When using the proposed modular DES methodology, the simulation expert does not have to understand the real world system, since the one who actually has the system knowledge will be the one building the model, i.e. not necessarily the simulation expert. To be able to handle *all aspects* of the modular discrete event simulation methodology, both module building and model creation, a person needs to be as skilled in the module supportive software as in any other DES software, such as QUEST, Automod or WITNESS. However, with a modular approach only one or two people in large companies need this competence level. They will develop the modules, while all the other employees including sales personnel only have to have the basic simulation skills to build a model out of the pre-defined modules. Even less knowledge is required to run a simulation model.

According to the models used for vocational knowledge and learning described in Nordell et al. (2003), this modular simulation methodology will use some of the simulation expert's explicit and tacit knowledge in the field of Discrete event simulation to build the modules. Consequently, the software module representation of the real module can be used by the simulation user without any demands on understanding the internal structure of the module. In other words, the simulation expert's knowledge will be embedded into the module, which simplifies and lessens the demands on knowledge for the simulation user.
A continuous striving towards converting tacit knowledge to explicit knowledge is desired. However, this is not an easy task, since tacit knowledge is "Unutterable and Unarticulated." But the modular approach of simulating manufacturing systems simplifies the conversion to a large extent and uses phenomena from Taylor's (1911) division of labor theories (see also chapter 5.5 Division of labor). Table 16 below gives the relations between tacit and explicit knowledge, modified from Nonaka (1994) and Gustafsson (1999).

Table 16 Matrix Model of the Different Aspects of Vocational Knowledge.

<table>
<tr><th rowspan="3" colspan="2">Vocational Knowledge model</th><th colspan="4">Theoretical knowledge</th></tr>
<tr><th colspan="2">Tacit knowledge</th><th colspan="2">Explicit knowledge</th></tr>
<tr><th>Unutterable knowledge</th><th>Unarticulated knowledge</th><th>Propositional knowledge</th><th>Scientific knowledge</th></tr>
<tr><td rowspan="2">Practical Knowledge</td><td>Practical skill (Needs simpler instructions)</td><td></td><td></td><td>C</td><td></td></tr>
<tr><td>Acquaintance (Needs plenty of experience)</td><td></td><td>A</td><td>B</td><td></td></tr>
</table>

This figure can be used to explain how the knowledge is transformed from tacit to explicit. When the simulation expert is formulating the modules from his mind into the computer (from A to B), the knowledge will change from tacit to explicit on the acquaintance level. Then the simulation software package architecture does the rest of the job by using the modular approach. The explicit knowledge is transferred from acquaintance to practical skill (from B to C), which can then be used by the simulation users with less experience. Traditional simulation software packages only make the transformation from A to B. The simulation user is thus left at the acquaintance level of propositional knowledge in such a system. It takes several months of practice to learn how to use traditional simulation software packages. However, the traditional packages can be used with tailor-made user interfaces to enable the same kind of modularity as in the Visual Components software package. Tailor-made user interfaces are a common solution for traditional simulation packages, but the reusability, parameterization and modularity are in this case much more limited than in the proposed methodology, since each and every new model will require another tailor-made interface. Three subsections following describe the skills and the level of knowledge needed for each type of user in the proposed modular approach.

7.5.1. Simulation specialist

In order to build modules out of nothing, the specialist skills are at about the same level as when using traditional simulation software, such as Extend, WITNESS, QUEST, Automod, ED, etc. The simulation specialist remains the same person as before when it comes to discrete event simulation model building, but instead of building the complete model, the specialists only creates the modules and enables specific input data to be put in later by the simulation user (system expert). The simulation specialist should have the following skills:

- Advanced Computing
- Advanced Programming
- General CAD
- Advanced mathematical skills in terms of statistics and probability.

Lead-time for skill development for a non simulation specialist is long, approximately six months. Typical users are module designers and simulation specialists. They belong to box “A” in the Vocational knowledge model, see Table 16.

7.5.2. Simulation user

In order to build simulation models out of the predefined modules made by a specialist, the simulation user needs to be aware of what impact the different modules have on the system. Moreover, general system knowledge is needed, in the present case, in the form of knowledge about manufacturing systems. The simulation user was previously the client in a traditional discrete event simulation project. The simulation user (client) is also most often the one possessing specific knowledge on the system to be modeled. The simulation user should have the following skills:

- General computing
- General production system
- General statistics.

Lead-time for skill development for a non-simulation user is short, approximately a few days. Typical users are sales personnel, system builders, plant designers, system integrators and continuous improvement personnel. They belong to box “C” in the vocational knowledge model, see Table 16.

7.5.3. Simulation observer

In order to watch and run the simulation models made by the simulation user on the basis of the ready-made modules, the simulation observer does not have to have any skills at all beforehand, except for being able to handle a computer for normal work activities.

The lead-time for skill development for a non simulation observer is very short, approximately five minutes. Typical users are people who may be interested in the function of the system, especially managers and operators. These belong to box “C” in the vocational knowledge model, see Table 16.

7.6. Simulation expert situations

When using the proposed methodology for modular discrete event simulation, the simulation expert has to put more effort into preparation work, since most of the modules have to be pre-constructed, and also validated and verified before a simulation project can utilize them. Other roles for the simulation expert are described below.

7.6.1. Module development

Module development can be found in at least two types of actions. The traditional case in discrete event simulation is when the *real-word module exists first* and needs to be modeled as a module in the DES software. In this case the real-world module developer might need to specify the functionality for the DES module developer (simulation expert).

The other case is a bit more proactive and occurs when a real-world module developer (see chapter 7.7.3 “Real world” module developers for the real-world module developer) utilizes the simulation expert in order to test and form a new module with new and desired functions. The functionality can then be tested in a full-scale manufacturing context without even existing in the real world. In this way the modular discrete event simulation methodology can be used to test and vet new modules for a possible realization into real-world modules. In this case the *discrete event simulation module exists first*.

7.6.2. Special purpose module

In most cases when modeling a manufacturing system there are specific solutions required at one or a few places. This is also the case when it comes to the modular discrete event simulation methodology. A special purpose module will be needed now and then. If it is likely to be reused, it can be included among the standard modules. However, in some cases a module will be used once only and for this specific module, the methodology employed will be equal to the Classical Discrete event simulation Project Methodology discussed in chapter 3.4.

7.6.3. Extra features in an already existing module

A similar approach to the one described in the previous section might be needed if there is a module which almost fits into the description of functionality requirements and parameters available. The simulation expert may then have to make a slight change in the standard module functionality in order to meet the specifications desired of the module functionality.

7.7. Simulation user situations

The user's role will mainly be to combine predefined modules, which the simulation expert has made, and then to "fill in the blanks" for specific purposes, such as lead-times, MTTR, MTBF, cost of equipment, etc. The following three situations are examples where the simulation user is active.

7.7.1. Sales personnel

The proposed modular discrete event simulation methodology is particularly valuable when a system is to be displayed to a customer. The methodology enables manufacturing system builders to send a salesperson to the customer and then build a great deal of the model together with the customer. Since the learning curve for this methodology is much steeper than for the classical discrete event methodology, customers will be able to build their own manufacturing systems after a short time. Sales personnel need to be familiar with the limitations of the modules and the contents of the modular library.

7.7.2. Production engineers

The production engineer's purpose in using discrete event simulation is not altered by the proposed methodology, but the usage is simplified with increased impact on results. For example, capacity, space on the shop floor, routing, priorities and order of machines can be examined easier and faster. Reconfigurations can also be handled more easily. For instance, it is easier to test the planned production for forthcoming weeks in the discrete event simulation environment and preventive maintenance activities can be scheduled more easily into the right time periods to have less impact on production output.

7.7.3. “Real world” module developers

Another situation where the proposed modular discrete event simulation methodology is valuable is when new modules for manufacturing systems are to be developed. The modules can then be pre-made by the real world module developer in cooperation with the discrete event simulation specialist. The role of specialist in this case is described in section 7.6.1 Module development. The module and its desired functionality can then be tested in a model where already existing, verified and validated modules interact with the new one. This will enable testing and evaluation of new modules in more valid contexts than before. It is thus possible to find out more about the system before it is actually produced. It can also be used as a base when formulating the functionality and part specifications that the real world module should consist of.

7.8. Simulation observer situations

The user and the observer can in many cases be one and the same person. As the person who builds the model is supposed to be very familiar with the manufacturing system at hand, it will be of interest for this person to know the results of the model built. However, an observer does not have to have any knowledge on discrete event simulation in order to understand the model, since it will be represented in a 3D environment and by output data. Below there are two cases where the observer and the user are not the same persons.

7.8.1. Management

Manufacturing plant management is one of the parties in most discrete event simulation models created. This is also the case when using the modular discrete event simulation methodology presented. Typical interest from a management perspective can be:

- What solution is most profitable under current circumstances?
- Is the model a valid representation of our manufacturing system?
- Which alternative is the best investment for our manufacturing system if we want to increase our capacity to meet customer demands, also taking future flexibility needs into account?

These kinds of questions will be answered by merely looking at the output data and the model while it is running.

7.8.2. Customer buying a manufacturing system

Another observer situation can occur when there is a customer who is looking for a manufacturing system with specific requirements. Then the modular discrete event simulation methodology can contribute with easy access to numerous accurate DES models showing different scenarios fulfilling the customer requirements. This situation would be the *customer viewpoint* when sitting on the other end of the table from the salesperson described in chapter 7.7.1 Sales personnel.

7.9. Lead-time benefits

This chapter will clarify the lead-time benefits, which can be achieved by using the proposed modular discrete event simulation methodology.

7.9.1. Overview of lead-time benefits

The proposed methodology aims at reducing lead-time for conducting a DES project; at the same time as it increases the accuracy of the model including input and output data. It also aims at decreasing the rework of already conducted activities such as reuse of pre-made modules, reuse of pre-typed input data, automatic generation of BOM, up- and down-loadable PLC programs for complete manufacturing lines. Figure 24 below shows a presumably decreasing lead-time due to the utilization of the proposed modular DES methodology. The validation of Figure 24 is clarified in chapter 8.5 Validation of research results, and also discussed in chapter 10 Future Research.

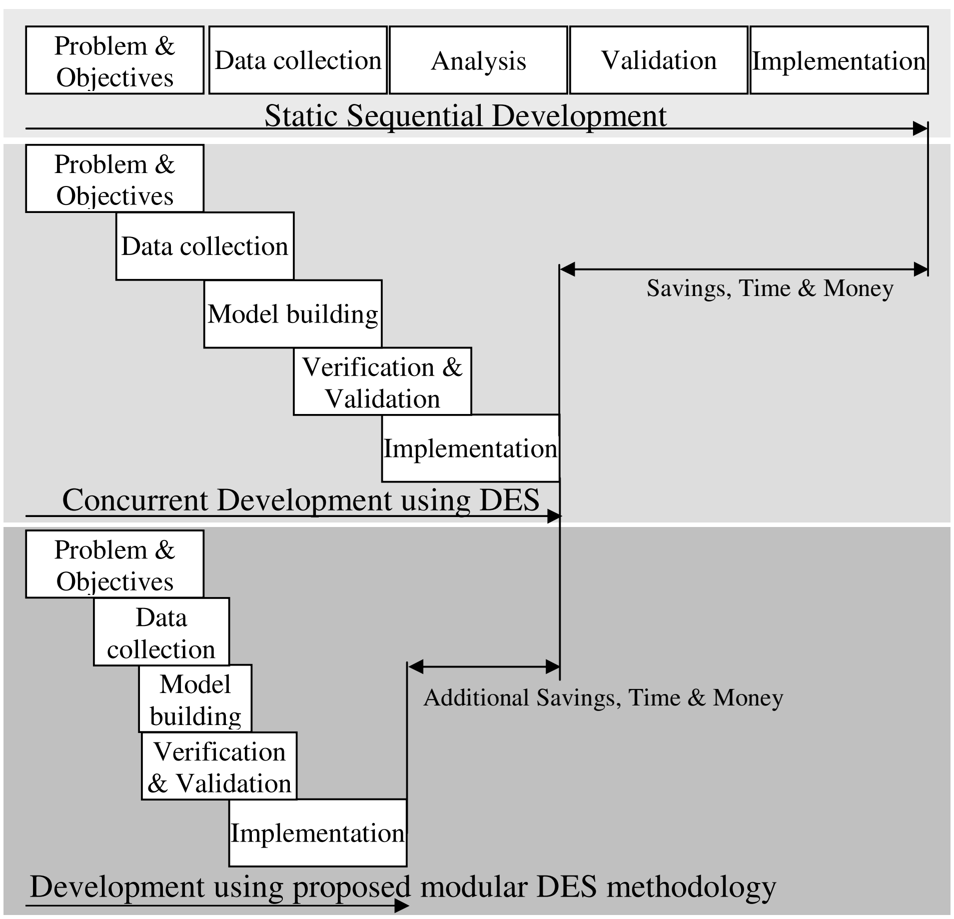

Figure 24 Schematic lead-time comparison between Static Sequential development, concurrent development using DES and development using the proposed modular DES methodology adapted and modified from Heilala (2005).

The specific lead-time benefits from using modular discrete event simulation of manufacturing systems are numerous. Figure 25 shows some of the activities where lead-time reduction events can be achieved through the use of modular discrete event simulation of manufacturing systems and the modular discrete event simulation methodology.

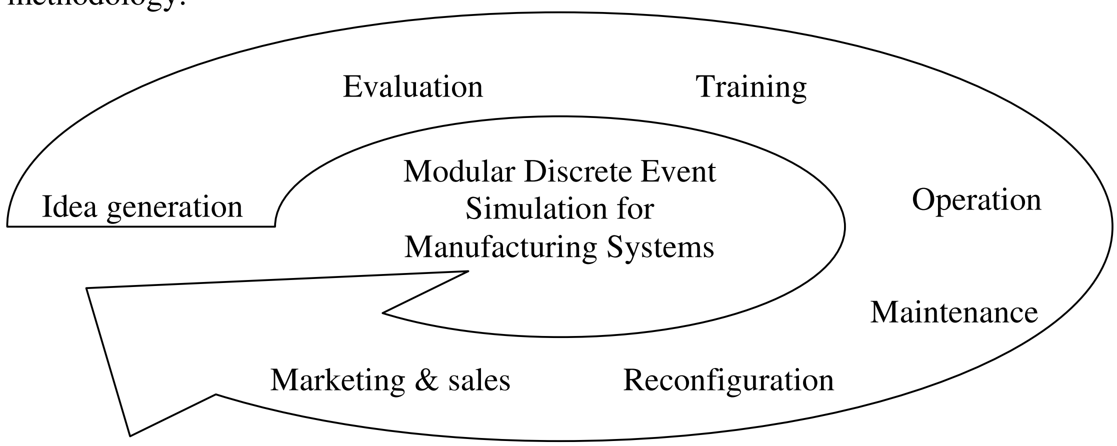

Figure 25 Some activities where lead-time reduction can be achieved by using modular discrete event simulation.

7.9.2. Idea generation

While designing manufacturing systems, modular discrete event simulation can be used as a "brainstorming tool" where, for example, the customer and the line builder salesperson can share, build, and discuss different layouts and concepts for the manufacturing system in order to prevent expensive mistakes. This is particularly useful in early offering stages when no real system exists. Questions clarified and analyzed in this phase could be:

- Does the production unit fit into our proposed building?
- What viable possibilities do we have?
- What is our approximate capacity?

7.9.3. Evaluation

Being able to compare and evaluate pros and cons of the different alternatives is a lead-time reducer (Johansson 2002). Questions clarified and analyzed in this phase could be:

- Are two parallel lines more productive than a single line with higher capacity?
- Which of our alternatives have the best dynamic behavior in terms of breakdowns, handling disturbances, etc.?
- How much will output be affected if we add/remove one machine?

7.9.4. Training

Having the actual system in a Modular discrete event simulation environment also affords enticing possibilities to train and learn how the dynamics of the specified system works. This opportunity is valuable for production engineers at early development stages. Since the logic within the system can also be simulated, control engineers can use the Modular discrete event simulation platform for training activities in terms of programming and interacting with the proposed system, even though the system may not exist yet. Questions clarified and analyzed in this phase could be:

- How does the overall system react if X happens?
- Will there be a deadlock if X and/or Y happen?
- What will happen if this PLC is set to do X?

7.9.5. Operation

For controlling the operational phase of the system this kind of Modular discrete event simulation model will prove to be most valuable if it serves as a “master” of the real system (Johansson 2002). In the same manner as CAD drawings are masters of the product, Modular discrete event simulation models should master the process. This would lead to offline bottleneck detection, capacity planning and continuous improvement work. Questions clarified and analyzed in this phase could be:

- Can our current production units handle an order intake increase of X%?
- Will we be able to deliver next week’s/month’s/quarter’s orders on time?
- Which investment will yield the highest output for our production?

7.9.6. Maintenance

Lead-time reduction for maintenance activities is also achieved through possibilities of scheduling maintenance more accurately by using the Modular discrete event simulation model. Lack of maintenance can be simulated in the Modular discrete event simulation model and recalculated to economical values and then related to the cost of preventive maintenance. Questions clarified and analyzed in this phase could be:

- What are the pros and cons of scheduling preventive maintenance on our bottleneck machine?
- What would the increased production output be if we could reduce failures on this machine by X%?
- What is the factory output effect of X-minutes failure on this machine?

7.9.7. Marketing and sales

Lead-times for marketing and sales will be shorter and more accurate. It will thus be possible to specify delivery dates and maximum order intake more accurately thanks to the modular discrete event simulation model. The modular discrete event simulation model could also be used for demonstrations at customer sites or sent to customers via the Web. The tracking of goods and the visualization of this in the modular discrete event simulation model are also possible. Questions clarified and analyzed in this phase could be:

- When can we deliver an order of X products to this customer?
- How does a customer react on our production philosophy?
- Customer questions, such as
  - What is the current status of my order?
  - When will it be delivered?
  - Can it be delivered in incremental shipments?
  - Can you reasonably grant me a price reduction of X% if I agree to a delivery delay of Y days?

7.9.8. Reconfiguration

Large lead-time reductions can also be found when New Product Introduction (NPI) is to take place in an already existing manufacturing system. The modular discrete event simulation model can then be used for testing various possible scenarios for reconfiguration of the system, product mix and batching, additional capacity requirements, etc. Since the modular discrete event simulation model already exists, only minor changes in layout and products will be needed in order to find a new solution for future manufacturing and reusability of the model for the next generation of products (see paper 6, Bagiu and Johansson 2004). Questions clarified and analyzed in this phase could be:

- How can we balance our line if we introduce a mix of these products?
- What will the capacity of our production be with this product mix?
- What changes are needed in order to produce this new product in our existing line?

7.9.9. Potential lead-time setbacks

The optimal scenario would be to only have positive influence on lead-times and always decrease them for faster and more accurate results. However, this is of course not the real world scenario. The modular discrete event simulation methodology presented can also be inappropriate to use. In cases of a simulation expert familiar with a traditional discrete event simulation package building a model, it would be highly unlikely that the lead-time benefits will be generated by using the proposed methodology. Arguments for using the traditional approach would be:

- Familiarity with the expert oriented software is already high
- The flexibility in a expert oriented discrete event simulation package is higher than in a modular one, providing additional functionality over the presented approach and thereby simplifying the work for a discrete event simulation expert who is building the model
- Another potential lead-time setback could be a scenario where a non simulation expert requires iterative consultations with the simulation expert in order to create additional functionality in an existing module, modify an existing module, or even create a totally new module in order to achieve the desired functionality.

7.10. Summary of modular DES for manufacturing systems

The present thesis, including appended papers and case studies, explains advantages, requirements and setbacks on modular discrete event simulation for manufacturing systems. Since manufacturing systems tend to contain increased modularity, following the visions described in chapter 1.2 Background, and increased support functions for manufacturing data and surveillance management (Ingemansson 2004), there will be an increased pressure on reconfiguration and reuse of equipment (NRC 1998, IVA 2000, and Manufuture 2003). In sum, manufacturing systems have the following advantages and requirements when it comes to the utilization of modular discrete event simulation (some of the listed advantages are not new, but strengthened):

- The use of modular DES methodology can give (See papers 5 and 7, Johansson et al. 2004, Johansson et al 2004);
    - Knowledge division
    - Increased possibilities for parallel work
    - Reuse of data
    - Reuse of modules
    - Potentially numerous lead-time benefits
- And in turn also requires;
    - Time and effort
    - Willingness of employees to use the methodology
    - Gathering of input data at least once per module
    - At least one simulation expert in order to create the modules
    - Decision support on when, by whom, and why to use discrete event simulation in each specific case

- The reuse of data can give (see papers 4 and 7, Johansson et al 2003, Johansson et al 2004);
    - Increased accuracy in early phases of the system performance and characteristics
    - Sounder requirements specification of the manufacturing system
    - Reuse of modules
    - Potentially numerous lead-time benefits
- And in turn also requires;

    - Time and effort
    - Willingness of employees to reuse the data
    - Structure and order on the documentation of simulation data and projects

- The reuse of DES modules can give (see papers 3, 4 and 7, Johansson et al 2002, Johansson et al 2003, and Johansson et al 2004);
    - Sounder requirement specifications of the manufacturing system
    - Increased accuracy in early phases of the system performance and characteristics
    - Reuse of data
    - Potentially numerous lead-time benefits
    - Increased possibilities for parallel work
- And in turn also requires;
    - Time and effort
    - Willingness of employees to reuse the modules
    - Structure and order on the documentation of simulation data and projects

- Knowledge division can give (see paper 7, Johansson et al 2004);
    - Increased possibilities for parallel work
    - Decreased risk for misunderstandings when building DES models
    - Less pressure on key personnel
- And in turn also requires;
    - Time and effort
    - Willingness of the simulation expert to let others use the modules
    - Management influences to create supportive work environment for knowledge division

- Emulation can give (See case 5, Walfridsson and Wertheimer 2005);
    - Increased predictability in early phases of the system performance and characteristics
    - Increased testing possibilities offline
    - Offline programming of the total manufacturing system
- And in turn also requires;
    - Time and effort
    - More detailed and additional efforts on input data

8. Discussion

Relieving bottlenecks yields large benefits (Adrian Murgau 2005)

8.1. Performance improvement for industry

Stevrin (1991) highlights three performance improvers for industrial companies when using discrete event simulation. These three are:

- *Control*, with the ambition to describe
- *Learn*, with the ambition to understand
- *Develop*, with the ambition to change and improve

Theoretically these three aspects make sense. In reality, however, manufacturing industry has access to appropriate data in only 6% of the cases when building simulation models. In other words, guessing, data collection, and/or estimates are used in 94% of the cases. Hence the *controllability* is very low. This is particularly the case when the input data is not collected and the description of a manufacturing system is done without *facts*.

In order to *learn* how the manufacturing system works, *control* needs to be reached first. At a first glance, the present situation is therefore quite remarkable as only the 6 % of the companies that have the data available can truly understand what the situation at hand is like. However, the situation is clearly not as bad as it seems. Most manufacturing systems are probably operated at a mediocre level. Nevertheless, it is quite clear that the possibilities for increasing productivity are fairly large. Hence some improvements are easy to identify and can therefore be achieved at very low costs resulting in payback times around a few months (Johansson and Kinnander 2004).

One way of *learning* how the manufacturing system works is to create a discrete event simulation model of the system. This type of learning is closely connected to the internalization described in chapter 5.3.4 Internalization. The other types of learning can also be used if there are more people involved who can discuss the situation and share their knowledge.

With the modular discrete event simulation methodology, the input data is more accurate since it can be pre-validated and pre-verified on a modular level. This will be profitable only when modules are to be used many times, and this is mostly the case with OEM companies.

The last feature brought up by Stevrin (1991) is development. The development today is mostly based on vague motives in comparison to what can be achieved. Fewer than ten percent of the companies today use discrete event simulation (Eriksson 2005, Savén 1994, SSG 1991). In order to have a valid discrete event simulation model, it is compulsory to go through both "*Control*, with the ambition to describe"-phase and "*Learn*, with the ambition to understand"-phase. In the end "*Develop*, with the ambition to change and improve" is therefore a natural outcome of the use of a discrete event simulation model since both a description (Control) and understanding (Learn) are compulsory steps in order to reach the desired changes and improvements (Develop).

The proposed method sets up a good working environment enabling easy access to these three steps: *Control, Learn,* and *Develop*. This goes especially for OEM companies that design manufacturing systems, such as line builders, machine builders, or system integrators. The strength behind the proposed methodology can thereby be referred back to knowledge and knowledge creation (see chapter 5 Knowledge) where data and information can be stored within the discrete event simulation modules in order to be used by other individuals, so that they can learn how the interaction in the systems affect the system characteristics.

8.2. Comparison with other discrete event simulation methodologies

In chapter 3.6 Previous work on modular discrete event simulation a number of other discrete event simulation methodologies are presented including a summary of their specific characteristics. This section will compare the presented modular discrete event simulation methodology with past methodologies presented by other researchers.

Table 17 shows critical parts requiring fulfillment in order to create the knowledge division prerequisite to building discrete event simulation models in line with the presented modular methodology. The key enablers are "*Division of knowledge*", "*Model creator*", and "*User-friendly modular software support*". All authors listed in Table 17 have addressed the issue of a need for modular libraries and the advantages of having the modules predefined by simulation experts.

Table 17 Author comparisons on modular discrete event simulation modeling.

Author	Division of knowledge	Model creation	Software support
Ball and Love (1992)	Yes	System Expert	No
Bhuskute et al (1992)	Yes	DES Expert	Yes
Meinert et al (1999)	No	DES Expert	No
Son et al (2000)	No	DES Expert	No
Valentin and Verbraeck (2002)	No	DES Expert	No
Randell (2002)	No	DES Expert	No
Heilala (2005)	No	DES Expert	Yes
Proposed Methodology	Yes	System Expert	Yes

Recent trends in discrete event simulation software packages show a strong tendency towards modular libraries. Old software packages, if they are still under development and frequently released, tend to focus on enabling modules and sub-models to be saved separately. Zooming and hierarchical models, i.e. modules in modules in modules etc., are other interesting issues for some simulation vendors, for example Extend.

New discrete event simulation software packages tend to have predefined software architecture which is modular-friendly and with modularity as one of the key enablers together with easy access to 3D objects and user-friendly interfaces. Some of these simulation packages are in line with the proposed methodology and could with a comparatively small effort be utilized together with the proposed modular discrete event simulation methodology. One example of such discrete event simulation software is the Visual Components package 3DCreate, 3DRealize and 3DVideo.

8.3. Flexibility vs modularity and user-friendliness

Ever since the early years of discrete event simulation, the striving towards functionality of the modular type has been discussed (Nance 1995). It can take the form of functional coding, enabling programmers to reuse code. An example from Automod;

```
use R_lathe for 3 minutes
```

Another way of solving the same functionality is to use;

```
get R_lathe
wait for 3 minutes
free R_lathe
```

It can take the form of functional building blocks such as in Extend, for example see Figure 26.

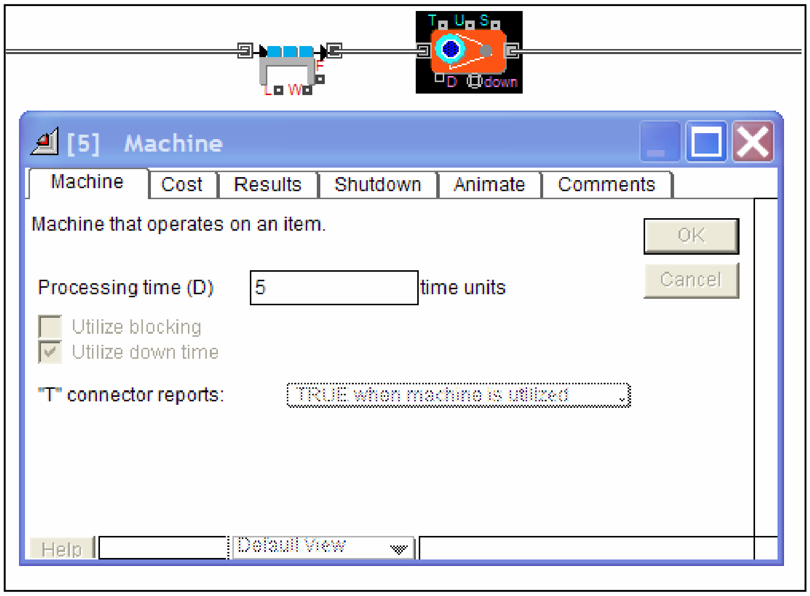

Figure 26 Example of a machine building-block and its attributes in Extend.

This thesis, however, aims at an even more functional view, which is enabling the availability of the desired functions in each module. The module itself is created by a discrete event simulation expert who is capable of pinpointing the actual needs of flexibility for each specific module. However, a tradeoff between flexibility of the module in comparison of the user-friendliness and modularity is always more or less present. Below in Figure 27, an effort is made to show how the influence of the module developer can affect the flexibility needs of a module in comparison with the user-friendliness and modularity. This figure is valid only in the case where the module developer is aware of the flexibility needs of the module, which is the case in the modular methodology, and thereby strengthens the flexibility and desired functionality aspects for the end user.

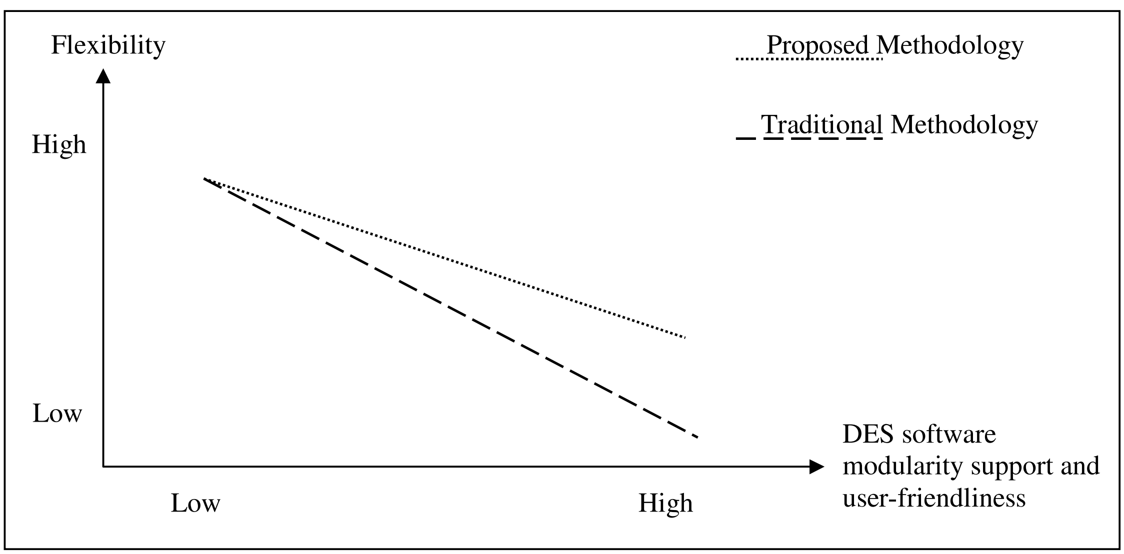

Figure 27 Schematic figure of flexibility vs. DES software modular support and user friendliness, proposed methodology and traditional methodology.

8.4. Making simulation a corporate norm

This thesis has presented a modular discrete event simulation methodology for manufacturing systems. The methodology can generate benefits and lead-time reductions in many lifecycle stages of manufacturing systems. Williams (1996) discusses the use of discrete event simulation as a corporate norm. The methodology presented is well suited to fit such a norm since it is structured, user-friendly, reuses information and data, and is available to everyone. It can be a natural tool for almost any situation that concerns manufacturing system design, operation, sales, reconfiguration, maintenance, scheduling, etc.

8.5. Validation of research results

The validation is aimed at verifying that the developed model for modular discrete event simulation and conclusions drawn on additional lead-time benefits are true.

Considering the complexity of the research on methodology development, a formal validation is hard to perform (Arbnor and Bjerke 1994). The grounds for these difficulties are:

- Theories valid in one system can only be generalized to other systems by means of analogies.
- The desired effects, reduced lead-times and division of labor concerning knowledge content, are difficult to measure. Such studies are difficult to arrange, and would take a long time to perform. Since no real system will be able to conduct both transformations, i.e. one using the proposed method used and one not using the proposed method. Hence, there is no real-life scenario where the actual benefits can be calculated and measured.
- Some of the desired effects, e.g. flexibility, quality, and increased utilization of individual knowledge on discrete event simulation and the specific manufacturing system, are difficult to measure since they are qualitative in nature and therefore hard to quantify objectively.

But in some way the research findings have to be proven valid. The validation concerns the following research results:

- The use of a modular discrete event simulation for manufacturing systems and the proposed modular discrete event simulation methodology, as specified in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems, can reduce time and cost, and enhance quality.
- The real world manufacturing system built according to Papers 5, 6, 7, and case studies 1, 6, 7, and 8 utilizing the modular discrete event simulation methodology, will have higher accessibility to reconfigurability and flexibility, and thus have higher adaptation ability. Validation was, however, not successfully executed in case study 9, which limits the methodology to

manufacturing systems with pre-specified flexibility needs (E.g., such as the ones OEM suppliers of manufacturing equipment can foresee).

According to Arbnor and Bjerke (1994) a set of methods can support the validation of this research. The methods from Arbnor and Bjerke (1994) examine whether the research is:

- Reasonable
- Based on valid theories
- True and possible to use
- Accepted by researchers

The validity is discussed with support mainly from:

- Experience made when developing discrete event simulation *models*
- The results from *case studies* and the development of the results presented in the *papers*
- Reflection on trends and recent developments of discrete event simulation software *vendors* and *users*

8.5.1. Reasonable – Face Validity

"Face validity" (Mihram 1972, cited in Norris 1986), also called "Common sense logical validity" described by Kibbee (1961), is used to check if the research results are valid on the surface, i.e. whether the results seem reasonable. In the present section, face validity will be addressed from two perspectives valid for the present thesis:

1. Achievements when using modular discrete event simulation based on the proposed methodology.
2. Higher accessibility to reconfigurability, flexibility and also adaptability as a result of the adoption of the proposed methodology.

The first issue valid for the first of these perspectives is *time*. The *time* required from one person to perform any work task would be reduced if the number of decisions taken by the person were reduced (Gullander 1999). Consequently, since the modular discrete event simulation approach provides the person with a sort of system template that relieves them from many decisions, it is reasonable to assume that the use of modular discrete event simulation methodology will reduce development time. Furthermore this division of tasks will permit reuse of data. Moreover the system caters for more parallel work, since division of labor is used.

The *cost* of the system is not always directly connected with development time. Other aspects, such as costs in terms of person-months, ramp-up of production, flexibility for NPI, or TPI and TTM (if it is a new manufacturing system and a new product) must also be taken into account. Since the proposed research results show increased flexibility, accuracy, and quality of the manufacturing system by using discrete event simulation, they point to substantial cost reduction for OEM companies of manufacturing equipment that employ the main contribution from this thesis. However, the greatest potential that the author sees for the manufacturing system is in *decision support* in early stages of the process.

The *quality* of the results by using modular discrete event simulation depends on the real-world system properties when large parts of the development project have already been completed. The actual properties of the discrete event simulation models will be defined by discrete event simulation *experts* for each module. However, it will be system users and the skilled persons for each specific manufacturing system who will specify the specific parameters for each unique model combined by modules. This approach enables:

- *Expert knowledge* on *discrete event simulation* to be utilized in its native environment to specify parametric modules characteristics.
- *Expert knowledge* on each specific *manufacturing system* to be utilized in its native environment to specify which module and which data for each module.

This sets the right task for the right person and gives high probability for reaching high quality in each case when using modular discrete event simulation for manufacturing systems.

The second perspective on face validity concerns accessibility. The present investigation suggests that it is reasonable to assume that high reconfigurability, flexibility and adaptability are more easily attainable when utilizing the modular discrete event simulation approach since:

- The ideas are in line with holonic, agile, and flexible manufacturing systems, increasing flexibility.
- The connection and reuse of data decreases processing time while reconfiguring systems.
- The availability of PLC-Emulation enables offline programming of manufacturing systems. As a result, parallel work increases, and ramp-up/NPI and TPI times for manufacturing systems are reduced.

8.5.2. Based on valid theories – Internal Validity

Internal validity as described by Schellenberger and Keyt (1983) aims at validating the research by looking at its origin and base of already validated theories. It also comprises a validation through looking at the *logical sequence* of *connecting research problems*, the *research questions*, and *the results*.

The theoretical bases used are described in the frame of reference chapters: 3 Discrete Event Simulation, 4 Manufacturing Systems and 5 Knowledge. These chapters cover several well-known and accepted theories on discrete event simulation methodology, manufacturing systems, and knowledge respectively. However, the research is not only based on theories, but also on experience and conclusions from the case studies and papers on discrete event simulation on various perspectives, such as user, interfaces, methodology, emulation, etc. Thus, it is reasonable to assume that the results from the research are valid in relation to internal logic.

8.5.3. True and possible to use –Applicability and Truth

The *truth* examines if the theoretical and practical results from the research can be used to explain real phenomena. However, in the case of validation when validating a non-repeatable phenomenon, it is more feasible to use the applicability validation. *Applicability* means that the application of the results increases the probability of successful problem solving. It does not necessarily lead to success every time, but over a period of time it will yield better results than if not used.

Many case studies carried out between 2000 and 2005 in which the author has participated, have focused on building discrete event simulation models by using the classical discrete event simulation methodology described by Banks et al (2004) and in chapter 3 Discrete Event Simulation. The industrial participants in these case studies (see Axelsson and Hjelte 2003, Ström and Turesson 2005, Bertilsson and Holmberg 2005 etc…) have requested parametric interfaces to the models in order to be able to use the models themselves after the case study is done. This indicates that there is a need for more user-friendly interfaces in discrete event simulation software. The knowledge needed to handle discrete event simulation software has traditionally been considered expert knowledge and has taken a long time to learn. Hence, there is obviously a need for a division of labor. Both specific knowledge on each unique *manufacturing system*, and *discrete event simulation* knowledge are needed.

The applicability of modular discrete event simulation methodology can also clearly be seen when looking at the *software development trends* at discrete event *simulation software vendors*. For instance, Brooks Automation has recently released hierarchical modularity for the discrete event simulation package Automod (Rohrer 2003). Sub-models can be stored separately and then be combined to larger models, or be run on their own. Automod also has an OPC interface to utilize Emulation of PLC (Walfridsson and Wertheimer 2005,). Similar experiments have been made utilizing QUEST from Delmia. 3DCreate, 3DRealize, 3DVideo from Visual Components. Visual Components is a fairly new software package on the market, which handles modularity in line with the proposed methodology for modular discrete event simulation. Also, ED, FlexSim and Extend have beneficial approaches on modularity, enabling effective use of the proposed methodology for modular discrete event simulation.

In addition, the applicability can be seen at *companies that use discrete event simulation*. Apparently, not only user interfaces are created. Further steps are taken towards libraries of parametric modules. For example, one large Swedish truck manufacturer uses Extend with libraries of predefined sub-models as modules, another large company in Sweden uses base models of manufacturing lines with parametric interfaces in Excel, and a third one uses a QUEST library with machines modeled in 3D with logic and parameters available; some other OEM companies uses Visual Components suite of 3DCreate, 3DRealize, 3DVideo. Recently one additional parametric virtual development software was launched, called Demo3D. See also Appendix, case studies 6, 7, 8, and 9 for more practical examples. The above software vendors and company users of discrete event simulation will benefit from using the proposed methodology. Since they already have the prerequisites, it is not as large a change for them to utilize the proposed modular discrete event simulation methodology, as it would be for a non-initialized company. These companies are in the forefront of discrete event simulation usage, and many other companies, approximately 94% of the companies investigated (see paper 4, Johansson et al 2003), are lagging behind. One consequence of this is that it is not yet possible to fully determine the applicability of the research results.

8.5.4. Accepted by researchers - Acceptance

The final validation method investigates if other researchers accept the theories used in this research, and that professionals are willing to use tools based on these theories.

Academic acceptance was achieved by:

- Discussing the results with fellow researchers in the area of discrete event simulation.
- Acceptance of papers at renowned conferences with thorough review procedures (E.g. Wintersimulation Conference, INCOM, and CIRP).
- Close comparison with other researchers' work shows an agreement on central issues, suggesting that the results are acceptable.

Industrial acceptance was achieved by:

- Discussing the trends on discrete event simulation development with software vendors.
- Having ideas accepted and included in forthcoming releases of software (E.g Statistics on Visual Components Software suit, and specific user conferences on AUTOMOD, Extend, ED etc…).
- Regarding future use of the proposed methodology for modular discrete event simulation, only the future can tell if the results will indeed be accepted or not. However some companies do already work in line with the presented methodology for modular discrete event simulation; see case studies 6, 7 and 8 for examples.

8.5.5. Validation through case studies

The case studies 6, 7, 8 and 9 (See Appendix) were made in order to validate the functionality of the proposed methodology for modular discrete event simulation.

Case study 6 covers module development in the modular DES methodology and validates simulation expert situations, which are further described in 7.6 Simulation expert situations.

Case studies 7, 8 and 9 cover model building and analysis phases in the modular DES methodology and validate simulation user and simulation observer situations which are further described in 7.7 Simulation user situations and 7.8 Simulation observer situations.

Cases 6, 7 and 8 do have a positive outcome for the methodology and validate it in the observed aspects; however case study 9 did not successfully validate the methodology, which limits the use of the results to fit only OEM suppliers of manufacturing systems and companies interested in such. Further positive aspects may be available in other fields; however, they are unknown for now.

9. Conclusion

The primary objective of this thesis has been to increase the efficiency of the development process for manufacturing environments by effective use of discrete event simulation (Pär Klingstam 2001)

9.1. Introduction to conclusion

In this chapter the conclusions and contributions of the research building this thesis are presented. The purpose fulfillment will be discussed. The research questions will be answered and commented on. Finally a summary of the results from the thesis will be presented.

9.2. Purpose fulfillment

In chapter 1.2.2 Purpose the main purpose of this thesis was stated and described. The purpose was to:

> "…present a methodology for modular discrete event simulation, which can be used to increase the benefits in terms of cost, lead-times, investments, and knowledge when designing, implementing, and using reconfigurable modular manufacturing systems. The thesis focuses mainly on how discrete event simulation can be utilized by companies which are OEM suppliers of manufacturing equipment. However, the presented methodology in general is generic and can be used on any system. But it will lack the advantages gained from modularity in other business areas, and in these cases become more equal to the traditional discrete event simulation methodology."

The methodology is presented in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems. It has been verified in case studies (6-8) that the methodology is beneficial for OEM suppliers of manufacturing systems and equipment. It has also been shown that the methodology is not suited well for non modularized manufacturing systems in case study 9, the validation failed due to the complexity present on a higher level than the modularity of the manufacturing equipment modeled. This made the model building in case study 9 to require a simulation expert to perform the manufacturing system related tasks instead of the person with the manufacturing system knowledge.

The modular discrete event simulation methodology presented in this thesis is suited for OEM suppliers of manufacturing equipment, which limits the general contribution of the research results from the thesis to manufacturing systems down to OEM suppliers of manufacturing equipment. However, based on a calculation of FlexLinks market shares, it is sound to estimate the investments in such manufacturing system equipment to over 1000 M€ yearly in Europe only. Lead-time reductions in the industrialization phase of these systems would surely yield quite a bag of profit…

Thus, the purpose of this thesis has been fulfilled; however the results are limited to include only OEM suppliers of manufacturing systems.

9.3. Research objectives fulfillment

The two research objectives stated in chapter 1.3 Research objectives were:

The primary research objective in this thesis is to develop a *modular discrete event simulation methodology* suitable for (1) *OEM suppliers of manufacturing systems*, which is (2) *easy to use*, and supports (3) *reuse of data* and (4) *increases productivity development* both for the (5) *simulation* and (6) *real world* manufacturing system, i.e. modular discrete event simulation for manufacturing systems.

The first objective is fulfilled (and verified in case study 5-9), thus:

(1) The presented modular discrete event simulation methodology is used by OEM suppliers of manufacturing systems.
(2) The proposed methodology is easy to use
(3) The proposed methodology reuses data, since a module only has to be created once, and after that it can be reused many times with very low effort.
(4) The proposed methodology *can* increase productivity development (E.g. in case studies 6-8, however not in 9.).
(5) Model building once the modules are created has far shorter lead-time for the proposed methodology compared to the traditional ones used in discrete event simulation projects.
(6) And finally, the general benefit from developing accurate discrete event simulation models faster fives benefits for the total lead time of the real world manufacturing system development as well.

The secondary research objective is to show numerous examples utilizing discrete event simulation for *manufacturing systems* as a *productivity enhancer* in order to *clarify* the *potentials* of the technology, as well as to *clarify*, *analyze* and *explain* difficulties while using discrete event simulation.

The second objective is fulfilled throughout the thesis, thus:

Case studies and papers presents how discrete event simulation was used in a wide variety of approaches as a decision support tool. Findings where the modular discrete event simulation methodology would have been handy to use was also identified (E.g. Paper 3 and Paper 5), it was however not used, since it was not developed by the time being of that particular model building phase.

9.4. Research questions fulfillment

The research questions were established in chapter 1.4. This chapter will follow up on these questions. The first research question to be examined was:

RQ1. How could lead-times for development and analysis of manufacturing systems be affected by the use of discrete event simulation?

As discrete event simulation does not actually decrease the lead-time in itself, it requires additional efforts to implement the findings from the discrete event simulation analysis. Integration aspects outlined in this thesis, such as offline programming of the complete manufacturing system, automatic generation of the Bill of Material, and, last but not least, the reuse of data during the development processes between different projects and also within the same projects when using modular discrete event simulation, has potential for lead-time reduction. Chapter 7.9 Lead-time benefits addresses lead-time benefits while utilizing the modular discrete event simulation methodology for manufacturing systems. Hence, a short answer to research question one is: Lead-times can be *decreased* and productivity can be *increased* in many operations when modular discrete event simulation for manufacturing systems is used. In addition papers 1, 2, 3 and 5 show lead-time benefits while utilizing discrete event simulation for development and analysis of manufacturing systems. This has also been verified in a number of case studies, see for example paper 6 (Bagiu and Johansson 2004) and case studies 6, 7, and 8 (in appendix). Unfortunately, it is extremely difficult to estimate how much the lead-time will decrease and the productivity increase in each specific case. However, to recall what was said earlier in this section, discrete event simulation in itself is not a productivity enhancer. This implies that building a simulation model increases the lead-time of a development project rather than decreasing it at first. Hence a decision whether to build a model or not is needed. The presented methodology does however have shorter lead-times during the model building phases than traditional discrete event simulation methodologies in some cases. In more specific, OEM suppliers of manufacturing equipment tend to benefit the most, since they also do tend to have a modular base for their realworld system architecture. And on the other hand, not as profitable for one of a kind modelbuilding of more traditional (read "tailor-made") manufacturing systems.

Thus, the first research question has been sufficiently answered from a scientific point of view, although the answer is hard to quantify and measure, some examples of lead-time reduction efforts has been made. Further research and validation could strengthen the results, see chapter 10 Future Research.

RQ2. How should a methodology for conducting a simulation project with modular discrete event simulation be outlined in order to be effective and user-friendly?

A methodology which is effective and user-friendly should support reuse of already typed data, provide the user with tasks appropriate to the needed knowledge for that assigned work (I.e. the simulation expert should handle complex simulation issues, the specific manufacturing system expert should handle manufacturing system specific issues, and management should be able to use the results/conclusions for decision support.). As the traditional discrete event simulation methodology requires at least expert knowledge in two fields simultaneously, *discrete event simulation* and the studied *manufacturing system*, the proposed methodology aims at disconnecting these two fields. The proposed methodology is described in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems. A short answer to RQ2 is therefore that a methodology for conducting a simulation project with modular discrete event simulation can be outlined as described in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems. The descriptions include an outline of the discrete event simulation expert's tasks in module creation, and the user perspective of utilizing these modules for model creation. The user perspective involves the combination of modules and the addition specific input data for each specific situation. Examples for validation of the presented methodology can be found in appendix Cases 6, 7, 8, and 9.

Thus, the second research question has been sufficiently answered from a scientific point of view, although further research and validation could strengthen the results, see chapter 10 Future Research.

RQ3. In what way does modular discrete event simulation methodology affect the knowledge requirements on the practitioners compared to traditional discrete event simulation methodology?

The proposed methodology aims at dividing the required knowledge into two separate events, on one hand discrete event simulation and on the other hand the studied manufacturing system. These events and its circumstances are described in chapter 7.5 Modular DES methodology competence aspects. The description used refers to both modern interpretations of knowledge creation as described by Nonaka, and Taylor's scientific management with division of labor from 1911. The results includes both the modes of knowledge creation when the discrete event simulation expert adds knowledge into the modules (Externalization), and the systems expert utilizes the modules and adds the systems perspective to form the full model of the manufacturing system. The discrete event simulation model can then be used to create knowledge using it through *Internalization.*

Thus, the third question has been sufficiently answered from a scientific point of view.

9.5. Summary of conclusions

This thesis indicates that:

1. Modular manufacturing systems will become increasingly utilized by industry in order to stay competitive in the future market (paper 5 Johansson et al. 2004, Paper 6 Bagiu and Johansson 2004, Paper 7 Johansson et al 2004, NRC 1998, IVA 2000, and Manufuture 2003), which sets the stage for a modular discrete event simulation methodology, following the modular structure from the real world stystems..

2. One way to facilitate responses for the ever-shortening lead-times is to develop discrete event simulation towards modularity (paper 1 Johansson and Grünberg 2001, Paper 2 Johansson et al 2002, paper 3 Johansson and Kaiser 2002, paper 4 Johansson et al 2003). Modular DES libraries at several manufacturing companies and the DES software development towards modularity (E.g. Visual Components software suite, and Demo3D) are indicators on this trend; additionally the proposed modular discrete event simulation methodology supports this development.

3. Discrete event simulation needs to become more easily accessible. In order to achieve this accessibility it needs to become less expert-oriented, enabling utilization of its true potential. This will increase the speed on the diffusion of DES into industry as well (paper 5 Johansson et al. 2004, Paper 7 Johansson et al 2004, Eriksson 2005). This thesis serves as a good basis for modular discrete event simulation mode building, supporting the initiation of such events in companies; especially OEM suppliers of manufacturing equipment, since their reuse of modules are more frequent.

These three main contributions formalize the conclusion of this thesis:

Modular discrete event simulation as described in this thesis supports modular manufacturing systems, increases the *user-friendliness* of discrete event simulation, enabling the *manufacturing system expert* to be more active in the model-building phase, increases *accuracy* and *availability* of *correct input data*, and *decreases lead-times* in sales & marketing, designing, training, operations, maintenance, and reconfiguration, thus enabling *enhancement of* the modular manufacturing system *performance* at large.

It has been shown that virtual development of manufacturing systems is eased by utilizing the presented modular discrete event simulation methodology as one aspect of the model building. In specific, the presented methodology is most beneficial when utilized for OEM suppliers of manufacturing equipment, and less beneficial for more complex one-of-a-kind manufacturing solutions.

10. Future Research

The trend towards ever-shorter product life cycles produces a need to find tools and methods of working for integrated product and manufacturing process development (Bertil Gustafsson 2002)

10.1. Introduction to future research

The results from this thesis contribute and move the research forward to some extent. Equally important for scientific progress are discoveries of unexplored ground; discoveries that open up new research opportunities. An unanswered question, which will remain, is: Is there an end? Or will new research areas always appear? This small chapter will briefly look into the area of possible future research efforts, which could *validate, strengthen,* and/or *improve* the research on discrete event simulation dealt with in this thesis. The discrete event simulation impact on manufacturing systems industry in the future will also be discussed briefly.

10.2. Additional validation for increased research quality

More thorough validations of the proposed modular DES methodology in real world cases would improve the quality of the research building this thesis.

The validity of the proposed lead-time benefits can be investigated with the help of a class of students, where half the students use the proposed modular DES methodology and the other half use the traditional DES methodology. A comparison of the lead-times for each project can then be made including measures on the statistical significance of the results.

10.3. Strengthen impact of the research results

The development of an implementation plan for companies to use in order to get started with the modular DES methodology, suitable for manufacturing industry, would ease the adoption of the modular DES methodology.

The development of a DES software package having the desired features explained in this thesis would ease the adoption and implementation of the modular DES methodology. Some DES software packages are close already [is it all right to name one or two of these packages which are close already? – EW], which might spawn possibilities for adoption of ideas from this thesis into already existing software.

10.4. Improve the research results

The proposed modular discrete event simulation methodology can be fine-tuned and improved. This can be achieved by conducting case studies utilizing the proposed methodology and by then using the case studies to provide feedback in order to improve and clarify the methodology more extensively than has yet been possible in this thesis.

Additional improvements could be achieved if additional measurements on DES usage in industry were made regularly and if the data needed for conducting DES projects were given thorough attention. The data constitute key information for understanding the industrial development both when it comes to DES usage and, more importantly, when it comes to using real world potentials, as these remain *inactive* potentials in each un-analyzed manufacturing system.

10.5. Additional connections to future research

Integration aspects are nowadays always interesting to discuss since the work should be carried out only once. Integration is a key enabler for that to be realized. Input data should be typed only once, PLC programs should be created only once, Bill of Material should be typed only once, etc… This integration also addresses the system interfaces and communication standards, which are other growing research areas.

Standardization of discrete event simulation models has not been considered in this thesis, but it is obvious that this is of importance and plays a key role for future compatibility. An effort on this area is actually already started: Cooperation with NIST on standard development for DES model building, including transformation of simulation models using XML.

References

Almström, P., 2005, Development of Manufacturing Systems, A Methodology based on Systems Engineering and Design Theory, Department of Materials and Manufacturing Technology ISBN 91-7291-634-6, PhD thesis, Chalmers University of Technology, Gothenburg, Sweden

American Heritage, 1996, Dictionary of the English language 3rd edition, Boston, Houghton Mifflin Company

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

Andersson, F., 2003, Total development of a web-based tool for daily operation control of production, (In Swedish), M.Sc. Thesis 30, ISSN 1651-1875, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, Sweden

Andersson, J., Åström, C., 2004, Development of a model to estimate manufacturing cost, M.Sc. Thesis 118, ISSN 1651-1875, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, Sweden

Arbnor, I., Bjerke, B., 1994, Företagsekonomisk Metodlära (In Swedish), andra utgåvan, Studentlitteratur, Lund, Sweden

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, Institutionen for Produktionsteknik, 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

Axelsson, H., Bengtsson, C., 2002, Produktionsutveckling med fokus på planering och kapitalbindning, (In Swedish), M.Sc. Thesis No. 11, ISSN 1651-1875, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, Sweden

Ball, P., Love, D., 1995, The key to object-oriented simulation: separating the user and the developer. In Proceedings of the 1995 Winter Simulation Conference, ed. Alexopoulos, C., Keebom, K., Arlington, Virginia, pp. 768 - 774

Bagiu, J., Johansson, B., 2004, Profitable Intelligent Manufacturing Systems for the Future, The 35th International Symposium of Robotics ISR 2004, March 2004, Paris, France

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

Banks, J., Carson, J. S., Nelson B. L., Nicol, D. M., 2004, Discrete-Event System Simulation, 4th ed. Upper Saddle River, New Jersey: Prentice-Hall Incorporated

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, in Proceedings of the 2000 Winter Simulation Conference, ed. J.A. Joines, R.R. Barton, K. Kang, P.A. Fishwick, Orlando, FL, December 10-13, pp. 1568-1576

Bauer, A., Browne, J., Bowden, R., Duggan, J., Lyons, G., 1991, Shop Floor Control Systems. New York: Van Nostrand Reinhold

Bell, D., 1973, The Coming of Post-industrial Society: A Venture in Social Forecasting, New York, Basic Books

Bertilsson, C-F., Holmberg, J., 2005, Development of a simulation tool for analysis of the materials handling in a future assembly plant (in Swedish), Department of Materials and Manufacturing Technology ISSN 1652-8913, Diploma thesis No. 3/2005, Chalmers University of Technology, Gothenburg, Sweden

Björk, E., 1999, Product development for users with special needs, Licentiate thesis, Chalmers University of Technology, Gothenburg, Sweden

Bley, H., Franke, C., Wuttke, C.C., Gross, A., 2000, Automation of Simulation Studies, in Proceedings of the 2nd CIRP International Seminar on Intelligent Computation in Manufacturing, pp.89-94, Capri, Italy

Bhuskute, H.C., Duse, M.N., Gharpure, J.T., Pratt, D.B., Kamath, M., Mize, J.H., 1992, Design and Implementation of a Highly Reusable Modeling and Simulation Framework for Discrete Part Manufacturing Systems. In Proceedings of the 1992 Winter Simulation Conference, ed. Swain, J.J, Goldsman, D., Crain, R.C., and Wilson J.R., pp. 680-688

Brade, D., 2004, Quantitative Metrics in M&S VV&A, in proceedings of Foundations '04 V&V Workshop, October 13-15,Tempe, Arizona

Buzacott, J.A., 1995, A perspective on new paradigm in manufacturing, Journal of Manufacturing Systems, 4 (2), pp. 118-125

Cato, C., Rosenström, H., 2003, Improved Prerequisites for Discrete Event Simulation in Early Project Stages at Volvo Car Corporation, (In Swedish), M.Sc. Thesis No. 47, ISSN 1651-1875, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, Sweden

Chryssolouris, G., 1992, Manufacturing Systems: Theory and Practise, Springer-Verlag, New York

CIMOSA, 1994, CIMOSA Open System Architecture for CIM: Technical Baseline, Version 3.0 CIMOSA Association, Aachen, Germany

Cochran, J.K., Chen, H-N., 2005, Fuzzy multi-criteria selection of object-oriented simulation software for production system analysis, Computers & Operations Research No. 32, pp. 153-168

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

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

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 pp. 147-159

Drucker, P., 1968, The Age of Discontinuity: Guidelines to Our Changing Society, New York, Harper & Row

Edvinsson, W., 2005, A market research of modular and reconfigurable manufacturing systems, Department of Materials and Manufacturing Technology ISSN 1652-8913, Diploma thesis No. 11/2005, Chalmers University of Technology, Gothenburg, Sweden

Ericsson, U., 2005, Diffusion of Discrete Event Simulation in Swedish Industry, One way to an Increased Understanding, doctorial thesis, Department of Materials and Manufacturing Technology, ISBN 91-7291-577-3, Chalmers University of Technology, Gothenburg, Sweden

Erixon, G., 1996, Modularity – the basis for Product and Factory Re-engineering, Annals of the CIRP, Vol. 45/1, pp. 1-4.

Erixon, G., Erlandsson, A., von Yxkull, A., Östergren, B. M., 1994, Modulindela Produkten, -Halverade ledtider och offensiv marknadsorientering, in Swedish, ISBN 91-7548-321-1, Ord och Form AB, Uppsala

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

Garro, O., Martin P., 1993, Towards new architecture of machine tools, International Journal of Production Research, 31 (10), pp. 2403-2414

Glaser, B., Strauss, A. L., 1967, The Discovery of Grounded Theory: Strategies for Qualitative Research. Chicago: Aldine De Gruyter.

Glossary – Study Manual www.geocities.com/clearbirds/study/glosstudy.htm (accessed 11th of April 2005).

Goranson H. T., 1998, Agile Manufacturing, in Molina, A., et al (editors), Handbook of Life Cycle Engineering – Concepts Models and Technologies, Kluwer Academic Publishers, Dordrecht, The Netherlands

Grünberg, T., 2003, Performance Improvement, Towards a Method for Finding and Prioritising Potential Performance Improvement Areas in Manufacturing Operations, Licentiate thesis, Department of Production Engineering, The Royal Institute of Technology, Stockholm, Sweden

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

Grünberg, T., Johansen, K., Johansson, B., Nordell, P., Tangen, S., 2002b, Productivity Improvement work at ABB Robotics, Västerås, Woxénrapport, KTH, Stockholm, Sweden. (In Swedish)

Grünberg, T., Johansen, K., Johansson, B., Nordell, P., Tangen, S., 2004, Produktiviteten i fokus - del 10, Produktivitet - Hot och Möjligheter, Bättre Produktivitet del 2. (In Swedish)

Gullander, P., 1999, On Reference Architectures for Development of Flexible Cell Control Systems, PhD. Thesis, Department of Production Engineering, Chalmers University of Technology, Sweden

Gupta, Y.P., Goyal, S., 1989, Flexibility in manufacturing systems: Concept and measurements, European Journal of Operational Research, 43 (2). pp. 119-135

Gustafsson, B., 1999, On the importance of integrating hand and mind in the automation process. Licentiate thesis (In Swedish), Department of Product and Production Development ISSN 1100-7524, PTA 99:05, Chalmers University of Technology, Gothenburg, Sweden.

Gustafsson, B., 2002, Rediscover the art of engineering, the 33rd International symposium on robotics (ISR), 7-11 October 2002, Stockholm, Sweden

Heilala, J., 2005, Use of simulation in manufacturing and logistics systems planning, to be published in www.hut.fi/Yksikot/Auttieto/ (http://www.tekes.fi/julkaisut/LASSI_Evalution_report.pdf accessed 11 April 2005)

Heilala, J., Montonen, J., 1998, Simulation-based design of modular assembly system – use of simulation module library. Eurosim Congress 1998, 3rd International Congress of the Federation of EUROpean SIMulation Societies. Espoo, FI, 14- 15 April 1998.

Heilala, J., Voho, P., 2001, Modular Reconfigurable Flexible Final Assembly Systems. Assembly Automation, 21 (1), pp. 20-28.

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

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

Ingemansson, A., 2004, On Reduction of Production Disturbances in Manufacturing Systems Based on Discrete-Event Simulation, Division of Robotics Department of Mechanical Engineering, ISBN 91-628-6149-2, Lund Institute of Technology, Lund University

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

Jaikumar, R., 1993, 200 Years to CIM, IEEE Spectrum, pp. 26-27

Johansson, B., 2002, Discrete event simulation - Present situation and future potential. Licentiate Thesis, Department of Product and Production Development ISSN 1651-0984, Report No 7, Chalmers University of Technology, Gothenburg, Sweden

Johansson, B., 2004, Produktiviteten i fokus - del 9, Kompetensutveckling för framtidens tillverkningssystem, ett måste för svensk industri, Bättre Produktivitet del 1. (In Swedish)

Johansson, B., Allander, M., 1999, Flow Simulation and 3D Animation of an Assembly Plant (In Swedish), M.Sc. Thesis, PTX 99:13, Department of Production Engineering, Chalmers University of Technology, Gothenburg, Sweden

Johansson, B., Bagiu, J., 2004, Modular Assembly Systems Simulation for Lead Time Reduction, The 2nd International Precision Assembly Seminar IPAS2004, February, Bad Hofgastein, Austria

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., Ericsson 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., Johnsson, J., Kinnander A., 2003, Information structure to support Discrete Event Simulation projects, in Proceedings of the 2003 Winter Simulation Conference, ed. S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, New Orleans, Louisiana, Dec 7-10, (Invited Paper)

Johansson, B., Kaiser, J., 2002, Turn Lost Production into Profit. -Discrete Event Simulation Applied on Resetting Performance in Manufacturing Systems, in 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

Johansson, B., Kinnander, A., 2004, Produktivitetsförbättring av manuella monteringsoperationer – Sekvensbaserad Aktivitets och Metodanalys (SAM) vid sex nordiska företag, Chalmers tekniska högskola, Produkt och produktionsutveckling internrapport ISSN: 1651-0984 Rapport Nr: 25. (In Swedish)

Johansson, B., Ottosson, S., Persson, L., 2005, Virtual Reality in Design for Manufacturing and Assembly, Journal of Engineering Design, (Invited Paper, in preparation)

Johansson, B., Tangen, S., 2000, Produktivitet –Undersökning på sex företag, Chalmers tekniska högskola, Institutionen för Produktionsteknik internrapport. (In Swedish)

Johansson, B., Tangen, S., 2003, Produktiviteten i fokus - del 6, Produktionssimulering som arbetssätt för ökad produktivitet, Bättre Produktivitet del 6, 2003. (In Swedish)

Johansson, B., Williams, E. J., Alenljung, T., 2004, Using Autonomous Modular Material Handling Equipment for Manufacturing Flexibility, in Proceedings of the 2004 Winter Simulation Conference, ed. R .G. Ingalls, M. D. Rossetti, J. S. Smith, and B. A. Peters, Washington DC, 5-8 December 2004 (Invited Paper)

Johnsson, J., 2004, Discrete Event Simulation as a Supporting Tool for Decision-Making in Virtual Enterprises, Licentiate Thesis, Department of Product and Production Development, ISSN 1651-0984, Report No 28, Chalmers University of Technology, Gothenburg, Sweden

Johnsson, J., Johansson, B., 2003, Discrete Event Simulation in a Virtual Enterprise Environment: a Case Study Reflection of Multiple Developers, 15th European Simulation Symposium and Exhibition, Delft, the Netherlands, October 26-29

Johnsson, J., Johansson, B., 2004, Managing Strategic, Tactical and Operational Performance in Manufacturing Collaboration, IGLS2004, Innsbruck, Austria

Jörgensen, T., 2000, Scheduling and Simulation of Letter Sorting Machines (In Swedish), M.Sc. Thesis, PTX 00:08, Department of Production Engineering, Chalmers University of Technology, Gothenburg, Sweden

Kaiser, J., 2002, Evaluation of Resetting performance in cellular manufacturing systems, a structured approach to sustainable improvement of resetting performance, PhD. Thesis, department of product and production development, Chalmers University of Technology, Gothenburg, Sweden

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

Kibbee, J. M., 1961, "Model Building for Management Games, in Simulation and Gaming: A Symposium, edited by Albert Newgarden, New York, American Management Association, pp. 8-15

Kidd, P.T., 1994, Agile Manufacturing: Forging New Frontiers, Addison-Wesley

Klingstam, P., 2001, Integrating Discrete Event Simulation into the Engineering Process, PhD Thesis, Department of Production Engineering, Chalmers University 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.

Koelster, A., 1967, The Ghost in the machine, Arcana books, London.

Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritchow, G., Van Brussel, H., Ulsoy, A.G. 1999, Reconfigurable manufacturing systems, CIRP Annals, 48 (2), pp. 527-540

Koren, Y., Ulsoy, A. G., 1997, Reconfigurable Machining Systems, NSF ERC/RMS Report 1

Koren, Y., Ulsoy, A. G., Mehrabi, M. G., Pasek Z., 1997, Reconfigurable Machining Systems: A New Paradigm, SAE International Manufacturing Conference Detroit

Koren, Y., Ulsoy, A.G., Landers, R.G., Mehrabi, M., Pasek, A., Yip-Hoi, D., 2001, NSF engineering research center for reconfigurable machining systems. Proceedings of the 2001 NSF Design, Manufacturing and Industrial Innovation Research Conference. Tampa Florida, USA

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

Law, A. M., Kelton, W. D., 2000, Simulation Modelling and Analysis, 3rd ed., New York: McGraw-Hill

Ljung, O., 2005, A vision for future production at Lear Corporation, Tanum (in Swedish), Department of Materials and Manufacturing Technology ISSN 1652-8913, Diploma thesis No. 04/2005, Chalmers University of Technology, Gothenburg, Sweden

Mackulak, G.T., Cochran, J.K., Savory, P.A., 1994, Ascertaining important features for industrial simulation environments, Simulation, No. 63, pp. 211-221

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

Manufuture, 2003, Working Document for the Manufuture Conference, European Commission, Milan, Italy 2003

McLean, C., Leong, S., 2002, A Framework for Standard Modular Simulation, in 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, pp 1613-1620

McLean, C., Leong, S. K., Harrell C., Zimmerman, P. M., Lu, R. F., 2003, *Simulation Standards: Current Status, Needs, and Future Directions*, in Proceedings of the 2003 Winter Simulation Conference, ed. S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, New Orleans, Louisiana, Dec 7-10, pp. 2019-2026

Meinert, T. S., Taylor, G. D., English, J. R., 1999, A modular simulation approach for automated material handling systems, Simulation Practise and Theory No 7, pp. 15-30

Mehrabi, M.G., Ulsoy, A.G., Koren, Y., 2000, Reconfigurable manufacturing systems: Key to future manufacturing, Journal of Intelligent Manufacturing, Kluwer Academic Publishers, Vol. 11, pp. 403-419

Microsoft® Encarta® Encyclopedia 2002, © 1993-2001 Microsoft Corporation

Mihram, G., A., 1972, Some Practical Aspects of the Verification and Validation of Simulation Models, "Operation Research Quarterly, Vol. 23, pp. 17-29

Monden, Y., 1998, Toyota Production System, 3rd edition, Engineering and Management Press

Murgau, A., Johansson, B., Pejryd, L., 2005, A Case Study on the Interaction between Physical and Knowledge Flows in Manufacturing Systems, the 38th CIRP International seminar on Manufacturing Systems, May 16-18, Florianópolis – Brazil.

Nance, R. E., 1995, "Simulation programming languages: An Abridged History", in 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

National Research Council, 1998, Visionary Manufacturing Challenges for 2020, Washington, DC: National Academy Press

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

Nonaka, I., 1994, A Dynamic Theory of Organizational Knowledge Creation, Organization Science, 5 (1)

Nordell, P., 2003, Identification of Productivity relationships for improving performance in cellular manufacturing systems, Licentiate Thesis, Department of Product and Production Development, ISSN 1651-0984, Report No 17, Chalmers University of Technology, Gothenburg, Sweden

Nordell, P., Gustafsson, B., Kinnander, K., 2003., Knowledge-based method for efficient reduction of losses in manufacturing lines, The 36th CIRP-International Seminar on Manufacturing Systems, 03-05 June, Saarbrücken, Germany.

Norris, D. R., 1986, External validity of business games, Developments in Business Simulation & Experimental Exercises, ,Vol. 13, pp 126-129

Ottosson, S., Björk, E., 2003, research on dynamic systems – some considerations. Accepted for publication in Technovation

Patel, R., Tebelius, U., 1987, Grundbok i forskningsmetodik. Lund: Studentlitteratur

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

Qiao, G., Riddick, F., McLean, C., 2003, *Data Driven Design and Simulation System based on XML*, in Proceedings of the 2003 Winter Simulation Conference, ed. S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, New Orleans, Louisiana, Dec 7-10, pp. 1143-1148

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

Redzic, H., 2004, Analys och förbättring av bromsutrustning (In Swedish), M.Sc. Rapport nr 63, ISSN 1651-1875, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, 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. W., 1999, Automod Product Suite Tutorial, in Proceedings of the 1999 Winter Simulation Conference, P. A. Farrington, H. B. Nembhard, D. T. Sturrock, and G. W. Evans, eds, pp. 220-226

Rohrer, M. W., 2003, Maximizing Simulation ROI with AutoMod, in Proceedings of the 2003 Winter Simulation Conference, , ed. S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, New Orleans, Louisiana, Dec 7-10, pp. 201-209

Sandman, D., Wallström, B., 2003, Study of Lean Production at Volvo do Brazil, M.Sc. Thesis 44, ISSN 1651-1875, Department of Product and Production Development, Chalmers University of Technology, Gothenburg, Sweden

Sargent, R. G., 2000, Verification, Validation, and accreditation of simulation model, in Proceedings of the 2000 Winter Simulation Conference, ed. J.A. Joines, R.R. Barton, K. Kang, P.A. Fishwick, Orlando, FL, December 10-13, pp. 50-59

Savén, B., 1994, Beslutsstöd och simulering i verkstadsföretag - en sammanfattning av två enkätstudier (In Swedish), Technical Report LiTH-IDA-R-94-17, Dept. of Computer and Information Science, Linköping University, Sweden

Schellenberger, R. E., Keyt, J. C., 1983, A Methodology for Assessing the Internal Validity of Business Simulations, Developments in Business Simulation & Experimental Exercises, Volume 10, pp. 6-8

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

Seidel, D., Mey, M., 1994, IMS – Holonic Manufacturing Systems: Glossary of Terms, IMS – Holonic Manufacturing Systems: Strategies Vol. 1, March IFW, University of Hannover, Germany

Simulation Study Group, 1991, Simulation in U.K. Manufacturing Industry, p 4.

Son, Y., Jones, A., Wysk, R.A., 2000, Automatic Generation of Simulation Models from Neutral Libraries: An Example, in Proceedings of the 2000 Winter Simulation Conference, ed. J.A. Joines, R.R. Barton, K. Kang, P.A. Fishwick, Orlando, FL, December 10-13, pp. 1558-1567

Standridge, C. R., Centeno, M. A., Johansson, B., Ståhl, I., 2005, Introducing Simulation Across The Disciplines, in Proceedings of the 2005 Winter

Simulation Conference ed. M. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, Orlando, 5-8 December 2005.

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

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

Ström, P., Turesson, J., 2005, Material flow simulation of the new heat treatment facility for the E-factory at SKF Gothenburg (in Swedish), Department of Materials and Manufacturing Technology ISSN 1652-8913, Diploma thesis No. 01/2005, Chalmers University of Technology, Gothenburg, Sweden

Tangen, S., 2002, A Theoretical Foundation for Productivity Measurement and Improvement of Automatic Assembly Systems, Licentiate thesis, Department of Production Engineering, The Royal Institute of Technology, Stockholm, Sweden

Tangen, S., 2004, Evaluation and Revision of Performance Measurement Systems, PhD Thesis, Department of Production Engineering, The Royal Institute of Technology, Stockholm, Sweden

Tangen, S., Grünberg, T., Johansson, B., Nordell, P., Johansen, K., 2004, "Produktiviteten i fokus (English title: Productivity in focus)", Woxénreport no 38, WoxénCentrum, The Royal Institute of Technology, Stockholm, TRITA-IIP-04-04, ISSN 1650-1888. (In Swedish)

Taylor, F., W., 1947, Scientific Management, New York: Harper & Brothers

Tarumarajah, A., Wells, A. J., Nemes, L., 1998, Comparison of Emergent Manufacturing Concepts, In proceedings of IEEE International Conference on System, Manufacturing and Cybernetics, SMC'98

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

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

Toffler, A., 1990, Powershift: Knowledge, Wealth and Violence at the Edge of 21st Century, New York, Bantam Books

Tönshoff, H.K., Menzel, E., Hinkenhuis, H., Nitidem, E., 1994, Intelligence in Machine Tools by Configuration, 7th International conference on Production/Precision Engineering, 4th International conference on High Technology, Chiba, Japan.

Valckenaers, P., Van Brussels, H., Kollingbaum, M., Bochmann, O., 2002, Stigmergy in Holonic Manufacturing Systems, Journal of Integrated Computer-Aided Engineering, Vol.9, No.3, pp. 281 - 289

Valentin, E. C., A., Verbraeck, 2002, Guidelines for designing simulation building blocks, in Proceedings of the 2002 Winter Simulation Conference, ed. E. Yücesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, San Diego, California, pp. 563-571

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

Von Krogh, G., Ichijo, K., Nonaka, I., 2000, Enabling Knowledge Creation. How to Unlock the Mystery of Tacit Knowledge and Release the Power of Innovation. Oxford University Press, New York

Von Krogh, G., Nonaka, I., Ichijo, K., 1997, Develop Knowledge Activists!, European Management Journal, 15 (5), pp 475-483

Walfridsson, T., Wertheimer, S., 2005, Emulering of a PLC-system (in Swedish), Department of Materials and Manufacturing Technology ISSN 1652-8913, Diploma thesis No. 9/2005, Chalmers University of Technology, Gothenburg, Sweden

Williams, E. J., 1996, Making simulation a corporate norm. Proceedings of the 1996 Summer Computer Simulation Conference, eds. V. Wayne Ingalls, Joseph Cynamon, and Annie Saylor, pp. 627-632.

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

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

Zoning Ordinance (Chapter 108), Article II Definitions, Accessed 20 June 2005 http://www.twp.cranberry.pa.us/codes/zoningordinance/zon2.html

Appendix

Introduction to case studies

In this part of the appendix the main contributing case studies will be summarized in order to set the scene for the proposed modular discrete event simulation for manufacturing systems and the methodology on modular discrete event simulation. Over the past five years, over thirty case studies and projects have been conducted (Johansson and Allander 1999, Klingstam and Johansson 2000, Johansson and Tangen 2000, Arne and Nilsson 2000, Johansson and Grünberg 2001, Karlsson 2001, Johansson et al 2002, Johansson and Kaiser 2002, Grünberg et al 2002a, Grünberg et al 2002b, Axelsson and Bengtsson 2002, Axelsson and Hjelte 2002, Andersson 2003, Johnson and Johansson 2003, Johansson et al 2003, Johansson and Tangen 2003, Cato and Rosenström 2003, Sandman and Wallström 2003, Johansson et al. 2004, Johnsson and Johansson 2004, Bagiu and Johansson 2004, Johansson et al 2004, Redzic 2004, Andersson and Åström 2004, Tangen et al 2004, Johansson 2004, Grünberg et al 2004, Johansson and Kinnander 2004, Murgau et al 2005, Edvinsson 2005, Ström and Turesson 2005, Bertilsson and Holmberg 2005, Ljung 2005, Walfridsson and Wertheimer 2005). However, only the last five in this list will be described here plus four more for validation purposes.

The purpose of this appendix is to:

- Show the lack of not having modular discrete event simulation for manufacturing systems and the modular discrete event simulation methodology
- Imply that it is needed
- Show requirements for, and benefits from, developing modular discrete event simulation for manufacturing systems and the modular discrete event simulation methodology
- Validation of the research results by examining four industrial case studies

The chronology of this appendix part is as follows:

- Firstly the cases will be summarized
- Secondly the papers will be summarized
- Thirdly the connection and contribution towards modular discrete event simulation of manufacturing systems and modular discrete event simulation methodology from each of the cases and papers will be clarified.

Case 1 Market research on modular and reconfigurable manufacturing systems

This case study was made as a diploma thesis (Edvinsson 2005). Reconfigurable and modular manufacturing systems have been given a good deal of attention in predictions of future important aspects of manufacturing systems (NRC 1998, IVA 2000, Manufuture 2003). In order to clarify the situation regarding modular reconfigurable manufacturing systems for profitable future manufacturing this case study was conducted.

Purpose

The purpose of this case study was to identify and describe the technologies and principles which are of importance for designing and realizing a modular reconfigurable manufacturing system, with focus on material handling. The purpose was also to interpret the trend towards continuing development and realization of modular reconfigurable manufacturing system and to identify conflicts and constraints related to the design process and implementation as well. Furthermore, an additional purpose was to carry out a market survey in order to find conveyor companies on the market which focused on modular manufacturing systems.

Method

Information and experience for the frame of reference was gathered from discussion with suppliers of material handling equipment, sales brochures, the Internet, and literature surveys on the recent research in the field of reconfigurable manufacturing systems. A market survey was also carried out focusing on catching the manufacturing system supplier's forecasts of the future regarding modular reconfigurable manufacturing systems. The material gathered was then thinned through the selection of the most appropriate solutions on modular reconfigurable manufacturing systems. Then the data collection on the most interesting systems on the topic of modular reconfigurable manufacturing systems was undertaken more thoroughly with both questionnaires and interviews of the selected companies. Thereafter the data was examined and analyzed. Figure 28 shows the distribution for participants in the survey. The results from all parts of the study were then summarized, discussed and concluded.

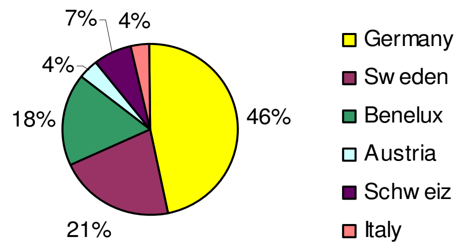

Figure 28 The geographical distribution of the interviewed companies.

The chronological sequence of the methodology used in this case study is shown in Figure 29.

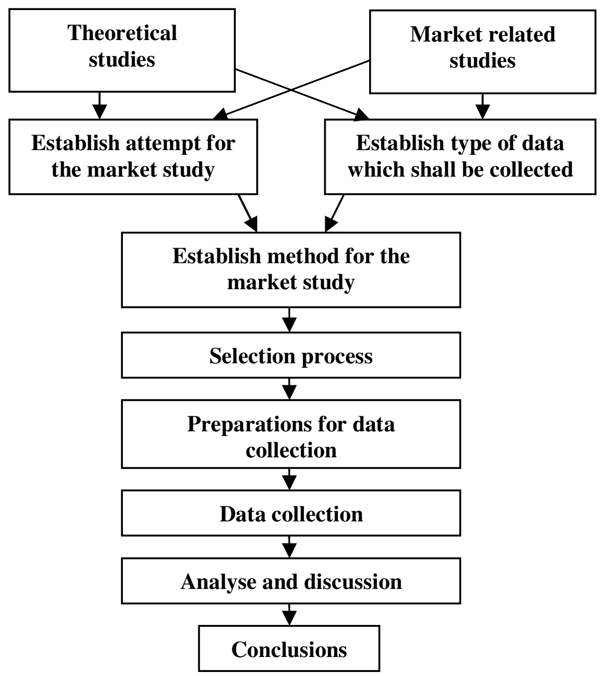

Figure 29 The chronological sequence of the methodology in case study 1 (Edvinsson 2005).

Result and conclusion

Existing concepts and current development regarding modular reconfigurable manufacturing systems are to a great extent focusing on the systems core processes; the material handling system is rarely the focus of attention. According to Edvinsson (2005), using a conveyor system is one of the most common solutions for the transportation of products within a manufacturing system. For these reasons, the material-handling system has great potential if it can be made modular and reconfigurable.

It is impossible to predict the future with 100% accuracy, but on the basis of the information gathered and the knowledge acquired while carrying out this case study, it is possible to identify some emerging trends (Edvinsson 2005):

- Modular and reconfigurable manufacturing systems will be demanded more often in the future than today.
- Future manufacturing systems will be characterized by openness and therefore several standards will have to be developed.
- The manufacturing system control will become more decentralized in the future.
- Modern, industrial and automated manufacturing systems will be based on digital networks.
- Ethernet will be implemented to a greater extent in industrial systems, which will make them more rapid.
- Product tracking technologies will be more important in the future and the literature means that RFID will become the most common technique in this field.
- Modeling and simulation tools will be developed and used for more functions than they are today.

Case 2 Discrete event simulation of material flow in a heat treatment facility

This case study was made as a diploma thesis (Ström and Turesson 2005). It is argued that a reliable heat treatment is essential for future production of bearings at SKF Gothenburg. After evaluating possible solutions, it was decided that SKF should invest in a new facility for heat treatment. In order to verify the capacity of the finished facility this case study was conducted.

Purpose

The purpose of this case study was to support the decision making for the requirements specification, which is to be distributed to potential suppliers of the future heat treatment facility.

Method

The methodology used in this case study mainly followed the one presented in Chapter 3.4 Classical Discrete event simulation Project Methodology. The methodology is also described in Banks et al (2004). Additional work has been carried out in order to create a user interface in Excel to the model, which was modeled in WITNESS. According to Ström and Turesson (2005) this user interface was made parametric on specific parameters such as conveyor speed, number of rollers, cycle times etc. in order to simplify further analysis and possible solutions of the future heat treatment facility.

Result and conclusion

The result of this case study is a discrete event simulation model with a user interface which together give an opportunity to simulate alternative material flows with respect to a number of parameters; see Figure 30.

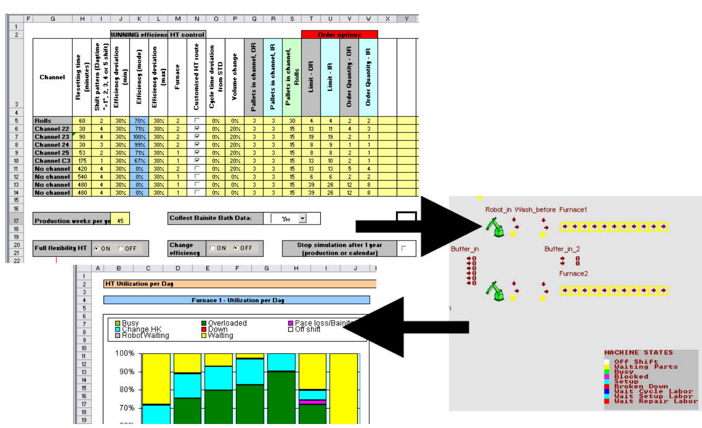

Figure 30 Communication between WITNESS and Excel.

Furthermore the simulations detect a low utilization of the furnace's capacity as well as big losses due to steel grades and uneven amounts of production time per pallet (Ström and Turesson 2005). The simulations also suggest that it would be of great value to investigate the effects of leveling the amount of production time per pallet and balancing the line products between flows.

Case 3 Development of a discrete event simulation interface tool for analysis of material handling in a future assembly shop

This case study was made as a diploma thesis (Bertilsson and Holmberg 2005). In the near future large conversions will be made at the gearbox and retarder plant at Scania CV, Sibbhult. The implementation of a new assembly plant is to take place. The layout will be changed completely, which also indicates that subassembly lines will have to be relocated. In order to secure the production Scania decided to proceed with a discrete event simulation study concerning the material flow from buffer stocks to the assembly stations in the new assembly workshop.

Purpose

The purpose of this case study was to simplify decision-making regarding layout planning and capacities for the new gearbox and retarder assembly line. Additionally a user interface in Excel connected to the discrete event simulation model should be provided for further analysis and experiments.

Method

The methodology used in this case study mainly follows the one presented in Chapter 3.4 Classical Discrete event simulation Project Methodology (see also Banks et al 2004). Scania Production System (SPS) was also used as methodology guideline. SPS follows the main ideas of Toyota Production System (TPS) (Monden 1998). Additional work has been done in order to create a user interface in Excel to the model, which was modeled in Automod; see Figure 31. In order to simplify further analyses and possible solutions of the future assembly line, this user interface was made parametric on particular parameters such as number of forklifts, orders per hour, cycle times, number of turns per forklift and hour, part lists, etc. (Bertilsson and Holmberg 2005)

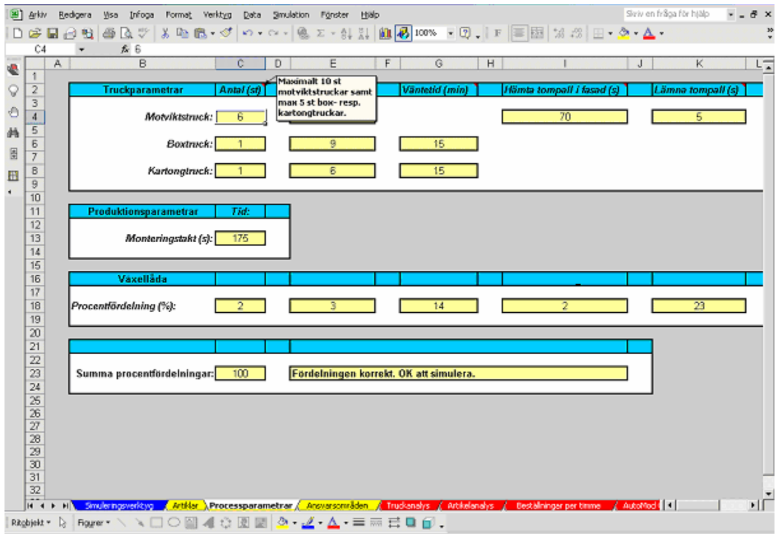

Figure 31 Example of process parameters in the user interface (Bertilsson and Holmberg 2005).

Result and conclusion

The result of this case study is a discrete event simulation model with a user interface, which together gives an opportunity to simulate alternative material flows with respect to a number of parameters. The result gives a good forecast on how to specify and build the assembly line for manufacturing of retarders in a productive manner when it comes to the evaluated parameters.

Productivity issues turned out to be problematic in the assembly line were for example batching variants of gearboxes and retarders. During the simulation runs it was proven that batching have a positive effect on production, but batching is against the rules in SPS.

The results also indicate that there is further need for an analysis before coming to the point of actually constructing the new assembly line. The reason is that there are too many uncertainties about major effect on the new assembly line.

Case 4 Discrete event simulation for productivity enhancement at a door panel manufacturing site

This case study was made as a diploma thesis (Ljung 2005). The motive for carrying out this investigation was that Lear Corporation in Tanum needed to increase the production performance at the door panel production line for Volvo XC90.

Purpose

The primary purpose of this case study was to propose actions in order to improve the production of door panels, while using the same production process as earlier.

Method

Initially a mapping of the actual manufacturing system was made in parallel with literature studies on productivity and performance enhancement work. Value Stream Mapping (VSM), identification of waste, and the construction, including validation, of a discrete event simulation model out of all the data was made as a second step in this study.
The second step followed the methodology outlined in Chapter 3.4 Classical Discrete event simulation Project Methodology (see also Banks et al 2004). From the VSM and DES model input, a vision of how the facility could be planned with buffers, order handling, personnel, batching etc. was made in order to find an improved solution on how to produce door panels.

Result and conclusion

The results suggests a production flow and rules to control the production that increase the portion of value added time by 350 % (Ljung 2005). An important part of the suggested concept is that the order point is moved upstream to a point where the product is not yet order-specific. It implies that the number of variants needed in buffer is heavily reduced. Hence the buffer levels can be reduced, resulting in shorter lead-times during production.

A large number of other improvement potentials were also found during the investigation. These can be summarized as follows:

- Adoption of phase time to customer
- Preventive maintenance at certain machines
- Elimination of a number of losses: maintenance, over production, further value adding production of already defect products, buffer sizes changed to needed size at needed place
- Decrease of WIP
- Adoption of shifts to customer (two shifts now possible to extend to three)

Case 5 Discrete event simulation and PLC-emulation of a material handling system

This case study was made as a diploma thesis (Walfridsson and Wertheimer 2005). The background to this case study comes from an idea where a complete factory should be offline-programmed, in the same way as a robot or a CNC-machine can use offline programming, thus enabling preparation, verification and validation of the planned production. Figure 32 shows the real world system to the left and the discrete event simulation model of the system to the right. The experiment in this case study is to control both systems with the same PLC program, both offline and online.

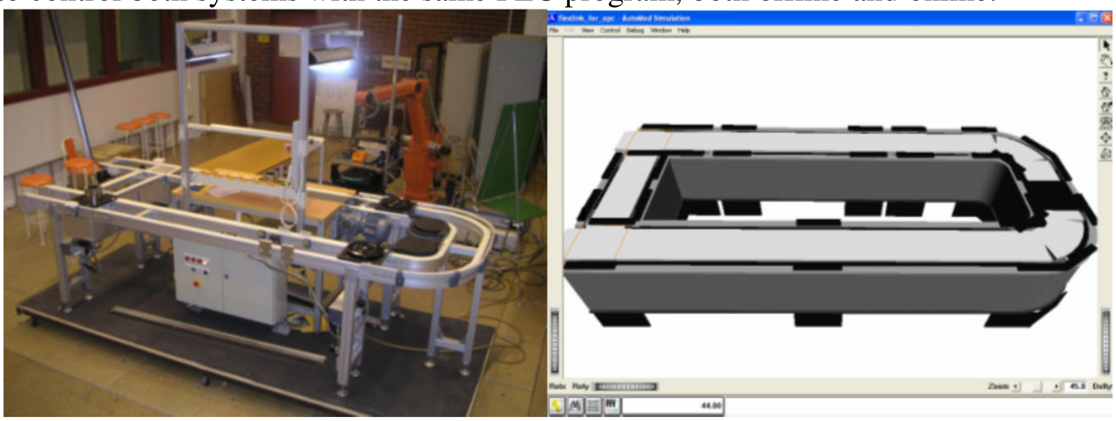

Figure 32 Left shows the real word FlexLink conveyor system, right shows the discrete event simulation model of the same system.

Purpose

The purpose of this case study was to elaborate a combination of discrete event simulation and PLC-Emulation, and to bring forth a structure on how to conduct similar projects in industry. A secondary purpose was to conduct a smaller market survey in order to see if there is a need for emulation in combination with discrete event simulation in industry.

Method

Since discrete event simulation connected with emulation is not a common combination, there were only a few publications available. However, both discrete event simulation and emulation are used more frequently on their own. A literature survey was the most promising start of the case study (see Figure 33). Since the real world system already existed, the second part was to build a discrete event simulation model of the system. This was built in Automod. Thereafter the PLC-program was analyzed and downloaded to the computer. The Emulation part was made in Siemens Soft-PLC WinAC™ 4.0, with control connection to AutoMod™ 11.2 and I/O connection via SimanticNet OPC. Siemens Step7™ was used to program the soft-PLC. The results were then analyzed and concluded in Walfridsson and Wertheimer (2005).

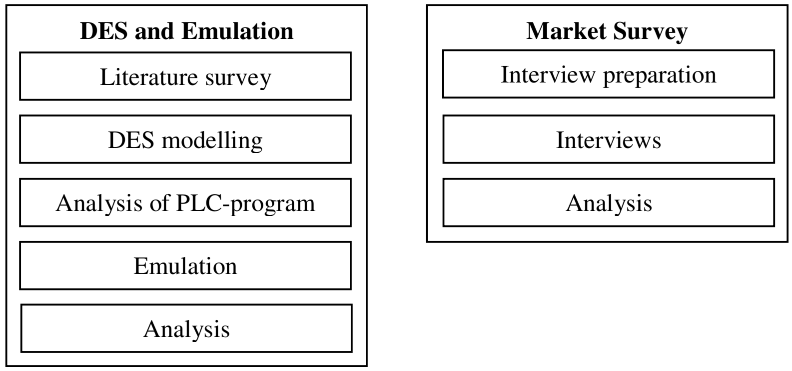

Figure 33 Illustration of the working procedure in case study 5.

The second part of this case study was to make a market survey of the industrial interest in the field of Emulation. The market survey was limited to contain eight companies and was made in a *qualitative* manner, in line with what is described in 2.1.1 Quantitative – Qualitative research and also in Patel and Tebelius (1987).

Result and conclusion

The result from the discrete event simulation-Emulation part of this case study shows that it is possible to control a discrete event simulation model with a soft-PLC. This also indicates that it is possible to conduct offline programming of complete manufacturing systems by using emulation in combination with discrete event simulation.

The market survey on the other hand, shows that emulation activities are rarely used in industry. Those who use it the most are system suppliers, and they are also the ones who can profit the most from using it, since they, according to Walfridsson and Wertheimer (2005), use it frequently and have the appropriate knowledge.

Case 6 OEM Development of Real World Modules with assistance of Modular DES

Purpose

This case study is analyzed in order to check if the modular discrete event simulation methodology presented in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems is valid, in specific the module development described in chapter 7.6.1 Module development is examined.

Method

The method of this study is described in Figure 34. The method has a *qualitative* (Patel and Tebelius 1987) nature and is made through an *interview* with the project leader of a conducted module development project.

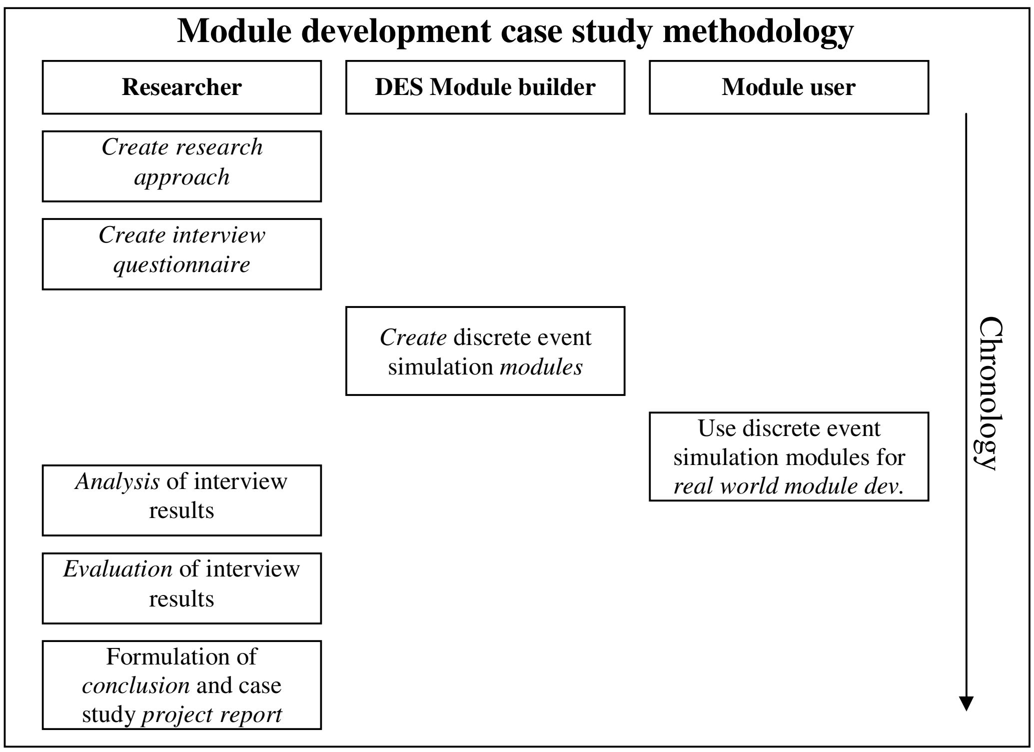

Figure 34 Case study methodology used in case study 6.

Interview questionnaire

During the interview with the project manager, the following questions were asked, and the following answers given.

Q: What was the purpose with the virtual module development project?

A:	The purpose is to conduct the engineering work only once. Then reuse the module functionality as much as possible.
The benefits from using a modular approach to achieve desired functionality are the parameterization possibilities. A number of parameters can then be used in a module to reconfigure the desired functionality into the desired one for just that application.
A module is parametric in both the physical representation and the logical representation. The module interfaces to the surrounding modules are both physical, flow, and control interfaces.

Q:	How does a module look?
A:	An example module is shown below in Figure 35.

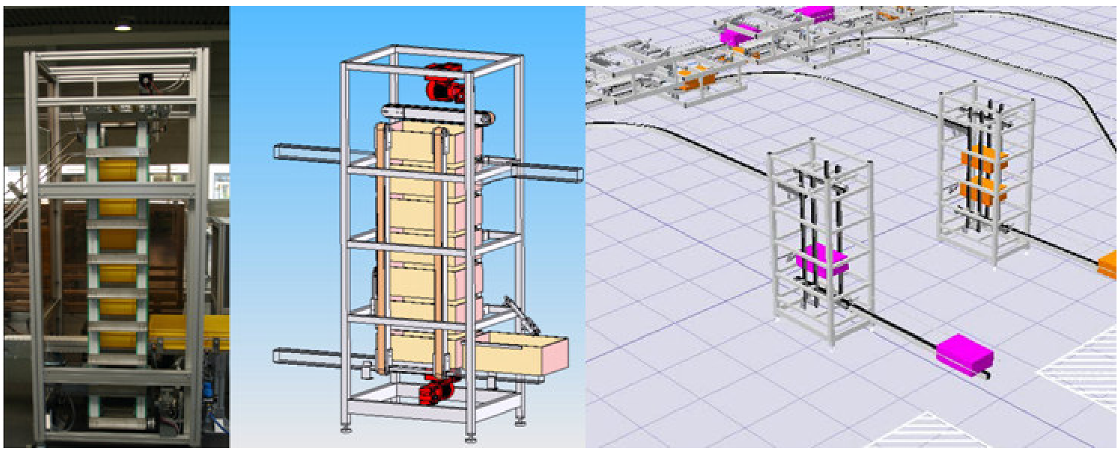

Figure 35 Pater Noster elevator (right photo, centre schematic drawing, left simulation environment).

Q:	Why did the module development need to be done virtually?
A:	In order to visualize and verify the functionality of each module, and also test and verify that our total line-solution is working as expected.

Q:	Who did model the modules?
A:	A Discrete Event Simulation expert

Q:	Who was intended to use the modules once it was created?
A:	Sales and application engineers are using them (Referred to as "*Simulation users*" in chapter 7.5.2 Simulation user.). Sales personnel are using the 3DRealize in front of (and together with) customers building manufacturing lines. If the line is a non-standard variant with complex logical mechanisms inside, then we will bring it in-house to our expert staff in order to solve such issues. About 75% of the work is done in standard manner (I.e sales personnel are taking care of this part) and about 25% needs additional modification for special purposes.

Q: What lead-time benefits did you find through utilizing the modular discrete event simulation methodology?

A: The absolutely largest benefit is that we can verify the solution more accurately with this technology available. Additional benefits as we see valuable as well are for example:

- The flexibility for changes in layout and logics increases
- The possibility to reuse modules for other purposes increases
- Lead-time from order to delivery of a line is shortened due to
    - Decreased manufacturing lead-time for mechanical parts
    - Decreased manufacturing lead-time of control system
    - Quicker installations
    - Quicker ramp-up procedures
    - Quicker to validate

Q: What are the setbacks from using this approach?

A: The setbacks can be summarized as:

- Additional cost is put into each project when modeling the modules and lines.
- The modular approach is flexible, however only to a certain level, and then the modularity is constrained. We are aware of this constrains and have chosen to go with this type of flexibility through parameterization both in real world modules and in the virtual world.
- An effort is needed to get the competence on discrete event simulation and it does also require continuous use in order to maintain the knowledge level.
- It is a hard task to get the customer to pay for the simulation modeling work.

Q: Was the module development project successful?

A: In terms of building the actual real world modules it is a success. The control system is today plug and play in the virtual world but not in the real world. In a future with decentralized control for the real world modules it is possible to achieve plug and play for the real world manufacturing line, however this is not economically beneficial yet.

Conclusion

This OEM supplier of automation equipment develops modules in-house (Has simulation expert knowledge in-house, see chapter 7.6 Simulation expert situations.) for modular discrete event simulation. Sales personnel and application engineers then utilize the modules. In 75 % of the cases the application engineer and the salesperson can model the line by themselves, and in 25 % of the cases it is too complex, which requires the simulation expert to create a specific solution or module (See chapter 7.6.3 Extra features in an already existing module and 7.6.2 Special purpose module).

Case 7 Modular Discrete Event Simulation of Manufacturing Cells at MYDATA Automation AB

Purpose

This case study is analyzed in order to check if the modular discrete event simulation methodology presented in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems is valid, specifically the roles for sales personnel and application engineers described in chapter 7.7.1 Sales personnel and 7.7.2 Production engineers are examined.

Method

The method of this study is described in Figure 34. The method has a *qualitative* (Patel and Tebelius 1987) nature and is made through an *interview* with the project manager of several conducted projects.

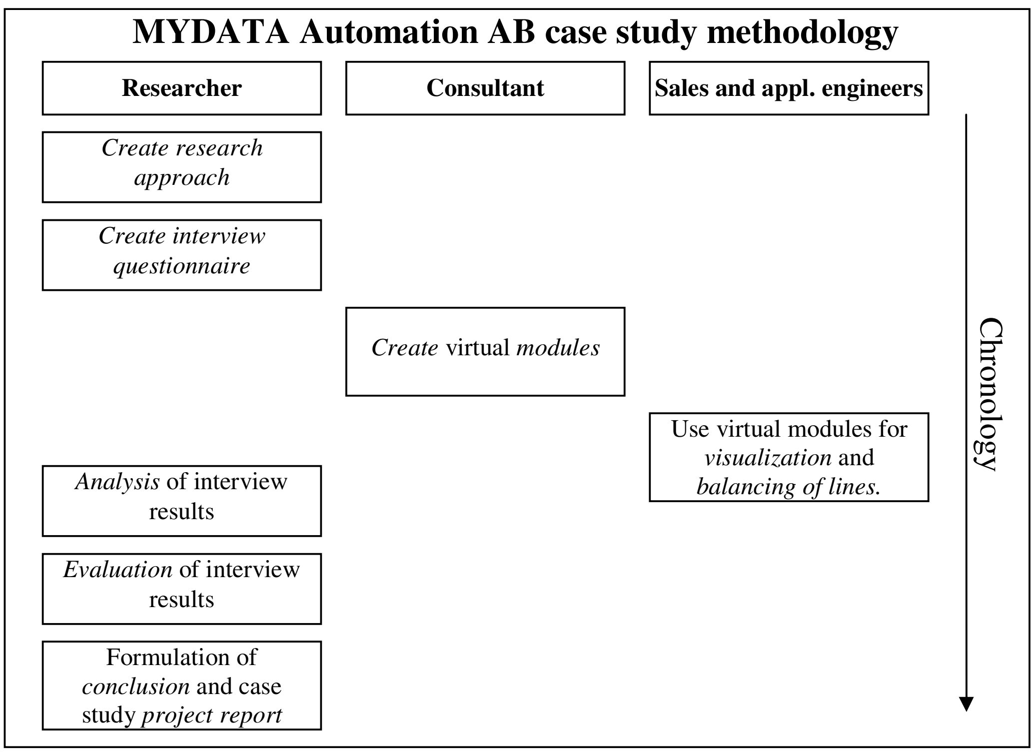

Figure 36 Case study methodology used in case study 7.

Interview questionnaire

During the interview with the project manager, the following questions were asked, and the following answers given.

Q: What is the purpose with virtual projects at MYDATA Automation AB?
A: Mainly to see if the units /machines fit.

Q: What does a module look like?
A: It is a 3D-representation of very good quality and it looks like our machine in a line configuration.

Q: Why do the layouts need to be done virtually?
A: We need to know if the line will fit into the space available, and if the layout is functioning according to the customer requirements.

Q: Who did model the modules?
A: A consultant with expert knowledge on the software.

Q: Who was intended to use the modules once it was created?
A: Sales people and applications engineers.

Q: What are the benefits from using this modular approach?
A: Quicker and easier way to build and change lines/layouts and to be able to give the customer a variety of alternatives with less time spent on engineering.

Q: What are the setbacks from using this approach?
A: Getting the customer to use the free viewer is hard, and it has not been used as much as we hoped for yet (Customer is referred to as simulation observer in chapter 7.5.3 Simulation observer).

Q: Is the use of virtual modules for line configuration and reconfiguration projects successful?
A: Yes.

Additional comments from the project manager:

In short one can say that using the virtual modules of our machines and equipment is good for sales personnel and using it gives a good preview of how the actual line will function and look as one unit. On one hand the visualization, i.e. our machines in combination with external equipment and our conveyors. Questions answered can be for example:

- What will the layout look like when it is made in the real world (Visualization)?
- How long will the real line be (Customer space requirements)?
- Will it fit our methodology for line construction (Work methodology)?

- Will it fit into our line-manufacturing facility (Local space requirements)?

Layout changes and modifications are extremely easy to conduct, which is not the case with pictures.
The logistical part of the program is not used as much as the visualization part.
In some projects we use the logic to show how fabs are moving and produced/refined throughout the line. One example, which is available through the web, is shown in Figure 37.

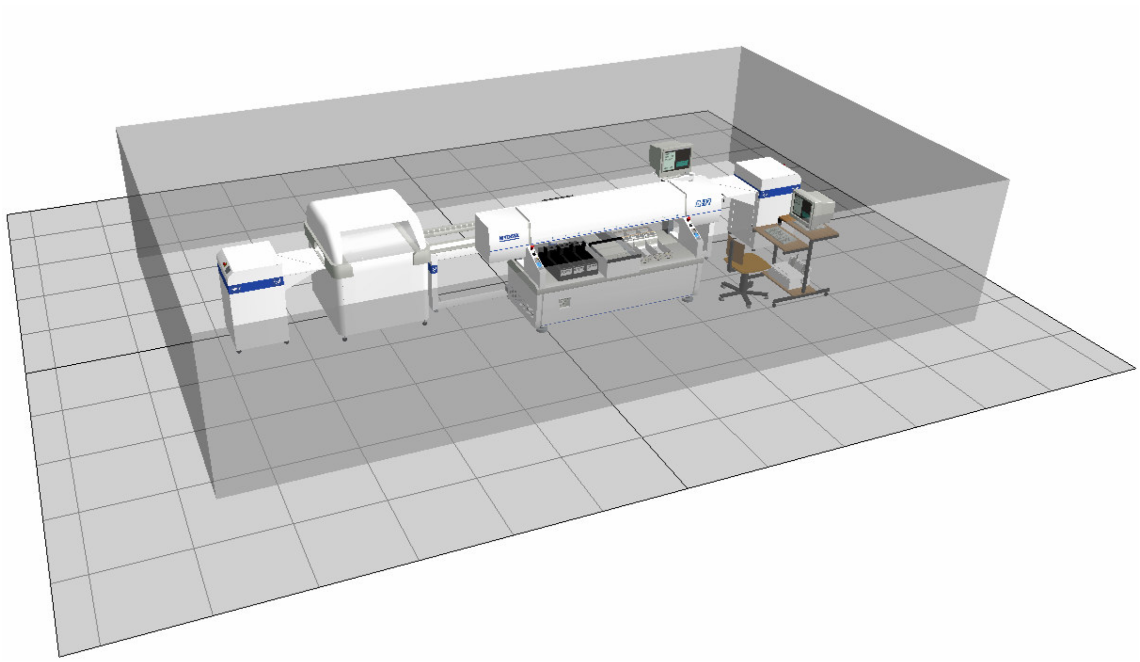

Figure 37 Example of a MYDATA Automation AB line visualized in 3DVideo.

Conclusion

MYDATA Automation AB use modules developed by a *consultant* (Referred to as "*Simulation specialist*" in chapter 7.5.1 Simulation specialist.) in order to let their own *sales personnel* and *application engineers* (Referred to as "*Simulation users*" in chapter 7.5.2 Simulation user.) build the virtual models of lines consisting of both own equipment such as machines and conveyors, but also other third party equipment such as desks, monitors, chairs etc. MYDATA Automation AB's *customer* (Referred to as "*Simulation observer*" in chapter 7.8 Simulation observer situations) uses the models for verification purposes in combination with the required specification of each line ordered from MYDATA Automation AB, however this is not done in all cases.

Case 8 Modular discrete event simulation of an automated filling line

Purpose

This case study is analyzed in order to check if the modular discrete event simulation methodology presented in chapter 7 Discrete Event Simulation for Modular Manufacturing Systems is valid, in specific the production engineer role described in chapter 7.7.2 Production engineers is examined.

Method

The method of this study is described in Figure 34. The method has a *qualitative* (Patel and Tebelius 1987) nature and is made through an *interview* with the project leader of a conducted module development project.

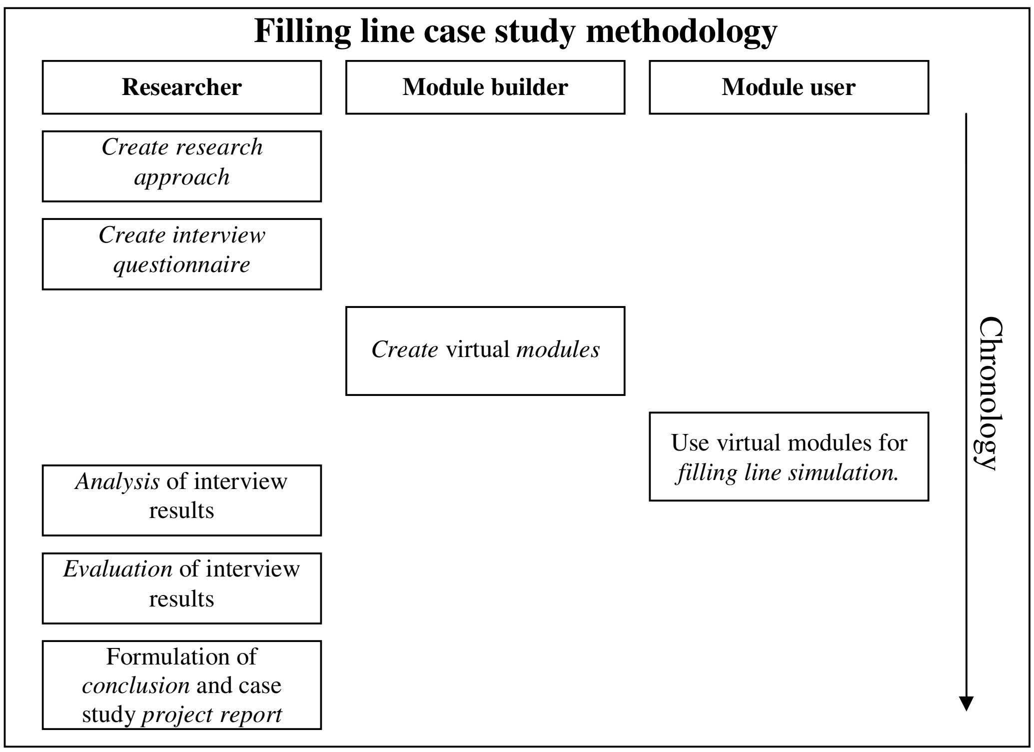

Figure 38 Case study methodology used in case study 8.

Interview questionnaire

During the interview with the project manager, the following questions were asked, and the following answers given.

Q: What was the purpose of the virtual filling line project?
A: The purpose was to prove the functionality and the throughput to the customer and to us.

Q: What does the model look like?
A: A part of the model is shown in Figure 39.

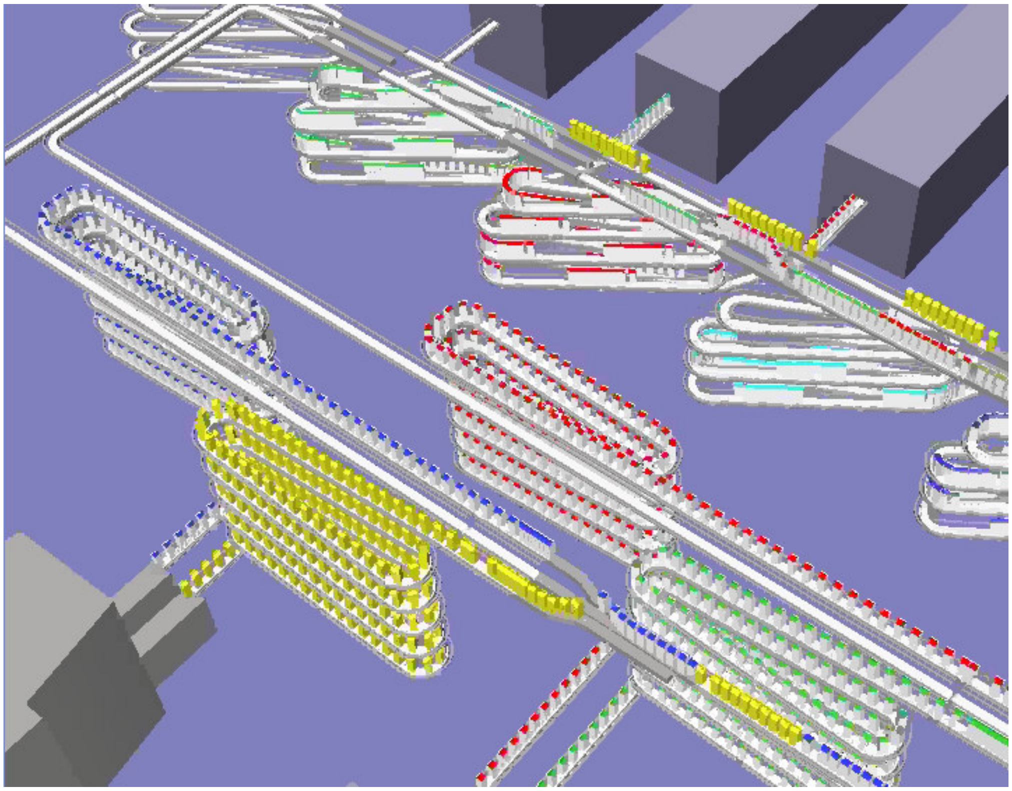

Figure 39 Filling line model used in case study 8.

Q: Who did model the modules?
A: Software experts form both Sweden and Finland made the modules.

Q: Who was intended to use the modules once it was created?
A: I can see several users:

- Our company management
- Our sales force in the hygienic business area,
- Customers
- OEMs.

Q: What lead-time benefits did you find through utilizing the modular discrete event simulation methodology?
A: Probably less than 5% of the lead-time and less than 1% of the cost, when using the modular approach, compared to traditional simulation.

Q: What are the benefits from using this approach?
A: The benefits from using this approach are:

- Fast with short lead-time
- Easy to change and re-use
- Low cost
- Easy to use anywhere you are (memory stick)

Q: What are the setbacks from using this approach?
A: Do not see any, besides maybe the trust in the model and the used data in the simulation.

Q: Was the filling line project successful?
A: Very much so!

Additional comments from the project manager:

The aim of the filling line simulation was to show how the conveyor layout can improve the flexibility and thereby increasing the utilization of the filling machines (which is important for a number of reasons).

There are a number of different possible situations that can happen, depending on the production setup. Three main events were simulated:

1. Breakdown of a filling or packing machine

   Two of the four fillers produce the same product, and the other two produces two different products. So, in this case there are 3 different types of products in the system. Suddenly, for some reason, one packaging machine breaks down. The flow to this machine is then diverted to another packaging machine.
   Packages that were on their way between the diverters to the broken packaging machine and the diverted packaging machine have to be “recycled” on the highway conveyor so that they can be fed to the diverted packaging machine. This recycled flow will momentarily result in more products to the diverted packaging machine than it can handle but the decline conveyors (between the diverters and the packaging machines) should be able to accumulate them.
   After a while the broken packaging machine is back in operation and the flow is restored. There’s now enough over capacity to quickly take care of any accumulated products in the decline conveyors.

2. New product introduction

   At some point the production of the product from one of the fillers is finished. After a short break a new type of product (i.e. new color) is being produced. This new product can be directed to a packing machine. During this change, the production of other products should not be affected.

3. Product changing packing or filling machine

For the sake of clarity it is nice to show how the packaging machine for a certain product can be changed from one packing machine to another.

Conclusion

This filling line analysis use modules developed by a *internal software experts* (Referred to as “*Simulation specialist*” in chapter 7.5.1 Simulation specialist.) in order to let their own *application engineers* (Referred to as “*Simulation users*” in chapter 7.5.2 Simulation user.) build the virtual models of the filling line consisting of both own conveyor systems and other third party equipment such as filling machines and packing machines. The *customer* buying this filling line (Referred to as “*Simulation observer*” in chapter 7.8 Simulation observer situations) use these models together with the company selling the filling line for verification purposes of the three cases mentioned above Breakdown of a filling or packing machine

Case 9 Modular Discrete Event Simulation of a mechanical workshop

Discrete event simulation software packages have been developing towards modularity since the 1960 when SIMULA was introduced, using the concept of classes and inheritance in the programming code (Nance 1995). Nowadays there are several software packages on the market, which uses modularity in one way or another in order to simplify the model-building phase. Examples of these software packages are FlexSim, GoldSim, Extend, Simul8, QUEST, Automod, Witness, ED, and many more.

Purpose

The background for this case study is that these software packages are supporting the simulation expert in the model-building phase, however the purpose of this study is to examine if a non simulation expert can use the most recent technologies for modular discrete event simulation with success. The purpose of this study is to examine a lathe workshop, which consists of complex routes of products and mixed production.

Method

The method of this study is described in Figure 40. The method has a *qualitative* (Patel and Tebelius 1987) nature and is made through *observations* (Yin 1994) of non-simulation experts building a model of a lathe workshop out of modules.

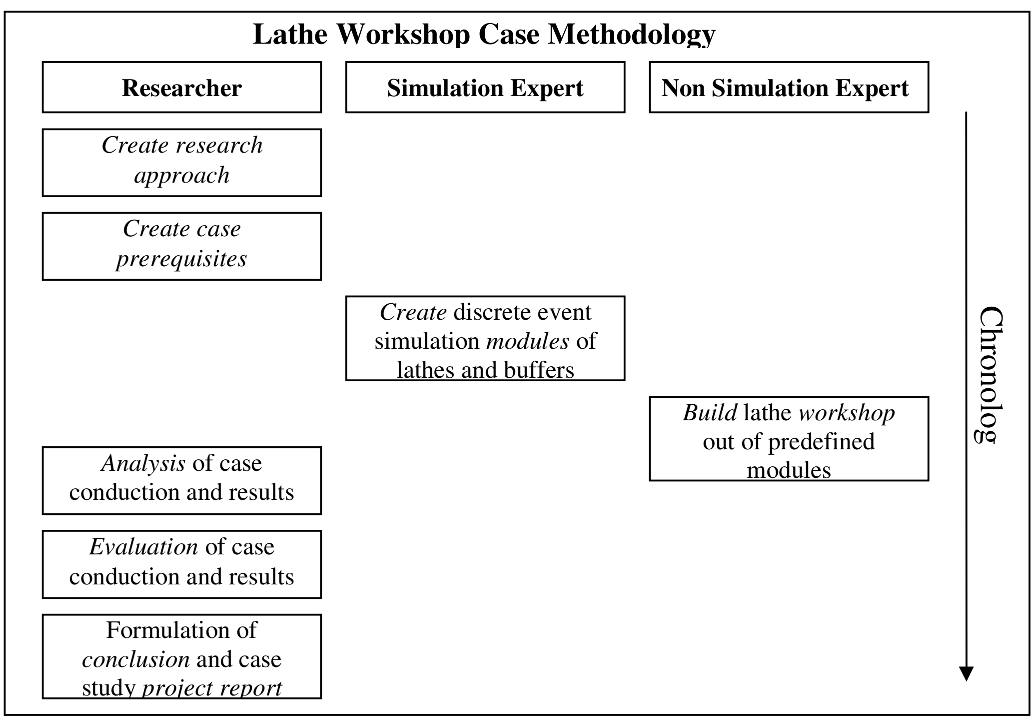

Figure 40 Case study methodology used in case study 9.

Setup

The workshop consists of four lathes (A, B, C and D) used independently by four operators. Each lathe can hold a buffer of 100 products in front of the operation. The products produced in the workshop in relation to priority and orders of operation are shown in Table 18.

Table 18 Products produced in the lathe workshop in relation to operation and priority.

Product	**Priority**	**Operation 1**	**Operation 2**	**Operation 3**	**Operation 4**
Small Candelabra	High	Lathe A	Lathe C	Lathe D	
Large Candelabra	Normal	Lathe A	Lathe C	Lathe D	Lathe B
Small Candleholder	Low	Lathe C	Lathe D		
Medium Candleholder	Low	Lathe C	Lathe B		
Large Candleholder	High	Lathe D	Lathe B		

The lathes, the buffers and the products are pre-modeled as modules in the simulation package. The lathes and the buffers have got predefined connection-points between each other and between themselves internally, i.e. lathe-buffer and buffer-buffer or lathe-lathe has the possibility to connect to each other in the simulation software.

Analysis

The study used two non-simulation experts with high competence on manufacturing systems in general. Each non-simulation expert was creating a model from the setup described above.

The model building started out quite easy for both case study practitioners. They managed to put 4 lathes and 4 buffers out on the manufacturing floor, see Figure 41. However, after introducing the first product on each lathe including the first connections and the cycle-time, problems started to appear:

- Routing the products correctly was *not* successfully executed
- Arranging the products in order of priority level was *not* successfully executed

Since the two last steps were not successfully executed, the case analysis is ended.

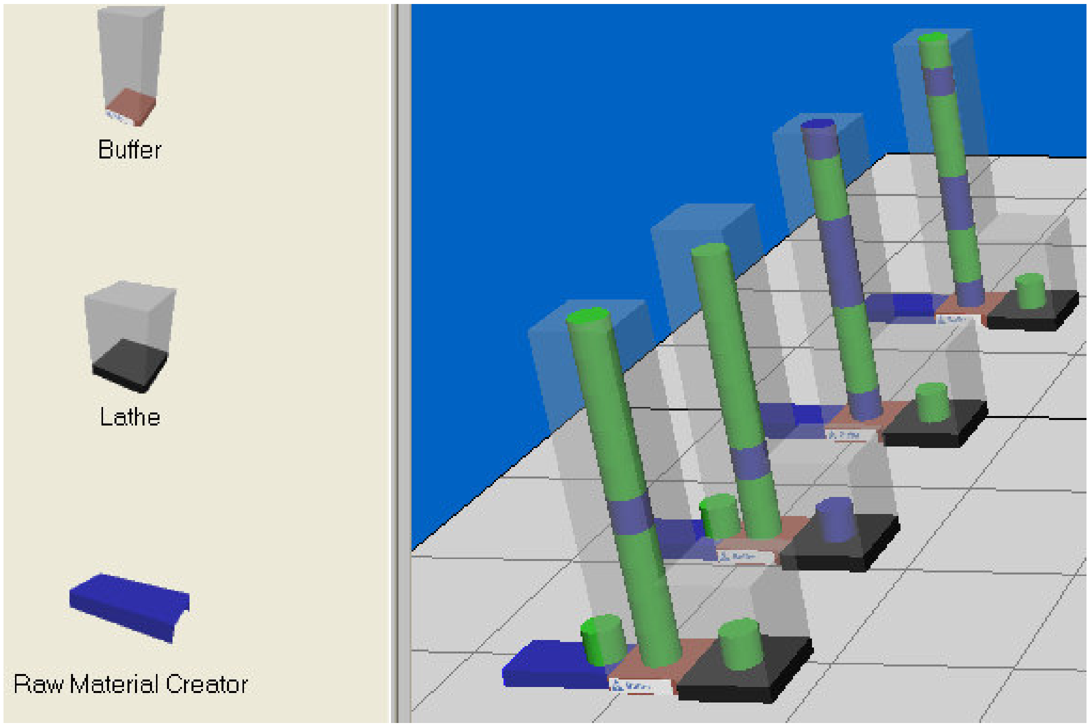

Figure 41 Four buffers and four Lathes processing candelabra parts.

Evaluation

By looking at the accomplished model-building made by non simulation experts, where using the predefined modules of buffers and lathes in order to create a lathe workshop, the evaluation can be summarized as follows:

The lathe and buffer modules are not flexible enough to handle priority and routing. There is enough software support in the software in order to add the functionality; however it requires programming skills and simulation expert knowledge. This result concludes the evaluation: The creation of a lathe workshop as specified above using pre-made parametric lathe modules and modular discrete event simulation methodology is not beneficial for non simulation experts.

Discussion

The functionality and flexibility needed to model unique lathe workshops with discrete event simulation software is multifaceted and no two cases are alike. The requirements on the modules used in this case study are very high and they need to handle too many aspects in terms of flexibility and user friendliness, which are contradicting each other. When the flexibility in the module interface is low, the user-friendliness is high, which means that the non-simulation expert can handle it. On the contrary when the flexibility is high, i.e. when C++, visual basic, or Python programming and alike is available, the user-friendliness deteriorates; see Figure 42.

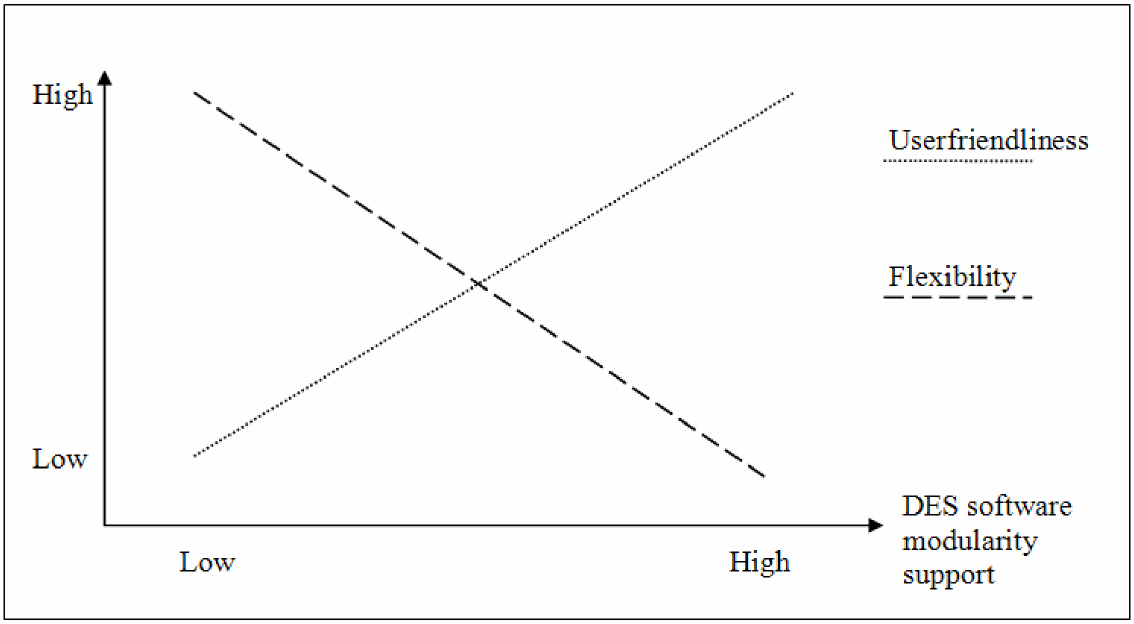

Figure 42 Flexibility and user friendliness in comparison to DES software modular support.

This contradiction explains why workshops are very complex to model in the modular DES manner. The flexibility both in level and in scope needs to be clearly defined in order to fit into the user interface of modular discrete event simulation software. This is not the case with traditional workshops such as the one presented in this case study. It is more suitable for automated material handling systems where the flexibility is determined well before construction of the modules, such as conveyor speed, conveyor length, specific routing modules, etc. This type of parametric flexibility is more profitably utilized in the modular discrete event simulation software.

Conclusion

Modular discrete event simulation is not suitable to use when modeling workshops with flexibility, which is uncertain, i.e. the flexibility needs has to be predefined within the simulation module when the simulation expert creates it. This limitation is constraining the flexibility to the specifics of choice implemented by the simulation expert. Additional flexibility needs will put the non-simulation user in a situation that will require assistance from the simulation expert in order to progress in the model building.

List of acronyms

AMHS	Automated Material Handling Systems
AR	Action Research
BOM	Bill Of Materials
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CIMOSA	Computer Integrated Manufacturing-Open System Architecture
DAS	Dynamic Assembly System
DES	Discrete Event Simulation
DFM	Design For Manufacturing
DOF	Degrees OF Freedom
DRCA	Dynamic Rough Cut Analysis
ERP	Enterprise Resource Planning
FMEA	Failure Mode and Effect Analysis
FMS	Flexible Manufacturing System
FORTRAN	FORmula TRANslation
GASP	General Activity Simulation Program
GERAM	Generalized Enterprise Reference Architecture and Methodology
GPSS	General Purpose Simulation System
HLA	High Level Architecture
HMS	Holonic Manufacturing System
IAR	Insider Action Research
IMS	Integrated Manufacturing System
ISO	International Organization for Standardization
IVA	Royal Swedish Academy of Engineering Sciences
JIT	Just In Time
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
NIST	National Institute of Standards and Technology
NPI	New Product Introduction
NRC	National Research Council
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OLP	Off-Line Programming
PDM	Product Data Management
PROPER	Programme for Production Engineering Education and Research
QFD	Quality Function Deployment
RMMS	Reconfigurable Modular Manufacturing System
RMS	Reconfigurable Manufacturing System
SIMAN	SIMulation ANalysis
SLAM	Simulation Language for Alternative Modeling
SMED	Single Minute Exchange of Die
SPS	Scania Production System

SSG	Simulation Study Group
TPI	Transfer Product Introduction
TPM	Total Productive Maintenance
TPS	Toyota Production System
TTM	Time To Market
WIP	Work In Process
VR	Virtual Reality
VSM	Value Stream Mapping

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 2002)

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 2002)

Definition 5. Effectiveness

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

Definition 6. Efficiency

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

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
2. A happening or occurrence.
3. An occurrence defined in the theory of relativity as a single point in space-time.
4. 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. (American Heritage 1996).

Definition 11. Manufacturing

The process of making wares by hand, by machinery or by other agency, often with the provision of labor and the use of machinery. (Zoning Ordinance (Chapter 108), Article II Definitions, Accessed 20 June 2005 http://www.twp.cranberry.pa.us/codes/zoningordinance/zon2.html)

Definition 12. Flexibility

Flexibility is the adaptive response to unpredictable situations. (Gupta and Goyal 1989)

Definition 13. Module

A module is a software entity that groups a set of (typically cohesive) subprograms and data structures. Modules promote encapsulation (i.e. information hiding) through a separation between the interface and the implementation. (http://en.wikipedia.org/wiki/Module_(programming) , accessed 30 June 2005)

Definition 14. Holon

Holon describes the hybrid nature of sub-wholes/parts in real-life systems, which means that holons are simultaneously self-contained wholes to their subordinated parts, and dependent parts of a larger whole that contains it (Tarumarajah et al 1998).

Definition 15. Autonomy

Autonomy is defined as the capability of an entity to create and control the execution of its own plans and or strategies (Seidel and Mey 1994)

Definition 16. 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. (American Heritage 1996)

1234567.89 is data.

Definition 17. 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. (American Heritage 1996).

"A person calls you and says that your bank balance has jumped 8087% to $1234567.89" is information.

Definition 18. 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. (American Heritage 1996)

"Nobody owes me that much money, something strange has happened" is knowledge.

List of Figures

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Appended Papers

Paper 1, An Enhanced Methodology for Reducing Time Consumption in Discrete Event Simulation Projects

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.

Paper 2, An Evaluation of Discrete Event Simulation Software for ”Dynamic Rough-Cut Analysis”

Johansson B., Johnsson J., Ericsson 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.

Paper 3, Turn Lost Production into Profit. -Discrete Event Simulation Applied on Resetting Performance in Manufacturing Systems

Johansson B., Kaiser, J. 2002. *Turn Lost Production into Profit. -Discrete Event Simulation Applied on Resetting Performance in Manufacturing Systems*, in 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.

Paper 4, Information structure to support Discrete Event Simulation projects

Johansson, B., Johnsson, J., Kinnander A., 2003, *Information structure to support Discrete Event Simulation projects*, in Proceedings of the 2003 Winter Simulation Conference, ed. S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, New Orleans, Louisiana, Dec 7-10, (Invited Paper).

Paper 5, Modular Assembly Systems Simulation for Lead Time Reduction

Johansson, B., Johnsson, J., Bagiu, J., 2004, *Modular Assembly Systems Simulation for Lead Time Reduction*, The 2nd International Precision Assembly Seminar IPAS2004, February, Bad Hofgastein, Austria.

Paper 6, Profitable Intelligent Manufacturing Systems for the Future

Bagiu, J., Johansson, B., 2004, *Profitable Intelligent Manufacturing Systems for the Future*, The 35th International Symposium of Robotics ISR 2004, March 2004, Paris, France.

Paper 7, Using Autonomous Modular Material Handling Equipment for Manufacturing Flexibility

Johansson, B., Williams, E. J., Alenljung, T., 2004, *Using Autonomous Modular Material Handling Equipment for Manufacturing Flexibility*, in Proceedings of the 2004 Winter Simulation Conference, ed. R .G. Ingalls, M. D. Rossetti, J. S. Smith, and B. A. Peters, Washington DC, 5-8 December 2004. (Invited Paper).