Production simulation as a management tool

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“I did it my way”
Abstract
This thesis focuses on process simulation and modelling in the context of production engineering. The thesis is presented in the form of seven papers which range in content from the holistic analysis of the application of modelling (papers 1-5) to a detailed examination of some of the areas of weaknesses in commercially available software (papers 6 and 7).

The papers can be summarised as follows;

Paper 1, *The Use of Virtual Reality Tools in Complex Work Cell Implementation - Experiences from Scandinavian Industry*; The main contribution of this work is a demonstration of the ability of process modelling tools to predict risks and disturbances during the implementation of robotic based manufacturing cells.

Paper 2: *The Virtual Arena; experiences from the first industrial application of a new AMT implementation methodology*; The main contribution here is a preliminary outline of a methodological approach for the application of process modelling tools in the development and implementation of AMT (advanced manufacturing systems).

Paper 3: *A new Modelling Approach to Support Identification and Development of Secondary Processes in an Industrial AMT Implementation*; The main contribution of this paper is a demonstration of extended process mapping and a modelling approach involving both main and supporting processes and the importance of staff competence.

Paper 4: *Competence requirements and their impact on manufacturing system performance*; This paper explains how staff competence can be implemented into process models to obtain a more representative simulation of overall system performance.

Paper 5: *Modelling the impact of supporting processes on manufacturing system performance – experiences from an industrial case study*. This paper demonstrates the use of the method introduced in paper 5 and its applicability in small cell configurations and SMEs.

Paper 6: *The effect of process interruption and scrap on production simulation models*; This paper investigates an area of weakness in commercially available simulation software; the treatment of breakdown related scrapping events. The paper explains the different types of breakdown/scrapping dynamic possible for any given machine and demonstrates the effect of these scrapping dynamics on the Overall Equipment Effectiveness. The paper demonstrates (for the first time) the need for careful analysis and the correct choice of breakdown/scrapping dynamics in simulation models.

Paper 7: *Simulation of production lines involving unreliable machines; the importance of breakdown statistics and the effect of machine position*; This paper the importance of choosing the correct values and statistical distributions for breakdown frequency and duration when simulating production line productivity. The pitfalls of making the wrong choices from those offered in commercially available software are pointed out. The paper also demonstrates that the common technique of reducing the standard deviation of variables to obtain a more deterministic model can lead to inaccurate results. Also, it is demonstrated that the productivity of a production line can be improved by simply re-arranging the order of unreliable machines in the line.
List of publications

The thesis is composed of the following seven publications:

**Paper I:**
Ilar, T, Legge, D, Kinnander, A
*The Use of Virtual Reality Tools in Complex Work Cell Implementation - Experiences from Scandinavian Industry*
Proceeding of the VRW-96 Conference, Stuttgart (DE), Feb. 1996

**Paper II:**
Ilar, T, D. Legge, H. Bylesjö, U. Eriksson, A. Kinnander
*The Virtual Arena; experiences from the first industrial application of a new AMT implementation methodology*
Proceeding of 29th ISATA Conference, Florence (I), 3-6 June, 1996

**Paper III:**
Ilar T, Kinnander A
*A new Modelling Approach to Support Identification and Development of Secondary Processes in an Industrial AMT Implementation*
Proceeding of the 4th ICCIM, Singapore, 21-24 Oct., 1997

**Paper IV:**
Kinnander, A., T. Ilar, U. Eriksson
*Competence requirements and their impact on manufacturing system performance*

**Paper V:**
Ilar, T., A. Kinnander
*Modelling the impact of supporting processes on manufacturing system performance – experiences from an industrial case study*
Proceeding of the 32nd CIRP International Seminar on Manufacturing Systems, Leuven (B), 24-26 May, 1999

**Paper VI:**
Ilar, T., J. Powell, A. Kaplan
*The effect of process interruption and scrap on production simulation models*
Submitted to the Journal of Simulation (2007)
also in: Proceedings of 2nd International Conference on Changeable, Agile, Reconfigurable and Virtual Production (CARV 2007), Toronto, Ontario, Canada, 22-24 July 2007

**Paper VII:**
Ilar, T., J. Powell, A. F. H. Kaplan:
*Simulation of production lines involving unreliable machines; the importance of breakdown statistics and the effect of machine position*
Submitted to the International Journal of Simulation Modelling (2007)
Preface

I would like to thank, together with the NUTEK, my former supervisor Professor Anders Kinnander as well as my former colleagues Hans Bylesjö, Ulf Eriksson and David Legge for their fruitful inputs to the development of the work presented in the first five papers of this thesis.

I would like to thank Professor John Powell for his help and encouragement during the final stages of my PhD studies.

I would also like to thank my supervisor Professor Alexander Kaplan and my former and present colleagues at the Division of Manufacturing Engineering for their help and assistance.

Last, but not least, I would like to thank my beautiful wife, Susanne, and my two wonderful children, Sandra and Gustav, for making it all worthwhile.
# Table of contents

Abstract ....................................................................................................................................... i  
List of publications .................................................................................................................... iii  
Preface ....................................................................................................................................... v  
Table of contents ...................................................................................................................... vii  
1. Thesis structure and theme ................................................................................................. 1  
2. Motivation ............................................................................................................................ 2  
3. Methodological approach ................................................................................................. 3  
4. Process modelling tools ..................................................................................................... 3  
  4.1 Introduction ...................................................................................................................... 3  
  4.2 Process mapping ............................................................................................................ 4  
  4.3 Geometric simulation ................................................................................................. 5  
  4.4 Discrete event simulation ............................................................................................ 6  
  4.5 Production simulation methodologies ........................................................................ 10  
5. Summary of papers ........................................................................................................... 12  
  5.1 Paper I – The use of virtual reality tools ........................................................................ 12  
  5.2 Paper II – The virtual arena .......................................................................................... 13  
  5.3 Paper III – A new modelling approach ....................................................................... 14  
  5.4 Paper IV – Competence impact ................................................................................... 15  
  5.5 Paper V – Modelling the impact of supporting processes ........................................... 16  
  5.6 Paper VI – The effect of process interruption and scrap ............................................. 17  
  5.7 Paper VII – Breakdown statistics and machine position ............................................. 19  
6. Discussion and conclusions ............................................................................................... 20  
7. Suggestions for further research ....................................................................................... 23  
8. References ......................................................................................................................... 24  

Paper I: The Use of Virtual Reality Tools in Complex Work Cell Implementation -  
Experiences from Scandinavian Industry ................................................................................. 27

Paper II: The Virtual Arena; experiences from the first industrial application of a new AMT  
implementation methodology ............................................................................................... 41

Paper III: A new Modelling Approach to Support Identification and Development of  
Secondary Processes in an Industrial AMT Implementation ................................................. 53

Paper IV: Competence requirements and their impact on manufacturing system performance.  
.................................................................................................................................................. 65

Paper V: Modelling the impact of supporting processes on manufacturing system  
performance – experiences from an industrial case study ................................................... 73

Paper VI: The effect of process interruption and scrap on production simulation models ..... 81

Paper VII: Simulation of production lines involving unreliable machines; The importance of  
breakdown statistics and the effect of machine position ..................................................... 95
1. Thesis structure and theme

In brief, the papers comprising this thesis begin with a holistic view of the applicability of different production modelling tools for management support and end with a detailed investigation of the hidden and unexpected problems of so called user friendly production simulation packages. The main common theme is a drive towards a more effective use of production simulation.

This thesis consists of seven papers which deal with the subject of process simulation and modelling in the context of production engineering. The first five papers consider various aspects of the application of simulation and process modelling to the management of engineering firms with a focus on the organisational factors. The final two papers investigate a specific area of process modelling which has not previously been researched: the simulation of process interruption and the time wasted in producing scrap components.

The main theme of the first paper is the use of simulation tools to support management in the development and implementation of an automated production cell. The paper also outlines the relationship between different application areas for production simulation. This discussion is further developed in the second paper, which analyses the ability of various production modelling tools to give support in the different phases of the implementation of an automated production cell, from the identification of performance measures to operator training. Both papers discuss the technical aspects of a cell implementation but the second paper also raises the subject of staff training. This is further stressed in the third paper where a two step modelling methodology is described with its main focus on the support processes which, in most cases, are organisational and human dependent. This paper also introduces the implementation of learning curve equations and a staff competence matrix in production simulation models.

The fourth and fifth papers demonstrate how competence and skill development affect performance measures, in terms of system productivity, and model accuracy. The effect of different management approaches is also demonstrated. The fifth paper introduces a small scale, SME oriented application including the implementation of internal expert support in competence development.

Papers six and seven focus on the accuracy of commercially available production simulation models, especially in the context of machine failure and part scrapping. The sixth paper introduces the previously neglected subject of breakdown imposed scrapping and its effect both on the equipment and system performance. In paper seven two other effects are analysed; those of machine positioning a production line and the need for careful choice of statistical distribution for the variables involved in any simulation model.

The aspects of ‘production simulation as a management tool’ covered by this group of papers are summarized in the table below;

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Table 1: The different focus areas of the seven papers comprising this thesis.
2. Motivation

This thesis work started during a research program, PIDUS, which began in 1994 with the aim of developing methodologies to assist in the design, installation and optimisation of production systems which are, by their very nature, complex. Production modelling and simulation tools were to be used to support the methodologies. This research program was, in part, initiated from the experiences of Swedish industry which showed that complex production systems seldom reached planned production rates following commissioning and, in some instances, never reach the planned production rates even after post commissioning development. The total investment in new production systems within Swedish industries is approximately 30 billion Swedish Crowns (3 billion euro) per year. The economic impact of developing a method which reduced unpredictability and unnecessary long implementation times is therefore significant.

Implementation of advanced manufacturing technology (AMT) almost invariably involves a high degree of technical as well as organisational complexity and risk. Traditional project management is usually very much focused on the technical aspects of the implementation and often neglects issues concerning the man-machine interaction. On the other hand, the degree of success of this type of project is often dependant upon operative staff developing a good understanding of the system.

The use of production simulation for decision support in this kind of project is now quite commonplace. However, its use is usually limited to evaluating alternative technical configurations and seldom takes supporting processes\(^1\) into account. In many cases, the actual gains from technical simulations are of limited benefit to the project as a whole due to poor correlation between the model and the real system.

The growth of simulation during the last 10 to 20 years has, in spite of the large number of tools available with high quality user interfaces, been weak and significantly overestimated [1].

The objective of this work is the development of methodologies and understanding to promote a more effective use of production simulation as a management tool. From this general objective following two research questions were formulated:

**Q1:** Can a method proposing an enhanced model scope (which includes the supporting processes\(^1\)) increase the usefulness of production simulation as a management tool in the context of the development and implementation of manufacturing systems?

**Q2:** What are the risks and limitations of so called user friendly (no programming required) production simulation software?

The first research question was the result from industrial studies in the early phase of the PIDUS project. The second research question was gradually developed from my consulting and teaching activities between 1999 and 2005.

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\(^1\) Supporting processes are defined as those not directly related to the customer value change, but in this thesis the term is restricted to the processes closely related to the factory cells, such as programming, tool preparation, maintenance and planning.
3. Methodological approach

Saunders et al. [2] state that a research strategy is a general plan of how to answer the purpose of the study. There are four main strategies:

- Experiment
- Survey
- Case study
- Action research

The method chosen for the bulk of this research (papers 1-5) was the use of industrial case studies aimed at investigating the benefits of the methodology proposed and developed during the work. The intention of this approach is to obtain involvement and feedback from the industrial partners in order to make the research results more industrially relevant. The final part of this thesis (papers 6 and 7) involved direct computer based experimentation to investigate an area of weakness in the application of commercially available simulation software.

4. Process modelling tools

4.1 Introduction

This section provides a description of the tools and concepts used during this research (IDEF0 for process mapping, geometric simulation for cell design and discrete event simulation for production system analyses). The different aspects of discrete event simulation are described including; the user interface, modelling of disturbances, successful simulation, inside simulation, human factors and production simulation methods. These subjects are discussed in the different papers composing this thesis.

One important component of the research was the use of commercial production modelling and simulation software. Simulation, in this context, is defined as the imitation of a system based on knowledge or assumptions regarding the behaviour of parts of the system, with the purpose of obtaining insights into the behaviour of the system as a whole. A system is defined as a set of interacting components which work together to achieve some pre-defined objectives. Commonly encountered systems include hospitals, airport check-in and industrial plants. Such systems are often large and complex and would be difficult and expensive to experiment with directly. A model is defined as an abstract and simplified representation of a system which includes the most important system components and the behaviour or interaction between these components [3]. One important, but often difficult task for the “simulator” is to define a suitable level of representation with respect to the overall objectives of the simulation study.

Simulation is one of several alternative methods of analysing systems. As already mentioned, it is also possible to experiment with the real system. Another technique is the use of mathematical analysis. Unfortunately mathematical analysis is limited to a relatively small
number of simple systems and the opportunity to represent manufacturing systems in this way is felt to be limited.

Simulation software is generally categorised as using either a continuous or discrete time representation. The first type is used for simulation of, for example, kinematic systems such as industrial robots where the status of the system can change continuously. In this case, the simulation program can calculate the path of the robot’s tool centre point using inverse kinematics. Other systems however, only change at discrete points in time. For example, in an industrial plant, the system status changes when a new part arrives at a machine or when a machine breaks down. Between any two events, the status of the modelled system remains constant. To represent the changes in the system, it is only necessary to describe the actions or events which cause the status of the system to change. This is referred to as discrete event system modelling.

4.2 Process mapping

A process can be defined as a chain of more or less dependent activities involving the resources needed to obtain a certain output or goal. An organisation can include a high number of processes, which are usually divided into main and supporting processes. The main processes consist of those activities that create value from the customer perspective and supporting processes consist of those activities needed to maintain the main process.

IDEF [4] is a group of modelling methods that can be used by an enterprise to describe different information and operations within it. IDEF stands for ICAM Definition, where ICAM is an acronym for the US Air Force program for Integrated Computer Aided Manufacturing. It was first introduced in the 70 and was originally developed for manufacturing environments only. IDEF is now under continuous development by Knowledge Based Systems Inc and has, since the 70’s, been adapted for wider use. The principles of IDEF methods are to aid in design, planning, analysis, improvement or integration in manufacturing systems.

There are 16 methods within the IDEF family and of these; IDEF$_0$ and IDEF$_3$ are most suited for manufacturing system design.

**IDEF$_0$**

This IDEF method, known as Function modelling, allows the user to create a graphical model (IDEF$_0$ diagram) consisting of boxes that represent a manufacturing function or activity. The information in these diagrams shows us: a. what is performed by the function (output), b. what is needed to perform the function (input), c. the controls that determine how input is transformed into output and d. the mechanisms that are guided by controls when transforming input to output (see figure 1).
Figure 1. *The IDEF₀ Diagram and its ICOMS, (inputs, controls, outputs and mechanisms)*

The IDEF₀ diagrams usually consist of between three to six high level activities/functions which can be expanded to lower level activities representing its inner structure (see figure 2).

![Diagram](image)

**Figure 2. A hierarchical structure of IDEF₀**

The main strength of IDEF₀ is that the diagrams give the user a good detailed description of manufacturing activities and resources (ICOMS). Its hierarchical structure allows the user to access information which is as detailed as needed for decision making.

### 4.3 Geometric simulation

Geometric simulation software use continuous time simulation techniques which enable the modelling of complex kinematic systems such as industrial robots as well as the information flow (signals etc.) associated with the operation of robot based cells. A good kinematic model of the robots is, of course, the main pre-requisite for realistic simulation and commercial robot simulators invariably include a library of models of most industrial robots found in the market. The robot model will include details of the number, type, orientation and operating limits of joints, the length of links, and the velocity, acceleration and deceleration capability of individual joint actuators. An inverse kinematic model of the particular robot configuration allows the system to determine and simulate the robot path between target points. Simulators also usually have a post processor to support off-line programming of the equipment being modelled.
Off-line programming is probably the best known application of robot simulation software. However, such systems are also used for detailed cell design, where the focus is on the capability of the proposed equipment, prediction of process times and collisions tests. Robot simulators can also be used to model human kinematics and thus can be used for ergonomics studies. Whilst they have been commercially available for the best part of 20 years, robot simulators are only now starting to find widespread use in industry. This is mainly due to the fact that the complex calibration process necessary to obtain a realistic model of the actual robot has been simplified during recent years and this has lead to more reliable off-line programming results. Other reasons which have affected take up, and which are true for virtually all production related software, are better user interfaces and price reductions coupled with the need to reduce product life and cope with shorter product runs and/or smaller batch quantities - all of which demand frequent re-programming of a robot cell.

4.4 Discrete event simulation

Production simulation systems are a group of discrete event simulation software packages specially designed for the representation of manufacturing systems. Such software is characterised by a high level user interface consisting of pre-defined objects for modelling the different resources typically found within a manufacturing system. The role of the user is to select appropriate objects and to provide specific data related to these such as; the relationship between objects, operation times, availability of resources, mean time between failure and levels of scrap or re-work. Unfortunately most software of this type also requires a significant amount of low level programming in order to fully describe the behaviour of the system. However, the software often has a number of pre-defined manufacturing related performance measures such as machine utilisation, lead time and work in process, built in as standard.

Discrete event computer simulation has been in use since the 1960’s for designing manufacturing systems, but it was not until the middle of the 80’s this kind of software could truly be defined as production simulation. The main use of this kind of software has been for decision support when evaluating different known alternative system configurations [5]. However, development during the last few years has lead to increasing use of high end 3D visualisation. This has made it possible to change the focus from supporting individual decision makers towards communicating information about the system to groups of people [5]. A good example of the latter is the SSIT\(^2\) method for individual and organisational learning [6] which was developed by Linköping university within the PIDUS program. The SSIT method incorporates the use of tailored production simulation models to allow the participants to work with problems associated with their own company. Training sessions are carried out in several stages where the complexity of problem tackled is gradually increased. Each session is followed by a group discussion to promote a common understanding among the participants of the problems being tackled.

User interface:
The main aim of any production simulation software is the accurate representation of real situations. It is also highly desirable that process engineers with limited programming skills should be able to perform the modelling process [7-9]. From such modelling exercises, the engineers and management can make strategic decisions about capital investments and

\(^2\) Simulation Supported Industrial Training
staffing levels etc. The phrase “user friendly” is also often used by software vendors as one of the main features of their production simulation package.

**Modelling production disturbances;**

Methods for applying simulation to the modelling of production disturbances and breakdowns have been discussed by several authors [10-16]. For example, Ingemansson et al [17-18] have reviewed a number of cases where production simulation was applied to the problem of optimising system performance. This type of work often includes machine breakdowns and in some cases part scrapping, but any possible links between machine breakdown and scrapping are ignored. Law [19] has demonstrated the importance of the correct interpretation of breakdown characteristics in achieving high model accuracy but this analysis involves only secondary performance measures (i.e. buffer size and product lead time) and not the overall productivity of the system in question. Papers 6 and 7 of this thesis demonstrate how the modelling of production disturbances needs to be improved in commercially available software.

**Successful simulation;**

Sadowski [20] defines a successful simulation project as one “that delivers useful information at the appropriate time to support a meaningful decision” (see figure 3).

The right information has the correct perspective for the audience for which it is intended, providing the information they need and the purpose of that information. The right timing is, of course, critical for the success of the project – “a high-fidelity answer that is too late to influence a decision is not nearly as good as a rough-cut estimation that is in time to help”. The last element for success, making the right decision, is probably out of the control of the modeller. “Wonderful simulation work, advanced analyses, and eye-grabbing animation, all completed on-time are of no value if they are not delivered to the right person in the right context”.

Robinson and Pidd [21] take these ideas somewhat further and propose a four-stage model of simulation project success shown in figure 4. The first stage implies that the simulation has achieved its objectives, or if that not the case, that some benefits has been derived from the work. This requires a correct conceptual model and a credible translation to a computer model. Stage 2 implies that the results are accepted, which requires more than just getting the right
results. Here organisational politics might have a significant impact on acceptability. The success of the next stage, the implementation, depends on the organisation knowing what to do and then implementing it. Once again, organisational politics and economic realities (lack of funding) might result in failure. The final stage involves checking whether the result of the study was correct once the recommendation was implemented. It is important to keep in mind that a typical time span, from the start of the study to when results from the implementation are available, can be several years.

The performer of a simulation project can only take responsibility for the stages 1 and 2 by providing a valid model and suitable communication to insure acceptance.

**Inside simulation:**
Thomas Schriber and Daniel Brunner [22] describe some aspects of how simulation works and why it is important to understand the details. As they point out, a “black box” approach is often taken in teaching and learning discrete-event simulation software. The external characteristics of the software are studied, but the foundations on which the software is based are ignored or are touched on only briefly. They also point out some examples of when a greater understanding would be helpful, such as the re-capture and allocation of resources.

Their proposal for dealing with this problem is to use “interactive runs to put a magnifying glass on a simulation model while it executes. The modeller can follow the active entity step by step and display the current and future events lists and the delay and user-managed lists as well as other aspects of the model. These activities yield valuable insights into model behaviour for the modeller who knows the underlying concepts. Without such knowledge, the modeller might not take full advantage of the interactive tools provided by the software or, worse yet, might even avoid using the tools”. It is, of course, debatable whether the inappropriate use of a particular tool is worse than ignoring it altogether.

The foundations of simulation software have also been discussed by Stewart Robinson [23], who also points out the different approaches for resource allocation and different definitions of mean time between failure (MTBF). In some software this is defined as the time from when a failure occurs to the next failure and in other cases it describes the time from when the machine is repaired to next failure. This might give high model errors if the modeller is not fully aware of the definitions involved.

**Human factors:**
One approach to modelling skill and competence development within an industrial organisation is the use of a theoretical learning curve. Learning curve theory has been applied to a wide range of industrial applications that include human operators in complex tasks such as assembly [24].
Rita Freudenberg and Henry Herper [25] describe an approach to the simulation of workers in manufacturing systems. They stress the importance of modelling workers in varying levels of detail which match the level of detail in the simulation model.

Modern production simulation software makes it quite easy to build models that consider many system variables and which reproduce the dynamic interactions of resources and the time dependence of activities. However, despite the sophistication of the technique, it has been observed that gaps can exist between the performance of the system predicted by DES models and the output which the real system generates in practice. A possible visualisation of this gap is shown in Figure 5, with simulation providing and over-optimistic representation of reality [26].

The situation described by figure 5 has been found to occur to a wider extent when the systems contain more human elements [27]. Modelling practitioners tend traditionally to consider people quite simplistically and to concentrate on the prediction, planning and positioning of the technological elements of the systems.

A more accurate representation of worker’s behaviour could be provided within the DES technique through a human performance modelling tool that integrates with computer-based simulation to give a holistic view of system performance [27-28]. Figure 6 illustrates the form that such a view would take within the context of manufacturing systems design. The human performance modelling tool is shown in the figure passing information about worker performance to a DES model and taking information on the factors that influence this performance as an input. To create such a modelling tool requires an in-depth understanding of the determinants of worker behaviour. In other words, a framework is needed to capture the worker’s key rules, assumptions, and relationships.
The human performance model suggested by Baines and Kays [29] is very complex and includes individual aspects (i.e. extroversion, job satisfaction, age and work attitude), the physical environment (i.e. noise level, temperature and ventilation) and the organisational environment (i.e. shift patterns, work teams, training, job rotation and hierarchical structure). This is a very ambitious approach but is also very challenging for simulation modellers.

4.5 Production simulation methodologies

One method of describing the steps in a simulation study which is often referred to was first presented by Banks et al [30]. The method is shown in figure 7 (based on Ingemansson’s and Bolmsjö’s interpretation [17]), where DES stands for Discrete Event Simulation. The last steps, implementation and follow-up, are well in line with the four-step model for simulation project success described by Stewart Robinson [23] (see section 4.4). However, it is questionable if these are tasks for the simulation project management team. As mentioned earlier these might be influenced by a number of other factors.

One of the more challenging steps in a simulation project is the development of the conceptual model. Stewart Robinson [23] has presented a framework for conceptual modelling (see figure 8). The first element in the framework is an understanding of the problem and the expectations of the simulation project. The next element is the determination of a set of modelling objectives. These are the foundation for the development of the conceptual model.
Ingemansson and Bolmsjö [17] have introduced a method where discrete event simulation and disturbance reduction techniques are integrated into a common tool for the improvement of manufacturing systems. There are three main functions included in the method (see figure 9): the creation and evaluation of data concerning the causes of disturbances; the test of different alternatives for disturbance reduction; and the application of the findings to the real system.
5. Summary of papers

5.1 Paper I – The use of virtual reality tools

The Use of Virtual Reality Tools in Complex Work Cell Implementation - Experiences from Scandinavian Industry

This paper outlines the use of commercial simulation tools with powerful 3D graphics to augment the traditional project management activities involved in the installation of a manufacturing cell at Scania Chassis Components in Luleå. A novel use of this kind of software in this project was for the education and familiarisation of workshop staff with the new cell prior to installation.

The paper presents a retrospective analysis of the project including validation of the model and discussion of the expectations and experiences of the project team as well as comments concerning prediction of results. The benefits and current limitations of this kind of simulation software during the various phases of this type of industrial project (see figure 10) are also presented along with practical suggestions concerning the use and future development of high end computer graphics (VR) in industry.

![Figure 10](image)

Figure 10  Different virtual reality tool features and their applicability in different stages of the development and implementation of manufacturing systems.
The reasons for deviation from predicted performance of the various processes in the cell such as handling, welding and grinding, have been investigated and the ability of the robot simulations to predict these disturbances has been evaluated. This investigation highlighted the inability of the robot simulation software to provide the project leader with realistic performance measures of the cell. This type of software would have made a much greater contribution to the project if it had been used to support communication within the project group in order to improve a common understanding of system complexity and the risks associated with the technical system being installed.

5.2 Paper II – The virtual arena

The Virtual Arena: experiences from the first industrial application of a new AMT implementation methodology

The second paper introduces the concept of the Virtual Arena (VA), which aims to link software suites supporting system modelling (IDEF0), production simulation (discrete event and continuous) and the ‘virtual factory’ (commonly used in support of AMT projects) into a seamless environment. Central to the VA concept is the use of different types of process modelling tools at different abstraction levels and the migration of data between these tools to support holistic system design. This paper outlines how the VA concept can be applied to support the implementation of complex manufacturing cells and is based on two case studies carried out in co-operation with Scania AB. The importance of addressing supporting processes to the successful implementation of AMT is also discussed. The application of various modelling tools to a case study is summarized in figure 11.

![Figure 11 Different modelling tools applied to a case study and their expected benefits as an management tool.](image-url)
5.3 Paper III – A new modelling approach

A new Modelling Approach to Support Identification and Development of Secondary Processes in an Industrial AMT Implementation

This paper discusses (in more depth than the previous paper) the importance of the modelling of supporting processes in order to obtain a realistic evaluation of advanced semi-automated manufacturing systems. Also, the need to introduce two level modelling techniques to support this evaluation is introduced. The paper also outlines a general approach for the implementation of advanced manufacturing systems using computer modelling. Some of the key features of this approach have been investigated in an industrial case study carried out in co-operation with Scania.

Figure 12 Two levels of the IDEF0 schema applied to an industrial case study with the purpose of identifying activities, resources, controls etc. for the supporting processes.

The main conclusions from this work were:

- The two level modelling method applied in this investigation offers excellent opportunities to support a deeper understanding of the interaction between the main and supporting processes in an AMT system. These interactions are often neglected but have a great impact on the total system efficiency. The use of process mapping tools (see figure 12 above) together with production simulation offers the opportunity to identify the most important process and activities, and to use dynamic analyses to communicate the important system characteristics to a broader audience within a company.

- The best source of knowledge about support processes is the work force and it is therefore of great importance to obtain models which can be easily communicated to this group. This does not necessarily require the use of high end 3D visualisation...
tools, but demands a close working relationship between the “modeller” and the project group.

- The investigation and active development of supporting processes can drastically improve the quality and scope of the actual system behaviour. Modelling this behaviour allows an increase in understanding of the staff and operators.

### 5.4 Paper IV – Competence impact

*Competence requirements and their impact on manufacturing system performance*

Research into “Next generation manufacturing systems” stresses the use of semi-automated systems to handle short product life cycles and customer oriented production. Despite our increasing dependency on technology, the importance of humans is expected to increase and to provide a realistic basis for decision support. Therefore, both technical and organisational processes must be included in simulation models. In a rapidly changing environment, skill development is also important and should be considered when developing simulation models.

![Figure 13 The basic layout and flowchart associated with a press line.](image)

This paper presents two case studies which demonstrate the effects of operator and team skill development and the need to include these characteristics when using simulation modelling in order to obtain a realistic evaluation of advanced semi-automated manufacturing systems. In both case studies, technical as well as organisational factors were modelled; technical factors being related to automated activities and organisational factors related to learning curve effects as the number of times a task is carried out increases. The technology dependent, fully automated, activities and the organisational dependent, manual, activities for the first case study, the press line, are shown in figure 13 above.

From these studies it was seen that the inclusion of learning theory in simulation modelling is important when modelling manufacturing systems are characterised by frequent re-
configurations and where productivity is directly affected by the organisation’s ability to adapt. The inclusion of organisational as well as technical factors is of great importance for understanding the effects of human/machine interaction on the overall system performance.

The most important application area for this technique is to support the development of manufacturing systems consisting of highly automated main processes and organisationally oriented supporting process. Traditional project management associated with this type of manufacturing system is usually very technically oriented and often neglects supporting processes. Nevertheless, overall performance is often highly dependent on the performance of the supporting process. The implementation of group competence development in the simulation model supports the management and team members, giving important insights into the expected performance development of the system (see figure 14).

![Figure 14 Outline of the relative performance rate (RPR) development over time for two competence management alternatives.](image)

Another conclusion of this paper is that even systems which are well established can behave in what might appear to be an unpredictable manner when subjected to change.

### 5.5 Paper V – Modelling the impact of supporting processes

*Modelling the impact of supporting processes on manufacturing system performance – experiences from an industrial case study*

This paper presents a modelling method which supports project management, evaluation and performance prediction in manufacturing systems where the interaction of the main process with supporting processes is significant. The method uses process mapping and discrete event simulation as a teaching tool to develop a common understanding of system functionality amongst the project group rather than simply for measuring or predicting system performance.

The processes of interest to this study are outlined in figure 15. It is important to note that the sequential nature of the processes is due in part to the present organisation.
The results of the case study have shown the significant impact that the organisation can have on supporting processes. Technical as well as organisational factors must be combined in any simulation study if the human/machine interaction on the overall system performance is to be identified.

Modelling supporting processes can drastically improve the accuracy of the predicted overall system behaviour. Using this method will thus significantly increase the usefulness of production simulation to develop solutions that are both technically and organisationally sound. Furthermore, mapping the supporting processes through operator participation in the project work increases involvement and gives valuable feedback in the development of the system.

The introduction of learning factors to the discrete event simulation model is also of great importance in achieving reliable predictions of actual system performance resulting from changes within the organisation.

5.6 Paper VI – The effect of process interruption and scrap

The effect of process interruption and scrap on production simulation models

This study explains that, for many manufacturing processes (such as welding and injection moulding), a machine breakdown will result in the scrapping of a component, and goes on to explain the effect that this can have on process simulation models. Breakdown related scrapping events are ignored by commercially available process simulation packages and this reduces their accuracy and thus their usefulness in decision support. This paper explains the different types of breakdown/scrapping dynamic possible and clearly demonstrates the effect that these scrapping dynamics have on the Overall Equipment Effectiveness (OEE – a measure of productivity). The paper clearly demonstrates that the next generation of simulation models needs to include a much more careful assessment of breakdown/scrapping dynamics.
Figure 16 The ideal production situation (100% productivity) and the three different types of breakdown dynamics for the case of: breakdown after 5.5 operations (cycles) and repair time of 2 cycles (\( \sqrt{\text{V}} = \text{acceptable product quality, X = product scrapped, R = repair taking place} \)).

It is clear from figure 16 that the interpretation of breakdown dynamics has a substantial effect on productivity levels. In the example shown, the Type B model produces 9% more products than Type D and 22% more than Type C. In situations where breakdowns are more frequent or cycle times are longer, the differences between the four dynamics would be even greater.

<table>
<thead>
<tr>
<th>Type</th>
<th>Breakdown Dynamics</th>
<th>Productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE A</td>
<td>No breakdown: No scrap</td>
<td>100%</td>
</tr>
<tr>
<td>TYPE B</td>
<td>Breakdown, No scrap</td>
<td>73%</td>
</tr>
<tr>
<td>TYPE C</td>
<td>Breakdown; item scrapped but must be left in machine untill cycle is complete</td>
<td>60%</td>
</tr>
<tr>
<td>TYPE D</td>
<td>Breakdown; item scrapped but remaining cycle time is available</td>
<td>67%</td>
</tr>
</tbody>
</table>

Figure 17 The OEE associated with the four production breakdown dynamics (A-D) as a function of the process time (MTTF = 10 min, MTTR = 2 min).

Figure 17 compares the OEE (Overall Equipment Effectiveness – a measure of productivity) associated with the four breakdown types as a function of process time with a Mean Time To Failure (MTTF) = 23 minutes and Mean Time To Repair (MTTR) = 2 minutes. This figure demonstrates the serious effect which breakdown associated scrapping can have on the OEE of a machine. It is also important to note that the results from the different types of breakdown dynamic diverge rapidly as the process time increases. In this case, for example, the difference between types C and D is only 5% when the process time is two minutes but this rises to 14% at a process time of five minutes.
The most important conclusions from this paper are:

The linkage between breakdowns and scrap is not a feature of commercially available production simulation software. This can result in the software supporting inappropriate conclusions when comparing systems or machines.

Breakdown/scrap dynamics of types A, B can be incorporated into existing production simulation packages quite easily. Type C can be introduced by a skilled software user using existing options. However, there are many non-interruptible engineering processes where dynamic D would be most appropriate to the model. It is extremely difficult to incorporate the type D dynamic into existing commercial simulation software. The lack of availability of the type D dynamic can lead to inappropriate decisions being made when comparing machines or systems.

For all three types of breakdown dynamic (B, C and D), equations which describe the relevant Overall Equipment Effectiveness (OEE) have been developed. These equations could be incorporated in future editions of production simulation software.

It is demonstrated in this paper that, when using production simulation software, the correct choice of breakdown dynamic (A, B, C or D) is essential if the results are to be useful in decision support. It is also clear that existing commercial software is inadequate in this respect.

5.7 Paper VII – Breakdown statistics and machine position

Simulation of production lines involving unreliable machines; the importance of breakdown statistics and the effect of machine position

This paper the importance of choosing the correct values and statistical distributions for breakdown frequency and duration when simulating production line productivity. The pitfalls of making the wrong choices from those offered in commercially available software are pointed out. Statistical distributions with a wide range tend to reduce the productivity of the line but this trend can be disrupted by a poor choice of mean values for the variables in question. The paper also demonstrates that the common technique of reducing the standard deviation of variables to obtain a more deterministic model can lead to inaccurate results. Also, it is demonstrated that the productivity of a production line can be improved by simply re-arranging the order of unreliable machines in the line.

The most important conclusions from this paper are:

The modelled productivity of a production line is highly dependent on the statistical distribution type assigned to each breakdown variable (e.g. Gaussian or triangular distributions of MTTF and MTTR). Statistical distributions with a broad range (such as Gaussian) will tend to result in low productivity. This is because occasional periods of low productivity on a specific machine will not necessarily be balanced by occasional periods of high productivity on that machine if the whole line is considered.

Although an increase in the range of MTTF and MTTR will generally result in a decrease in productivity, this trend can be severely disrupted at small values of standard deviation
or if fixed mean values are used. If fixed or almost fixed values are used it is important that the values are selected very carefully to avoid setting up breakdown ‘rhythms’ which could result in unrealistically high or low productivity results (see figure 18). For the same reason fixed or small standard deviation values cannot necessarily be used to validate the performance of simulation models (This technique of variation reduction for model validation is in widespread use).

Figure 18 Results such as these reveal the difficulties inherent in the identification of reliable trends in the detailed behaviour of production simulation models.

The modelling of any engineering system must consider whether the process involved at each step can be interrupted and later continued to produce a usable component. Many engineering processes such as casting, welding or painting cannot be interrupted and any mid operation breakdown will result in a scrap component.

The productivity of a production line involving unreliable but interchangeable machines is improved if the less reliable machines are positioned towards the end of the line. This effect diminishes as the reliability of the machines in question improves. The magnitude of this effect is strongly dependant on the statistical distribution assigned to the breakdown parameters.

6. Discussion and conclusions

Two research questions were outlined in section 2 and the purpose of this section is to discuss how well the results of this work correspond to these questions.

Q1: Can a method proposing an enhanced model scope (which includes the supporting processes) increase the usefulness of production simulation as a management tool in the context of the development and implementation of manufacturing systems?

To answer the first question an extended simulation method was developed and evaluated through a number of case studies.
The unique feature of the method is its focus on the integration of the supporting systems into the conceptual model of an automated production system. This implies, from the perspective of a project manager, a more holistic view the system design including both the technically dependent main process and organisationally dependent supporting processes. The latter demands an extended project group including staff with knowledge of the supporting processes (i.e. operators and shop floor managers). The focus of the method can be seen in the figure 19.

Figure 19 Outline of the method to support evaluation of scenarios.

The approach supports the step by step reduction of system complexity, from process to individual activities, and thus gives operators and technical staff the opportunity to recognise their role in the supporting processes. It thereby provides realistic inputs in terms of activity scope, time and required resources. This approach has been found to result in a high acceptance of the model by the staff involved in the project. The use of simulation also provides the project group with performance benchmarks to support the development of the system.

On important and unique character of the enhanced simulation model is the inclusion of a measure of operator competence and how this competence is expected to develop during the performance of the different activities in the supporting process. In this case the method used to collect the relevant information in the case studies was mainly interviews and discussions with shop floor managers.

The main advantages of the enhanced model are:

- Common understanding of main and supporting processes interactions.
- More realistic performance measures taking technical as well as organizational (supporting processes, competence and competence build up) aspects into account.
- Opportunity to include learning potential in the evaluation of different alternatives.
- More desirable start up situation and thus reduced commissioning time due to:
  - actual and active participation from the operators (process owners).
  - knowledge capturing.
  - parallel and gradual development of the processes.

This is summarized in figure 20.
There are also some risks/challengers related to the proposed model such as:

- Requirements of a more cross-functional project team which might be harder to manage.
- The capture of the initial operator competence data.
- Increased modelling time and effort.
- A possible reduction of the model accuracy compared to purely technical models due to less accurate data and more stochastic activities.
- The pedagogical shift from a model with the purpose of providing performance measures to that of providing and communicating insights.

Keeping those advantages and risks in mind I believe that the answer to question 1 is yes; the proposed method can increase model usefulness in the right context. The context must be a system where the performance is expected to be affected by the interaction between the main and supporting processes.

The research and method presented by Baines et al [27-29] also demonstrates that the integration of human factors into production simulation model is still on the research agenda. However, I think that their approach is too complex to be industrially applicable and I doubt that there is a positive relationship between the efforts required and advantages of this approach. In that sense I think that our more straight forward approach has greater applicability and can, from the production manager’s perspective, include most of the advantages with much less effort.

**Q2: What are the risks and limitation of so called user friendly (no programming required) production simulation software?**

To answer the second question I first tried to identify a software feature which has not been investigated in previous studies [22] and which has some practical use for industry. The feature selected was part scrapping, more specifically, part scrapping as a direct consequence of a machine failure. The option of part scrapping has been including in simulation software since the introduction of production simulators in the mid 80’s. A common approach uses a percentage distribution where, for example, 10 % of parts are scrapped and routed out from the system and the remaining 90% are routed to next stage in the process. However the opportunity to have a direct connection between breakdowns and scrap is not a standard
feature in simulation software and requires, where it is possible, high level programming skills.

As has been demonstrated (see paper 6), a simplified modelling approach concerning scrap and breakdowns can lead to substantial modelling errors. One might claim that there are always errors in a simulation model due to necessary simplifications and lack of accurate input data. However, it is of great importance, from the perspective of the user of the result, to have some estimation of the level of errors and model accuracy. It will otherwise be hazardous to estimate the usefulness of the results to support any decision.

Models with machine failure imposed scrapping also demonstrate some special features (see paper 7) in terms of machine position effects and changes of the system’s performance due to the choice of mean values of variables and their statistical distribution. Both these effects are the consequence of dependent events where the failure of a machine leads to the loss of the process time. Depending on the mean value and deviation of the distribution applied to a variable the results can give a bias towards short or long losses and, from a black box user point of view, strange model behaviour.

I think that the work presented in paper 6 and 7 clearly demonstrates some of risks and limitations with user friendly production simulation software. The work also stresses the important point, also pointed out by other authors [22], that people involved in simulation should have some understanding of the fundamental software behaviour.

7. Suggestions for further research

I think that there is still a lot of uncertainty amongst people in industry regarding the usefulness of production simulation. Typical questions raised are:
Is this problem or system suitable for production simulation?
Do we have the data needed for a simulation model?
Do we have the necessary knowledge?
Which tools and software are the most applicable for this case?

Based on this I suggest following research topics:

1. A quantification of the effects of production simulation based on several industrial case studies and modelling approaches (technical versus organisational etc.).
3. A standard for how different manufacturing system features shall be implemented and handled in production simulation software.
4. A quantification of the effect of data accuracy on the model performance.
5. Formalized and concrete guidance for system characters and problems applicable for production simulation.

Another area for further research is to perform a comparison study between the relatively simple inclusion of human factors suggested in the first papers of this thesis and the more advanced method suggested by Baines et al [27-29] for the simulation of human factors in manufacturing systems design.
8. References


The Use of Virtual Reality Tools in Complex Work Cell Implementation - Experiences from Scandinavian Industry
The Use of Virtual Reality Tools in Complex Work Cell Implementation
- Experiences from Scandinavian Industry.

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ABSTRACT
The process of designing, installing and commissioning advanced manufacturing technology (AMT) involves a high degree of uncertainty, especially during the initial phases of a project. The use of virtual reality and simulation tools allows increased knowledge of the planned system, in this case a complex manufacturing cell, to be gained at an early stage of the project and hence reduce problems after the cell design is finalised.

This paper describes the use of a commercial VR and simulation (virtual simulation) tools to augment the traditional project management activities involved in the installation of a manufacturing cell at Scania Chassis Components in Luleå. This cell is to be used for the fabrication of rear axles for heavy goods vehicles and includes a total of five industrial robots along with a number of conveyors and other ancillary and processing equipment. A novel use of virtual simulation in this project was for the education and familiarisation of workshop staff with the new cell prior to its installation.

The paper presents a retrospective analysis of the project including validation of the model and discussion of the expectations and experiences of the project team as well as comments concerning prediction of results. The benefits and current limitations of virtual simulation tools during the various phases of this type of industrial project are also presented along with practical suggestions concerning the use and future development of VR in industry.

The paper also includes a review of the current state-of-application of this type of VR within Scandinavian industry gained from our own experiences and through ongoing projects with the vendors of VR and simulation systems.

1. BACKGROUND
This paper presents results from an ongoing research program, PIDUS, which is one of a number of nationally co-ordinated programmes aimed at studying complexity and complex systems in a wide variety of disciplines. The aim of PIDUS is to develop methodologies for the design, installation and optimisation of production systems which are, by their very nature, complex, where virtual reality and simulation techniques are applied to support these methodologies. PIDUS addresses system aspects, not just those related to automated systems, including organisational and human factors.

The work reported here is one of several PIDUS projects and has been carried out in close cooperation with Scania Chassis Components, during the design, installation and commissioning of a manufacturing cell for the fabrication of rear axles for heavy goods vehicles; an investment of ca. 8 MSEK. This project was started in the end of 1994.

1 Swedish *Projektering, kdrifttagning, drift och underhåll av tekniska system, Designing installing and commissioning of technical systems. This work is being carried out with Linköpings University and in cooperation with several major Swedish companies.
1.1 “VR” IN MANUFACTURING INDUSTRY.

The software used in this project are commercial geometric and discrete event simulation systems with traditional user interfaces (i.e. keyboard, mouse and screen). Whilst some distance from fully immersive VR, these tools satisfy our criteria of virtuality by allowing the development of a computer model which mimics the behaviour of the modelled system. An implied requirement is also that of visualisation of the system at various levels of abstraction.

A taxonomy of VR applications in use in manufacturing industry and their demands on VR-tool are summarised below in Table 1. These demands will be further discussed in section 2.

<table>
<thead>
<tr>
<th>VR-tool applications</th>
<th>Virtual Reality Features</th>
<th>Model appearance</th>
<th>Logic modelling</th>
<th>System behaviour</th>
<th>Model outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Table 1: Virtual reality features vs. application demand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1: Investment Analyses</td>
<td>2D Schematic Layout with Animation</td>
<td>Realistic 3D Model with animation</td>
<td>Immersive - Gloves and HMD Interface</td>
<td>Discrete and random events</td>
<td>Virtual equipment communication</td>
</tr>
<tr>
<td></td>
<td>Physical modelling - geometric and kinematic accuracy</td>
<td>Physical Process simulation</td>
<td>Performance measures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2: Cell design</td>
<td>Feasibility of Cell Configuration</td>
<td>Development of Logical Control</td>
<td>Robust analyses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3: Implementation</td>
<td>Evaluation of test procedures</td>
<td>Operator training and involvement</td>
<td></td>
<td></td>
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<tr>
<td>4: Operation</td>
<td>OLP Optimisation</td>
<td></td>
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</tbody>
</table>

Table 1: Virtual reality features vs. application demand

1.2 SCANDINAVIAN VR - The ‘STATE-OF-THE-ART.’

The principle use of virtual simulation within Scandinavian manufacturing industry is currently for discrete event simulation of proposed and existing systems and for off-line programming of industrial robots. Fully immersive VR has yet to make its mark in both research and industrial applications associated with manufacturing technology. There are however, there are a number of VR projects which lie nearer design, and which are therefore of peripheral interest to production engineers, which use what can best be described as ‘high end’ VR systems.

1.2.1 Production Simulation

The most basic VR-tool in our taxonomy are the production simulators of which WITNESS is probably best known. These systems are typified by allowing modelling of the logic and behaviour of a system, but with limited visualisation capability; typically 2D icon models. These systems have been on the market for upwards of 10 years, although industry take up has been relatively limited. Witness, AutoMod, TaylorII and Quest are all leading systems in use in Swedish industry, typically, but not exclusively, in the major industrial concerns such as SAAB, Volvo and ABB. Installations in Scandinavia number in the hundreds.
This type of discrete event simulator is currently undergoing a revolution as far as the standard of visualisation possible. Full 3D models are now the accepted norm for visualisation purposes, development of these to include high end VR functionality and user interaction is fully expected to take place within the next couple of years.

1.2.2 VR and Off-Line Programming Software.
Full VR applications fall into two categories; dedicated VR engines and robot simulation and off-line programming tools with advanced visualisation capabilities. The principle difference between these systems is that the latter allow modelling of the kinematics and specific functionality associated with modelling of robotic systems, whilst the former stress the importance of graphic presentation, be that speed of response (frames per second) image quality or level of immersion in the VR world. As already stated, high end VR has yet to find application in manufacturing industry.

Whilst available commercially for the best part of 10 years, off-line programming (OLP) systems are only now starting to find widespread use in industry. The main reason is the drastic reduction of product life times and reduced product runs and / or batch quantities which demand frequent re-programming of the robot cell and where OLP can reduce cell down time significantly. Robotic simulators (IGRIP, Grasp, RobCAD etc.) are the main VR-tool for these types of applications. There are a total of 80 academic and commercial installations in Sweden and it is worth mentioning that Volvo has the goal of carrying out all programming of their robotic systems using off-line programming by the end of 1996.

One project of great interest concerning for the robotics community is the international project Realistic Robot Simulation (RRS) [1] which aims to more closely mimic robot behaviour by implementing the actual robots control system against a virtual model. Swedish industry is directly involved in this project through the participation of Volvo Automobiles and ABB Flexible Systems. ABB have developed the first version of an RRS interface between an ABB S4-controller black box and a computer robot model which is currently under evaluation. This development is of direct interest to OLP vendors rather than high end VR vendors.

OLP systems are also starting to be used outside their original area of off-line programming of robotics. The use of OLP systems for programming of PLC cell controllers is now being implemented in Igrip and Robcad. VVT Manufacturing Technology Research Group in Finland are using a commercial virtual reality system (IGRIP) to design and analyse safety systems. The objectives are to develop techniques and concepts to support safety evaluation at the design conceptual stage [2]. Such applications are clear contenders for the application of high end and immersive VR.

The department of Computer and Information Science at Linköping University has an ongoing research program, “Process Simulation for Organisational Learning” [3] which aims to develop and evaluate methods and interfaces for simulation as a support to holistic knowledge for personal involved in the order process in an industrial organisation. This work is currently concentrating on the manufacturing phase.

In Finland there is an ongoing research activity lead by Tehdasmallit OY, within the Intelligent Manufacturing Systems (IMS) research program. This research aims to created a virtual factory; an exact computer model of an actual or proposed factory, that can be visualised as a three dimensional model providing logic and data of the factory. The simulation is connected by interface software to the factory product and production model databases for process planning and control [4].

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4 Including inverse kinematics for generating correct robot postures associated with reaching a particular position / orientation in space.
2. VR supported AMT implementation

The key phases typically involved in the planning through implementation of AMT in industry are shown in Figure 1.

![Figure 1: Phases of interest for industrial VR utilisation](image)

VR tools can and are used in all phases of a project; although often on a somewhat ad hoc basis. In the following discussion, each phase will be dealt with separately.

### 2.1 System Assessment

Implementation of a new system is often based upon a perceived need to increase production capacity and / or take advantage of technological developments. Assessments of the existing manufacturing system will often, but not always, begin with an attempt to **quantify** the capability of the system followed by an effort to **optimise** the system. If such efforts indicate that additional capacity is required, assumptions regarding the required system output can be used as a basis to **re-dimension** the manufacturing system. This naturally must be carried out in conjunction with some form of **investment analysis**.

The main objective of using virtual simulation tools during system assessment phase is to evaluate the impact of the investment on the output of the factory and organisation. Important requirements are the ability to model the performance characteristics of the system as a whole, typically through the use of discrete and random events, as well as the presentation of performance measurements. Whilst 3D-animation can have a great impact on the credibility of the model and its accessibility for a broad range of people it is the ability to carry out ‘what if’ analysis that is the principle requirement. It is in this area that traditional discrete event simulation systems have their home.

### 2.2 System Design

Specification of the cell’s expected throughput for a given product mix will normally have been completed by this stage. The use of VR-tools during system design is usually for the purpose of evaluating alternative equipment, layouts and cell designs. This **feasibility** study can be used to assess what combinations of equipment are necessary to achieve the required throughput. An equally important consideration is the **physical layout** of the cell, i.e. whether an industrial robot is able to reach the desired position without collision, estimation of cycle time etc. When working with the physical layout, 3D models and animation are typical virtual
simulation applications and allow a far better understanding of the proposed cell to be gained than through the icon based discrete event simulation systems\(^5\).

A technique which, in our experience, is seldom used in cell design, but which has a direct impact on the productivity of the final cell is **robust design**. The objective of robust design is to identify the risks associated with a particular cell configuration and to establish if the equipment in the cell will be able to fulfil the process demands. It is not uncommon to find that one critical piece of equipment is found to have been specified which is only just capable of fulfilling its designed task in a cell and is hence a liability or potential bottle neck - under design - or stands idle for significant periods of time - over design - with a corresponding implied over investment; achieving the right balance is not an easy matter. Robust design aims to not only to consider if, for example, that the robot will be able to reach a position and follow the desired paths but also if it can reach all desired positions and follow paths with the accuracy and within the time required. This is of course direct dependant upon the process in question and to be able to analyse this, the VR-tool must be able to handle the dynamics (e.g. robot overshoot during high speed movements.) of the equipment in the cell as well as analyse displacement in position and speed and couple these analyse to the process. This capability is to be found on some leading edge OLP systems.

Another important step in the cell design is the development of the **logical control**. In this case 3D virtual models of the system can be important for the validation of the controller, but the most important VR property is the modelling of communication between the equipment in the cell. Once again, high resolution graphics help in presenting the propose cell, but it is the provision of software features allowing the control of the model world which are important from industries point of view.

### 2.3 System Implementation

Whilst the third application area, implementation, is very much concerned with the installation and commissioning of actual equipment, VR can be used to support two important activities carried out in parallel; namely **identification of critical components and processes** and **operator training and involvement**.

Whilst the contract to supply and install AMT will invariably contain performance clauses, the use of VR-tools to support design of test procedures can help to identify critical equipment and processes and propose adequate test procedures for during commissioning. This task requires the same level of equipment modelling accuracy and process coupling, as is necessary for robust design.

The use of VR tools for operator training is a relatively recent innovation. The key factor here is that the simulation tool must mimic the actual equipment as closely as possible. This puts great demands on the 3D animation capability and, more importantly, user interface, since operative staff are not usually computer literate. This is an area where significant advances are necessary for VR training to become a reality.

### 2.4 Operational Management and Control

**Off-line programming** is currently THE major application for VR-tools within manufacturing industry. Whilst OLP may well be used during implementation phases of the project, its principle advantages are to be gained during the use of the system. OLP systems place high demands on the accuracy of equipment modelling in the system, although fourth

\(^5\) The boundary between discrete event simulation and 3D visualisation is somewhat blurred. In this instance, it is assumed that discrete event simulation, with or without 3D graphics, is used to dimension a cell using generic equipment. During the system design phase, the physical dimensions of the equipment become more important.
generation of robot controllers has drastically reduced these demands, and calibration of the virtual model against reality is still, invariably, necessary. This system features which where discussed under the robust design and test procedure task are not generally included in commercial software.

**System optimisation** or evolutionary improvements of complex AMT systems are often of a very limited nature due to difficulties to comprehend the consequences of system change and the long system down time to implement these changes. VR-tools offer great potential to increase the understanding of system and give opportunity to test “off-line implementation” of new processes.

### 3. INDUSTRIAL PROJECT BACKGROUND

Scania have considerable experience in the use of robots for different types of applications in the manufacture of axles and chassis components for heavy goods vehicles. The first industrial robot installation at Scania Luleå plant was in 1974 and today there are some 30 industrial robots in use at the Luleå site.

In the summer of 1993 Scania decided to invest in a new automated production cell in Luleå for fabrication of rear axles. A preliminary system requirements specification was sent to several vendors of industrial robotics systems. Based upon the budget costs given the board of directors approved the go ahead of the project. Evaluation of the different proposals resulted in the decision to invest in a cell consisting of five industrial robots for the handling, grinding, and welding of the axles along with various items of ancillary equipment (Figure 2).

![Figure 2: Layout of the welding cell](image_url)
3.1 Project outline

The objective of this project was to evaluate the opportunities and limitations of commercial simulation, visualisation and off-line programming software as supporting tools in during the design, installation, commissioning and use of this cell. A secondary objective was the retrospectively analyse the project to identify those areas which either did not benefit from VR or simulation support or which would have benefited from some form of support or additional VR system functionality. The principle tool used was an OLP system which allowed both the geometry and kinematics of the robotic system as well as the logic of the cell control to be modelled, complemented with a discrete event simulation system.

The project was divided into following stages:

- development of a 3D computer model (see figure 3) of the cell based upon the system specification including geometric model, kinematics and logical control.
- refinement of the model through contact with the vendor’s project leader and feedback on the model from Scania’s project group, including the operators.
- detail retrospective analyse of the project to identify disturbance in the implementation of the cell and the under laying causes to these disturbances.

The model was used to:

⇒ visualise the cell for workers / project group (They had not seen a model rather just 2D drawings) and education / familiarisation with the functionality of the cell.
⇒ check and improve the logical and geometric design of the system.

![Figure 3: Virtual model of the planned welding cell](image)

*The OLP system used has subsequently been enhanced to provide capability to carry out discrete event simulation using the 3D model.*
Due to the turn-key nature of the installation, it did not prove possible to use the available VR tools in all aspects of the project; much work was carried out at the vendors design and project offices where established methods for design and implementation were used. The objective of the project was therefore not to act as a direct support to the actual implementation but rather to gain knowledge about the opportunities for and demands on VR-tools for these types of applications, especially as a support tool for the organisation buying the system during pre- and post-implementation decision making and on site activities such as training and familiarisation. Indeed, the most important stage of this project was in fact post installation where the model was used for a retrospective study of the implementation and, in some cases, to point out cell improvements opportunities.

4. RETROSPECTIVE ANALYSIS

One of the major objectives of this project was to analyse the implementation stages and from this analysis identify the demands of and for computer models. The main stages, constrains and information flow involved in the development, implementation and commissioning of the welding cell at Scania AB are presented in the IDEF0 diagram in figure 4.

The installation of the cell has proceeded much to plan; although some delays have been encountered, partly due to Scania’s insistence of waiting for the next generation of robot control software and partly due to problems with this software’s inability to handle multi-axis interpolation in combination with seam tracking and weld gun toggling.

The disturbances that have occur during the installation and commissioning of the system and their likely causes along with discussion of the opportunities for VR-tools to assist the project leader in the development and early test stage to avoid these disturbances are now presented.

4.1 Robot Controller Performance

The project was initially extended by four months to a sign off date in October ’94 to allow Scania to benefit from the release of a new generation of robots and control software. A
further delay of four months due, for the most part, to the new robot controller’s inability to handle multi-axis interpolation in combination with seam tracking and weld gun toggling also occurred. This problem was not wholly unexpected due to Scania’s insistence of being one of the first users of a new release of control software. Whilst a kinematic model of the cell was developed by the university, the OLP software used was unable to predict this controller specific problem as it assumed an ‘ideal’ robot behaviour, divorced from the actual behaviour of the control software. For this type of “first time” application, using the actual controller software to drive the model would drastically improve the opportunities for identifying controller, rather than kinematic, problems and thus ensure a smooth system implementation. The development of a software ‘black box’ which mimics the behaviour of the controller, but which can be implemented in any simulation / OLP system is one of the aims of the realistic robot simulators project. (RRS-project). Naturally, such a ‘black box’ must be available before the robot is to be installed.

4.2 Cell Logic

During installation and start up of the welding cell some changes from the original PLC cell control programme were required. Reprogramming associated with the loading a plate to be spot welded to a banjo/ring was the result of an inefficient cell controller (PLC) logic which lead to long and unnecessary waiting times for the two robots involved. Whilst it would, quite rightly, be expected that the need for these corrections should have been spotted in the VR model that was developed, or better still, a discrete event simulation package, other changes necessary were due to variations in cycle times from those expected leading to a change in cell control logic in order to more efficiently co-ordinate the various robots and ancillary equipment. The availability of an interface between the VR-tool and the cell controller would increase the opportunity to predict PLC errors and improve the overall cell control, but again, performance of real equipment is very difficult to predict and is certainly not within the scope of currently available OLP, simulation or VR tools. The ongoing developments of a STEP and EXPRESS to support equipment modelling standard will also have positive effects on the opportunities for VR-interfaces.

4.3 Process Parameters / Cycle Times

The first commissioning tests with actual products started in May ’95. These tests indicated significant deviations in actual process times from those assumed during the design stages of the project. (Table 2.)

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Deviation from estimated cycle times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Handling and Grinding</td>
<td>+50%</td>
</tr>
<tr>
<td>Loading Plasma</td>
<td>+20%</td>
</tr>
<tr>
<td>Plasma cutting</td>
<td>0%</td>
</tr>
<tr>
<td>Grinding of plasma cut and pre welding of plate, drain plug and ring</td>
<td>+30%</td>
</tr>
<tr>
<td>Final welding</td>
<td>+ 200 %</td>
</tr>
</tbody>
</table>

Table 2: Deviation from system proposal estimated times for key equipment

7 One of the principle uses of discrete event simulation is to gain information about utilisation and queue time. The use of such software would probably have flagged up the above problem.
8 These deviations have been drastically reduced during the last weeks.
As the estimated operation times were used as a basis for the final system proposal, these deviations had a significant effect on the system performance and consequently the configuration of the cell.

4.3.1 Handling and Grinding
The reason for the deviation in the handling and grinding is thought to be due to optimistic assumptions related to part handling and lack of process specific knowledge concerning grinding. The first cause could have been predicted using the VR-tool used in this project given specific knowledge and experience of the limitations of robot handling for large components, which was not available. Process specific knowledge of achievable grinding rates would be necessary to solve the second. This level of process modelling is many years away from commercial implementation. A reduction in the positional tolerance for many ‘via’ points combined with more rational robot sequence has reduce the handling time by more than 50%.

4.3.2 Welding
The high deviation between the estimated and actual operation time for the welding operations is due to the assumption of high seam welding speeds which were not attainable in practice due to the wiring feeding equipment not functioning reliably at the required wire feed rates and the robot controller not being able to handle the combination of high speed, seam tracking and nozzle toggling. Again, these are partly process specific problems.

Whilst the VR-tool used could not to predict process specific problems, it could be used to support the project leader in assessing alternative solutions and system configuration. The ability to “sense” problem areas during the early stages of the project and to assess alternative solutions would be much simplified given an early assessment of the robustness of the cell design by identifying time critical processes. The formal use of robustness analysis could drastically increase the ability of the implemented cell to cope with process deviations.

4.4 Operator Training
Although the cell is designed to be fully automated, it is still obviously necessary to train staff to deal with problems should they arise. Early familiarisation of the staff with the proposed cell using the VR model was successful. However, a more realistic user interface, which mimics the actual look and feel of the robot control pendant rather than the VR tool specific keyboard / menu commands would be necessary for VR to be used for operator training. The use of immersive environments in the training and involvement of operators using such as gloves and HMD’s is also expected to increase over the next years [6].

5. CONCLUSIONS
Our work with Scania has shown following:

- The disturbances that occur during the installation and commissioning phase of the cell implementation are, in most cases, the result of insufficient knowledge and insight into the system complexity and process demands during the preparatory and analytical phase (A2 in figure 4); awareness of the robustness of the individual processes being especially critical.

- Even “unsophisticated” VR-tools provide good opportunities to support a project leader in all phases of a manufacturing cell implementation for testing out different ideas, identifying critical factors, etc. Again, access to this support should drastically increase the robustness of the implementation.
• The last generation of robot systems is much more predictable than the earlier generations without robot individual characters.

• Another research area of great interest is the improvement of the man-machine interface through the use of interfaces mimicking actual systems control pendants and the interface of VR tools with actual equipment interfaces for operator training.

• Accuracy evaluation and process “simulation” is still not implemented in commercial OLP tools. This is a critical research area if these tools are to be used for more than visualisation. Modelling of the functionality of cell control PLC’s will also increase the opportunity to confirm desired functionality prior to the actual installation.

6. REFERENCES


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Paper I: The use of virtual reality tools

Torbjörn Ilar
Paper II

The Virtual Arena; experiences from the first industrial application of a new AMT implementation methodology.
The Virtual Arena; experiences from the first industrial application of a new AMT implementation methodology.


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Abstract
A ‘turn-key’ approach whereby a single supplier has contractual responsibility is one way to reduce the uncertainty and risk inherent in the implementation of advanced manufacturing technology (AMT). However, the turn-key concept is no guarantee for a successful AMT implementation as success is a function of both the robustness and quality of the system design and execution as well as the organisations ability to handle and accept the system.

The Virtual Arena (VA) concept aims to link software tools such as IDEF0, production simulation and the ‘virtual factory’ commonly used in support of AMT projects, into a seamless environment. Central to VA is the use of different types of process and manufacturing modelling tools at different abstraction levels and the migration of data between these tools to support holistic system design.

This paper presents the VA concept in the form of two case studies from an ongoing research program, PIDUS, which is one of a number of nationally co-ordinated programmes aimed at studying complexity and complex systems in a wide variety of disciplines.

Introduction
Every year vast sums of money are invested in new equipment in manufacturing industry. As manufacturing systems become more complex, the economic and technical risks involved increases due to the difficulty of fully comprehending and foreseeing the behaviour of such systems. There are numerous reported examples of the problems can and do occur at any point during the planning, implementation and adoption process. Whilst few problems are insurmountable, their solution can be time consuming and have significant financial impact, both directly and indirectly. Equipment may reach its planned output much later then expected or, even worse, never achieves the expected performance. In today’s highly competitive world, failure of an investment to fully live up to expectations can have a significant effect on a company especially in small and medium sized enterprises (SME’s).

Project background
This paper presents results from an ongoing research program, PIDUS, which is one of a number of nationally co-ordinated programmes aimed at studying complexity and complex systems in a wide variety of disciplines. The aim of PIDUS is to develop methodologies for the design, installation and optimisation of production systems which are, by their very nature, complex.

PIDUS builds upon the collective experience of members of engineering departments at Luleå University of Technology and the University of Linköping in the application of discrete event simulation in solving production engineering and logistics problems in numerous industrial cases. The PIDUS project has been extended to included full three dimensional modelling of the geometry and kinematics of robots and other ancillary equipment; this is often referred to
as the ‘Virtual Factory.’ PIDUS also takes a ‘systems’ view and includes organisational and human factors as well as methodology in which software tools can be applied.

The work of the two main academic participants in PIDUS concerns the full spectrum of factors affecting the success of implementation of AMT from hard automation to soft systems. The work at Linköping University concerns simulation as a support for organisational learning [1] whilst the team at Luleå University have addressed the implementation of hard automation through the application of high end simulation / visualisation tools in support of manufacturing system implementation in local industry.

PIDUS has taken a case study approach to investigate the benefits from developing alternative project structures to the classic turn-key project which are more in keeping with contemporary thinking. The intention with this approach is to have an early involvement and feedback from the industrial partners within the PIDUS research program and, through this feedback, make the research results more industrial adaptable.

Some examples of ongoing industrial case studies are:

- The simulation supported industrial training (SSIT) methodology has been tested in co-operation with Samhall Klintland where it has been applied to support organisation learning of supervisory personal [2,3]. This case study has produced some very positive results. This work will continue with further case studies in co-operation with Saab Military Aircraft.
- Production simulation and high end visualisation tools have been used in co-operation with Scania CV in Luleå to support the implementation of a complex welding cell [4]. This project was carried out between 1994 and 1995 and was the initial spur to develop the Virtual Arena methodology and will be further described later in this paper.
- Parts of the VA toolbox and project management philosophy will be evaluated through applications at the implementation of a transfer press line, which a second ongoing co-operative project with Scania CV. This project will be further described later in this paper.
- A project concerning tools for organisational analyses and order flow simulation has recently been started in co-operation with Alimak. This project aims to improve the order management process. These tools is of great importance for the business basic frames analyses in the Virtual Arena concept.
- Different simulation tools are being applied to support the implementation of a more flow based layout in co-operation with Saab Military Aircraft.

Problems with Turn Key Implementation

It is generally accepted that uncertainty inherent in the implementation of advanced manufacturing technology (AMT) can be reduced by taking a ‘turn-key’ approach whereby a single supplier has contractual responsibility for the whole system implementation through to acceptance based upon some stipulated level of performance. Whilst this is a proven method, sign off-criteria typically only relate to specific technical performance of the system. Whilst one measure of performance, it will seldom show the overall performance of the system in the larger context of the organisation.

This is a major problem as the efficiency of the adoption process to bring the new system into the working of the organisation as a whole is critical to the success of a project. Early
involvement of those with specific process knowledge and those who will be involved directly and indirectly with operating the new system is hence very important.

The traditional turn-key approach has thus a number of pitfalls, which are confirmed by our own industrial studies. These include:

- In-house process knowledge in the buyer organisation are seldom transferred or accessible to the system supplier. This can lead to sub-optimum design and disturbances during installation and commissioning of the system as this knowledge is revealed.

- The opportunity to influence and understand the new system is limit to the few people within the customer organisation involved in the project. This is often restricted to senior management who lack direct operating knowledge.

- Supplier knowledge is seldom transferred to the buyer, which limits the development of the in-house knowledge base. In the worst case, which is unfortunately not uncommon, the system supplier continues to have responsibility for developments or even ongoing problem solving and maintenance long after sign off.

- Risk reductions are often illusory since the risk to the buyer organisation is far more than the cost of the system. The cost of lost production and disturbance to other manufacturing activities can be significant and for which there is little chance to get compensation from the system supplier.

There are of course a number of examples successful turn-key installation as well but in many cases has these pitfalls drastically reduced the performance of the AMT system.

**Organisational Learning**

The traditional use of turn-key concept is therefore no guarantee for a successful AMT implementation. Success is a function of the robustness of the system design, the organisation's ability to handle and accept the system. The latter point implies both a 'mental' as well as a technical implementation are necessary; the organisation must have time to adopt the system. A study of a wide range of industrial AMT project using the turn-key concept have indicated a tendency to under estimate the importance of the organisation part of the implementation.

One way to support the process of organisational adaptation is to apply a gradual / long-term implementation plan when handling new AMT investments, and thus give the organisation opportunity the develop in phase with the technical implementation [5]. One potential drawback with this approach is the potentially long elapsed time associated with the gradual introduction of AMT and which would be contrary to the general situation in industry, which is tending towards ever shorter product life cycles and where the rapid and successful AMT is necessary to take advantage of "market windows".

The ideal methodology would thus provide tools which were able of supporting early identification of the best technical AMT strategies with respect to the fundamental business goals whilst at the same time encouraging and supporting early general involvement of the workforce and the necessary mental implementation required prior to, and in parallel with the system physical installation.

Holistic design involves a dynamic system thinking based on business strategy. To design today’s manufacturing systems, consideration of the total view of technology, organisation and human aspects is needed using the varying levels of abstraction of data available throughout the life of a project. What is needed is a common framework which can be used
Paper II: The virtual arena

Torbjörn Ilar

during development of a system to allow modelling and analysis at various levels of abstraction throughout the life of the project. We therefore propose a virtual arena for use by a project group, throughout all stages of an AMT project as a complement or alternative to a pure turn-key implementation [6].

**The Virtual Arena - a New Paradigm**

Implementation of AMT in the form of integrated manufacturing cells involves a high degree of uncertainty at all stages of the project from system design through to commissioning and sign off. The use of software tools, such as production simulation, is a relatively common method used to increase knowledge of the planned machining cell and thus reduce the degree of uncertainty. However, for production simulation to be used successfully requires it to be correctly applied and thus, both the project organisation associated with the AMT implementation as well as the effective use of complementary tools such as and IDEF0 must also be considered.

Whilst this could be addressed by good implementation methodology, i.e. using a sensible range of these complementary tools in concert, our aim in developing the concept of a Virtual Arena is to link the tools commonly used in support of AMT projects in a seamless environment. Key to the VA concept is the use of different types of process and manufacturing modelling tools at different abstraction levels, ranging from IDEF0 to virtual reality, and the migration of data between these tools to support holistic design of the AMT cell.

**The Virtual Arena Framework**

The development of the VA concept is presented here in the form of case studies from two co-operative projects between Luleå University of Technology and Scania CV; firstly application of production simulation and off-line programming tools in the implementation of a complex welding cell and secondly in the implementation of a transfer press line.

Problems with conventional techniques encountered during the first project acted as the spur to develop the Virtual Arena methodology. The embryonic VA toolbox and project management philosophy was subsequently applied in the second project. It is expected that lessons learnt from the latest work will allow the VA concept to be further developed, tested and refined in the course of other projects ongoing with Swedish industrial partners.

Key to the VA concept is the use of different types of process and manufacturing modelling tools with different abstraction levels and the migration of data between these tools to support holistic design of the AMT cell (see figure 1). This can be seen as falling into three distinct, but overlapping phases.

Initially, IDEF, management analyse tools and production simulators play an important role in an AMT project by providing a mechanism to the coupling the new investment to the existing business framework and to develop holistic measurements for analysis of the best AMT opportunities and to asses process robustness. In the second phase, the gradual development of the AMT cell, geometric simulators and virtual reality are the most important tools where expertise from operators and technicians has the opportunity to mature and react to the initial system idea and which subsequently undergoes a gradual developed process from the contributions from these experts. The tools should also support the development of cell logical controller and control programs. In the third phase, the operative management, off-line programming software and VR tools is important for an evolution improvement of the cell performances and to gaining a learning organisation. Production simulators are also of importance for the operative management of the cell.
Industrial Case Study I: Complex Welding Cell Implementation

In the summer of 1993 Scania began preparatory work for the investment in an automated production cell in Luleå for fabrication of rear axles. A preliminary system requirements specification was sent to several vendors of industrial robotics systems who in turn submitted budget proposals. Based upon these, Scania’s board of directors gave the go ahead of the project.

Evaluations of the different proposals lead to the decision being made to invest in a manufacturing cell consisting of five industrial robots and various items of ancillary equipment. Two of the robots are dedicated to welding the differential cover onto the rear axle whilst the other robots are multi-function and carry out various handling operations between stations in the cell as well as preparatory grinding of some ‘to-be -welded’ surfaces and spot welding of ancillary components onto the axle cases. The cell included several new process technologies, such as the grinding process and high speed welding (HSW), which together with the general complexity of the cell gave the project a high technical risk factor.

The objective of this case study was to apply and evaluate commercial simulation, visualisation and off-line programming software as supporting tools during the design, installation, commissioning and initial use of this cell. This ‘hands on’ application in a real project situation gave the opportunity to explore the scope and limitations of this kind of software. This included the retrospectively analysis of the project to identify those areas which either did not benefit from the VR or simulation support or which would have benefited from some form of support or additional VR system functionality. The principle tool used was an OLP system which allowed both the geometry and kinematics of the robotic system as well as the logic of the cell control to be modelled, complemented with a discrete event simulation system.

The most significant results from this project were:

⇒ The cell model created in the geometric simulator (GRASP) has a high visual, kinematic and logical representation of the proposed cell design. (see figure 2). The introduction of the project group to this VR model for was very positive. The main problem for operator involvement being the relatively long learning curve associated with the software used.

⇒ Discussions with the operators indicated that some of the unexpected problems which occurred after the installation could have been foreseen if “skill from the floor” had been utilised. However this requires the support of models with low levels of abstraction i.e. highly detailed models both geometrically and functionally. In combination with realistic robot simulator technique (RRS [7]) the problem of predicting , for example, the performance of the robot controller could have been foreseen (see figure 3). Access to this support should drastically increase the robustness of the implementation.

⇒ Problems associated with other processes, for example grinding, requires levels of process simulation or modelling, which are still not implemented in commercial production or geometric simulation tools (see figure 3).

⇒ A retrospective analyse showed that even “unsophisticated” VR-tools provide good opportunities to support a project leader in all phases of a manufacturing cell implementation for testing out different ideas, identifying critical factors, etc.

One unique character of this implementation was the opportunity for the operators to gradual learning and to get comfortable with the system, due to the long on site installation time.
However, this is not the most cost efficient way to implement AMT systems. This problem was the initial spur to develop the Virtual Arena methodology.

**Industrial case two - Transfer Line Implementation**

At the end of 1994 Scania agreed to invest in a new production line for the manufacturing of sheet metal parts, from blanks to finished pressed parts. This proposed press line consists of three 1250 tons presses and five ABB 6400 robots for material handling between the presses. (see figure 4). This new press line will directly replace two existing presses and introduces a flow oriented layout and fully automated material handling. However, both the sheet metal forming processes and the use of robots to handle components produced in a press, are established technologies at Scania and in this respect this AMT implementation can be considered as having a low technical risk.

Whilst the technical risk is fairly low, the uncertainties and risk related to the organisation and supporting process much higher. The total set-up time for the line is specified to maximum 6 minutes and the total number of personnel is 7 persons per shift. This represents a significant improvement over current standards and is consequently expected to place great demands on support processes such as operative planning, external material handling, press tool handling and preparation, quality control and system maintenance and it is these processes that are initially expected to be the limiting factor on system performance.

The co-operative project between Luleå University and Scania CV was started in the end of 1995, when the press line project had reached the stage of on-site installation of the presses and associated equipment. The objectives of the case study were to apply different Virtual Arena tools to support the development of the organisation and support process and consequently evaluate VA with respect to this type of application. Another important issue with this project is to develop the conceptual models for the migration of data between these different tools. Examples of VA tools applied in this project and their objectives are (see figure 4):

- **IDEF0**, to identify and structured main process and their related activities. An initial model created by the research group was presented to the project group (including operators). The reactions to this model became the input for the gradual development of the model. IDEF0 modelling also allows a software neutral documentation of the computer models which can be transferred to other systems.

- **Various management analyse tools** to identify performance measure with respect to the overall system requirements. Overall (holistic) performance measures are identified through discussion with the plant management’s and these measures are then divided to more “floor based” performance measures through discussions with the project group.

- **Production simulation** to identify and analyse bottlenecks in the organisational part of the system with the aim of developing the best management philosophy for the cell. The initial input for these models is the result from the IDEF0 modelling but the simulation models also develop through time in response to reactions from the project group.

- **3D visualisation tools and VR tools** are applied to support model creditability and system acceptance. These tools are also intended to be used to support organisational learning and a evolution improvement of the system performance.
Multivariate processing supports the analysis of a numerous inter-related variables with the aim of identifying of underlying parameters and factors. This is also used in conjunction with factorial design of experiments for the simulation.

The preliminary result from this ongoing project indicates a great potential for models with high level of abstraction to support the involvement and creativity from the whole project group. The division of processes into activities via sub-processes gives the operators opportunity to identify his or her process, react to it and propose important changes.

Conclusions

The main conclusions from the work with the Virtual Arena concept and industrial applications are:

⇒ The disturbances that occurred during the installation and commissioning phase of the AMT implementations studied are, in most cases, the result of insufficient knowledge and insight into the system complexity and process demands during the preparatory and analytical phase. The effect of individual processes on the overall performance and reliability (process robustness) being especially critical.

⇒ Even relatively “unsophisticated” VR-tools provide good opportunities to support a project leader in all phases of AMT implementation for testing different ideas, identifying critical factors, etc. Again, access to this support should drastically increase the robustness of the implementation.

⇒ The success of an AMT implementation is very dependent upon the involvement of a broad range of expertise, from highly educated technicians and process specialists to operators. Project management must take account of this by developing long term suppliers relationships and including multi-disciplinary project groups and using modern modelling tools.

The experiences from the presentation and first industrial applications of the VA concept have been very promising. The industries involved can clearly identify the problems area and the demands described in the concept.
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1. Lobell, J. & Lantto, S. "Computer Simulation as a Support for Learning in Industrial Organizations - an evaluation of the SSIT method.", LiTH-IDA-Ex-9549


Torbjörn Ilar  

Paper II: The virtual arena

Figure 1: The Virtual Arena Methodology

Figure 2: Virtual model of the planned welding cell
Disturbances: Disturbances:

Four months delay in installation
Deviation in robot handling times
Late online PLC cell programme adjustment
Deviation in robot process times

Causes:Causes:

Robot controller inability to handle multi-axis motion
Inefficient robot sequences and unnecessary high bypass point tolerances
System complexity leads to difficulties to predict PLC-performances
Lack of process specific knowledge and robot controller inability

VR-support:

Kinematic model in combination with RRS black boxes techniques
PLC algorithms implemented with support for control optimization
Demands for high degree of process modelling

Figure 3: Disturbances, causes versus VR-support

Objectives:

Identify performance measure with respect to holistical aims
Model documentation, identifying critical processes
Identifying best operation strategies and process robustness
Support model credibility and system acceptance
Identifying underlying parameters/factors

VA: System migration

Management Analyse Tool
IDEF
Production simulation
3D visualization tool
Multivariate processing

Figure 4: Modelling tools applied in the Transfer Line
A new Modelling Approach to Support Identification and Development of Secondary Processes in an Industrial AMT Implementation
Abstract Implementation of semi-automated manufacturing cells always requires development of both the technical system and also the organisation required to manage and support this system. Overall system performance is highly dependant on the interaction between the technical and organisational systems and it is thus of great importance to consider both of these during the different phase of the design and implementation of such a system.

This paper is a result of a co-operative project between Luleå University of Technical and SCANIA Truck Components where different types of production modelling and simulation tool have been applied to support development and implementation of an advanced press line consisting of three 1200 tons presses and five industrial robots. The project has used two different production modelling tools to analyse different development strategies. An extended process mapping and production simulation approach has been used where both the main and supporting processes are modelled and where the use of the simulation model is focused more towards communication of information about the system than towards generating performance measures for the systems. This model approach is compared with the more common industrial application of simulation as purely a decision support tool; an approach applied during the earlier phases of this AMT project.

**Key words**

AMT, system implementation, process mapping, IDEF0, discrete event simulation.

1 Introduction

1.1 Problem definition

Industrial implementation of advanced manufacturing technology (AMT) almost invariably involves a high degree of technical as well as organisational complexity. Traditional project management is very much focused on the technical aspects of an AMT implementation and often neglects issues concerning man-machine interaction. Nevertheless, the degree of success of this type of project is often dependants upon how well this interaction is manage which implies that developing understanding and acceptance among personal is important for overall project success.

The use of production simulation for decision support in this kind of project is now quite commonplace. However, its use is usually limited to evaluating alternative technical configuration and seldom takes supporting processes into account. In many cases, even the gains from the technical simulations are of limited benefit to the project as a whole due to poor correlation between the model and the real system where both system complexity as well as limited modelling time is significant constraining factors.
Ongoing research (Gaines & Norrie et al, 1995) into the next generation of manufacturing system stresses the need for semi-automated systems where an organisation’s ability to handle rapid changes caused by short product life cycles and customer driven production will become the most important productivity factors. The development of this kind of AMT system must therefore be aimed at addressing continuous change rather than a steady state situation which never will occur.

1.2 Scope of the Paper
This paper investigates the importance of modelling both the main as well as supporting process in order to obtain a realistic model of an AMT system. The work is based on an investigation carried out in co-operation with Scania AB in Luleå to evaluate an extended production simulation and process mapping approach where both the main and supporting processes are modelled and where the used of simulation models is for communication rather then evaluation.

This approach is compared with the more common industrial application of simulation as purely as decision support tool and which was used in an earlier phase of the AMT implementation studied. One important feature of this study was the implementation of an individual learning model to capture the knowledge build up process.

1.3 Learning Curve
One approach to modelling and predicting competence development within an industrial organisation is the use of a theoretical learning curve. Learning curve theory has been applied to a wide range of industrial applications (Naime & Towill et al, 1994) that include human operators in complex tasks such as assembly.

A number of different mathematical equations has been proposed for modelling learning. However, the most widely utilised is probably still the time constant model.

\[
Y_M(t) = Y_c(1 - e^{-t/\tau})
\]

where: \(Y_M(t)\) is the model output at time \(t\),
\(Y_c\) is the model output at time \(t=0\),
\((Y_c + Y_f)\) is the model output at time \(t=\infty\),
\(\tau\) is the model time constant

It is this model that is used in this study.
2 Project History
At the end of 1994 Scania decided to invest in a new production line for the manufacture of sheet metal components from cut blanks to finished pressed parts. This was to be a turn-key installation and the press line consist of three 1250 tons presses and five ABB 6400 robots for material handling between the presses (see figure 1). One of the objectives of the project was to introduce a flow oriented layout with fully automated material handling with a group oriented organisational structure.

From a technical point of view, this AMT implementation can be consider as having a low technical risk as it used existing technology bought as a turn key system from a known system supplier.

Scania also has a long experience of sheet metal forming processes as well as material handling and there are a large number of similar references installations. The main technical concern was the ability of the press tools to handle the high press stroke rate required and also the system’s ability to handle the scrap material resulting from the clipping of blanks. Whilst the technical risk was fairly low, the uncertainties and risk associated with the organisation and supporting process was much higher. The new group oriented organisational approach represents a significant change from current management style and placed new demands on the workforce ability to handle support processes such as planning, press tool handling and preparation, quality control and system maintenance. It was these supporting processes that were initially expected to be the limiting factor on system performance.

2.1 Decision support
Scania was very much reliant upon the systems supplier’s knowledge of the overall system configuration. However, production simulation was used to support the Scania project management group (Bengtsson et al, 1995). The main objectives of this simulation was to provide the project management team with information and guidance concerning maximum capacity, appropriate batch size, bottle-necks, material flow; all technical aspects of the system (and thus part of the main process).

The only support processes modelled in this simulation study was material handling and, to a limited extent, direct tool set-up in the press line. A retrospective analysis showed that the omission of supporting process in the simulation model used by the management group resulted in poor correlation between the simulation results and the output from the real system was achieved. In fact, the results from this study were of very little use in reducing the uncertainties involved in this project.

**Fig. 1. General System Lay-Out**
3 Supporting Process Modelling

The main objective with the present study was to identify and model supporting process using IDEF0 schema for process mapping. This was followed by an investigation where production simulation was used to evaluate the robustness of these processes and to communicate the results to management and shop floor personnel. This communication was seen as being very important for providing a common understanding of the supporting processes. A more general objective was to develop a modelling approach which supported analyses of both main and supporting process.

An important factor which dictates the usefulness of any methodology is the acceptance of the model by the staff involved in the project. There are many different views as to what is required to achieve such user acceptance. One option is to use "high end" simulation tools which offer a high level of visual fidelity. A second option is to reduce the perceived system complexity by using a hierarchical modelling approach to model processes, sub-processes and activities. The former technique is dependent upon access to technical documentation about the system and its component parts. The latter approach requires information which is not always clearly documented and thus requires frequent meetings between the model builder and the project group (including shop floor personnel) to allow incremental development of a model.

A hierarchical modelling approach using two different modelling tools was used in this investigation. IDEF0 was used for process mapping and discrete event simulation was used for communication of the dynamic aspects of the system.

3.1 Process Mapping

The process mapping investigation consisted of the following steps:

1. Identification of supporting processes,
2. Dividing the support process into sub processes,
3. Identification of activities and activity chains,
4. Identification of inputs, outputs, constrains and resources for each activity.

The processes identified in step 1 are presented in figure 2. These steps were closely followed in sequence; although there was some overlap between steps 3 and 4 due to an increase in common understanding within the project group. An initial model created by the research group was presented to the project group whose reactions formed the input to the next phase of development of the model. The IDEF0 modelling software used allowed export of models in an ‘open’ format for transfer to other software; in this case a discrete event simulation system.

Fig. 2. Identified main and supporting processes
The two level IDEF₀ schema for the tool preparation process is presented in Figure 3. One unexpected result from this highly abstract model was gaining an insight into the importance of the conveyor, which is a resource in almost every activity in the tool preparation process and which potentially acts as a bottleneck. Should this information have been available earlier in the project, it is likely that the conveyor system would have been re-designed.

**Fig. 3. Two levels of the IDEF schema for Tool Preparation.**

### 4 The Simulation Model

As mentioned earlier in this paper, the objectives of the simulation model was not to obtain data which could act directly as a decision support for the project leader but rather to communicate the behaviour and complexity of the system and thereby increase the insight and awareness of the production group manager and operators.

The next step was to identify appropriate constraints for the simulation model i.e. processes to be included. The decision was made to include the main process (sheet metal forming), tool preparation, set-up and maintenance processes. These processes were considered to be the ones with the highest impact on the overall system performance.

The simulation model was built in the commercial production simulation software *Taylor II*. A high level of correlation between the IDEF₀ structure and the simulation software was aimed for and the same activities and activity chains were used.
This model is presented in Figure 4. Unfortunately, this figure cannot convey the logical behaviour of the model since this only becomes apparent when the model is run. This is a common drawback of discrete event software, and is an important constraint when communicating using simulation models.

4.1 Modelling of competence profile
To be able to model 'learning' associated with the support processes, a competence profile and learning curve were included in the model for two tasks; the tool related process and the maintenance related process. Two values (which change as the model is run) describe a unique competence profile for each operator. These were initially set by the group manager.

The competence index for each operator is updated when s/he performs an activity following the time constant learning model described earlier. For the tooling processes this is:

\[ x = x + 1 \]

\[ tu_{ij} = tu_{ij}^{opt} + \Delta tu_{ij} \times e^{\frac{x}{c_t}} \]

where:
- \( x \) is learning curve index,
- \( tu_{ij} \) is the operation time in the updating matrix for operation \( i \) and operator \( j \),
- \( tu_{ij}^{opt} \) is the optimum operation time,
- \( \Delta tu_{ij} \) is the initial activity time and
- \( c_t \) is a learning curve factor.

A similar algorithm is used in the maintenance process.

5 Designing and analysing the simulation experiments
Factorial design was used when planning the simulation runs. Four factors were of interest which gives a total of 16 combinations to achieve a four factor, two level, full factorial experiment (Law & Kelton, 1991). The following factors were included in the simulation experiment:

1. The constant in the learning curve equation. This is mainly for sensitivity analysis since an exact value for this constant is very difficult to find. Level 0 equates to 5 and level 1 to 15.
2. The level of operator availability. Level 0 represents 90% and level 1 70%.
3. Batch size. Level 1 equals 200 and level 0 equals 50.
4. Two different human management philosophies. Level 0 represents an expert concentration philosophy where the operator who will complete the activity in the shortest time is given the highest priority. Level 1 is for a competence spread philosophy where the operator with the longest activity time has the highest priority. Factor 3 and 4 of this study can be controlled, so that data may be obtained about how these factors influence another variable referred to as the response variable or performance measure.

The experimental study was conducted in two steps. The first step focused on knowledge build up including factors 1 and 4. In the second step, the best knowledge build up result for each human management philosophy was used as an input and factors 2 and 3 were introduced. The 4 factor composition for the first step and 8 factor compositions for the second step were simulated 5 times to achieve four replicates. This is known as a full experiment run. The mean and the variations could then be calculated for each response. Statistical analysis also generated confidence intervals for each response.

5.1 Model responses

The model responses used were selected with the aim of supporting communication of the behaviour of the system under these different scenarios rather than for providing direct measures of the performance of the real system. The following responses were selected:

- **Relative production rate**, which was defined as the actual production rate versus the production rate from the previous decision support simulation run.

- **Performances of supporting processes**, which was the mean time and variations associated with carrying out tool preparation and maintenance processes.

- **Group competence build up**, which including the current competence index divided by the optimum competence (SDO), variation in competence (VIC) and the competence build up time. The latter response was defined as when operator group reached a competence index of 50% of optimum and the first two responses were calculated as:

\[
SDO = \frac{\sum_{i} \sum_{j} t_{ij}}{\sum_{i} \sum_{j} t_{ij}} \quad \text{and} \quad VIC = \frac{\sum_{i} \sum_{j} (t_{ij} - \bar{t})^2}{\bar{t}} \quad \text{(Box & Hunter et al)}
\]

Where: \( t_{ij} \) is the operation time in the updating matrix for operation \( i \) and operator \( j \), \( t_{ij}^{opt} \) is the optimum operation time.

The responses were "measured" after a completed simulation run (50 days).
5.2 Results
The most significant results from the simulation study were that:

- The highest initial relative production rate will be achieved with the expert personal management approach and high operator availability, independent of all other factors. It is important to note that this production rate is still less than 75% of the prediction from the earlier simulation study. This shows the importance of expanding production simulation to include both main and supporting process.

- The shortest tool preparation and maintenance process times will be achieved with the expert management approach. However, these times are subject to very high variations due to the inability to handle personnel disturbances.

- The learning curve factor, $c_l$, has no significant effect on the ‘best’ personal management approach. The lower factor value will, of course, lead to a slower group competence build up, but still offer better performance than the competence spread approach.

- A low operator availability combined with small batch sizes is preferable with the management approach of spreading competence. This indicates the group’s ability to handle rapid change, which is expected to be of great importance in the next generation of manufacturing systems.

These results were validated through a presentation and discussions with the project group, rather than a direct compare with the actual system performances.

6 Discussion
Concurrent engineering has been used in industry for many years and also investigated in the academic world. This research has mainly focused on traditional product development (Jeppsson, 1997) neglecting manufacturing, or focuses on an expert oriented project group (Nelson, 1996). It is often suggested that concurrent engineering requires all functions within the company to share and communicate information (Jeppsson, 1997 and Nelson, 1996) and that the use of different computer based support tools is of great importance.

Development of advanced manufacturing systems has very much in common with traditional product development with similar opportunities to avoid costly mistakes by putting in more resources and utilising computer based modelling tools during the early development phases.

Organisational issues in manufacturing have been described generally in numerous papers (Lei & Goldhar, 1993; Tie & Lin, 1992) as well as specifically for AMT implementations (Towill & Cherington, 1994). All these papers indicate that organisational learning, and thus the development of the supporting process, can only start after the installation and commissioning of the system is complete. The main drawback with developing supporting process after installation is complete is the high negative effect on systems productivity during this development period.

The implementation approach outlined in this paper addresses the importance of the supporting process with the aim being able to carry out parallel development of both main and supporting processes. Two important factors are the close interaction between the end user and the system modeller and the use of models with different levels of abstraction. This approach also requires utilisation of high end visualisation and interactive modelling tools in the early phases of the project. An example of such a model is presented in figure 5. This model was built in the commercial VR software Superscape.

This methodology is based upon the concept of Rapid Factory Modelling (Legge & Ilar, 1997) which addresses the need to quickly develop a digital factory model based upon the
information available during pre-operative stages of the development of the manufacturing system. Current methods of model building are so time consuming that it is often only realistic to build a model once the system design is stable.

The ability to quickly develop a complete model of a proposed manufacturing system is considered important for both testing and user involvement.

At the early stages of a project, the level of detail available will be low. However, it is important that a detailed ‘generic’ (i.e. non specific) model can be created quickly to allow early user involvement and feedback.

This approach must also contain support for the extraction of important variables (responses), which has been addressed by other researchers utilising discrete-event simulation in combination with PLS-modelling (Eriksson & Kinnander, 1997).

7 Conclusions

This paper discusses the importance of modelling the supporting processes in order to obtain a realistic evaluation of advanced semi-automated manufacturing systems and introduce a two level modelling techniques to support this evaluation. The paper also outlines a general approach for implementation of advanced manufacturing systems using computer modelling. Some of the key features of this approach have been investigated in an industrial case study carried out in co-operation with Scania.

The main conclusions from this work are:

- The two level modelling method applied in this investigation offers excellent opportunities to support deeper understanding of the interaction between the main and supporting processes in an AMT system. These interactions are often neglected but have a great impact on the total system efficiency. Using process mapping tools together with production simulation offers the opportunity to identify the most important process and activities, and to use dynamic analyses to communicate the important system characteristics to a broader audience within a company.

- The best source of supporting processes knowledge is from the work force and it is therefore of great importance to obtain models which can be easily communicated to this group. This does not necessarily require the use of high end 3D visualisation tools but rather demands a close working relationship between the “modeller” and the project group.

- Investigation and active development of supporting processes can drastically improved the quality and scope of the actual system behaviour. Modelling this behaviour allows an increase in the understanding by the staff and operators.
The next step in this industrial investigation is to apply high end visualisation and interactive modelling tools to support a continues process and competence development within the system operators.

8 Acknowledgements
The work presented here is part of the research project PIDUS, which addresses the design, implementation, commissioning, management and maintenance of production system. The authors would like to thank: David Legge and other co-workers in the Department of Manufacturing Engineering; Jonas Rindeskog and his staff at Scania and especially the Swedish National Board for Industrial and Technical Development (NUTEK) for funding this work.

9 References
Competence requirements and their impact on manufacturing system performance.
Competence requirements and their impact on manufacturing system performance.

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Abstract
Research into “Next generation manufacturing systems” stresses the use of semi-automated systems to handle short product life cycles and customer oriented production. Despite increasing dependency on technology, the importance of humans is expected to increase and to provide a realistic basis for decision support, both technical and organisational processes must be included in simulation models. In a rapidly changing environment, skill development is also important and should be considered when developing simulation models.

This paper describes two case studies where competence and skill development was modelled using learning curves to obtain a more representative simulation of system performance.

Keywords
Manufacturing, simulation, performance, evaluation.

Introduction
Ongoing research into so called “next generation manufacturing systems” stresses the importance of semi-automated systems, i.e. systems where humans play a significant role (Gaines & Norrie et al., 1995). The absolute productivity of such systems will be determined by the ability of the organisation to adapt to and use them.

One way to support this adaptation is to use an extended implementation plan when installing new manufacturing systems thus give the organisation opportunity to develop in phase with the technical implementation (Towill & Cherrington, 1994). A significant drawback with this approach is the long project lead time required which is contrary to the general situation in industry today where rapid and successful implementation is necessary to take advantage of “market windows“.

The use of various simulation tools such as discrete event simulation for decision support when developing manufacturing systems is now quite commonplace. However, their use is usually limited to evaluating alternative technical configurations and seldom takes organisational aspects into account. In many cases, the results from such “technical” simulations are of limited benefit to the project as a whole as they correlate poorly with the behaviour of the real system where organisational factors affect system performance.

Production simulation models of semi-automated systems should therefore model both the technical configuration and the organisations ability to handle the system.
One approach to modeling skill and competence development within an industrial organization is the use of a theoretical learning curve. Learning curve theory has been applied to a wide range of industrial applications that include human operators in complex tasks such as assembly (Naime & Towill et al., 1993).

The use of simulation incorporating learning curve theory to model the behavior of manufacturing systems is explored in the following two case studies.

**Case study 1**

The aim of the work presented in this case study was to increase understanding of the impact of worker competence on overall productivity in a recently commissioned highly automated press line. The simulation model developed included both technical (main) and organizational (supporting) processes and focused on the interaction between these (Figure 1).

Whilst production simulation had been used as a decision support tool in the early phases of this project, these initial models covered only the main processes (filled symbols in Figure 1). The effects of operator learning and interaction effects associated with the sub-processes were neglected. These initial models, in retrospect, indicated performance / production levels far higher than seen in practice.

In the present study process mapping was used to identify the processes to be included in the discrete event simulation model (Ilar & Kinnander, 1997). The processes chosen were the main process as well as tool preparation, set-up and maintenance processes all of which had the greatest impact on overall system performance.

To be able to model the ‘learning’ or increase in operator skill associated with the supporting processes, a competence...
profile and learning curve was included in
the model for two tasks; the tool related
process and the maintenance-related
process.

A number of different formulae have been
developed to model learning. (Naime &
Towill ET al, 1994). The one used in this
case was based on the “time constant”
formula:

\[ T_c(x) = \left( T_{opt} + \Delta T \times e^{-\frac{x}{C_t}} \right) \]

where:  
- \( T_c(x) \) is the operation time for
  index \( x \);
- \( T_{opt} \) is the operation time \( x \rightarrow \infty \);
- \( (T_{opt} + \Delta T) \) is operation time at \( x = 0 \)
  and;
- \( C_t \) is the learning curve factor.

In the simulation model, the competence
index for each operator was updated
according to this formula each time s/he
performed an activity. The initial
competence index for each operator was
obtained through discussions with the
group supervisor.

Two different human management
philosophies were evaluated; one using
dedicated operators and another
developing broad operator competence and
hence flexibility. The impact of the
management philosophy used was
evaluated for both short term productivity
as well as after a learning period of 10
weeks. Different levels of work load,
operator availability and product batch
sizes were investigated. A factorial design
was used to plan the simulation which
required 8 combinations to achieve a three
factor, two level, full factorial experiment.
(Law & Kelton, 1991.)

Results

Table 1 shows the relative production rate
(RPR) in %, defined as the production rate
from this simulation study, vs. the
production rate from the previous decision
support simulation run. The results are
based on simulation of 10 weeks
production preceded by a 10 week
competence build up period and with a
highest level of workload.

The study indicated that the highest initial
RPR is achieved using dedicated operators
However, developing “broad competence”
offers advantages after the build up period
and when the workload is increased.
(Figure 2.) Short-term (two shift)
measurements of the RPR also shows a
much lower variation for the broad
competence approach compared to the
dedicated operator approach.

It is important to note that the production
rate decreases by approximately 70% for
both alternatives compared to predictions
from the earlier study which focused
almost entirely on the technical
configuration. About one third of this
decrease is explained by the more frequent
sets up in the present study. The remainder is due to the introduction of organisational factors and the inclusion of more realistic breakdown data. This indicates the importance of including both main and supporting process.

These results were validated through presentation and discussions with the project team rather than through direct comparison with actual system performance.

Case study II

The model in this case study is of an assembly line for manufacture aircraft wing beams. The line has, at this point in time, produced 31 batches of beams.

The line is currently undergoing a period of re-organisation and improvement due to the likelihood of winning a major export order which is expected to result in an increase of approx. 50% in order volume. In order to complete this order on schedule, the ‘door to door’ lead time must be reduced.

The workers in the assembly line are currently divided into four groups; mechanical sub-assembly, mechanical final assembly, assembly of electronic equipment, and final seal and dry. Five different types of beams are assembled in the line (Figure 3.)

In order to meet the demands of increased order volume and reduced door to door time, it has been suggested that the two mechanical assembly groups, sub assembly and final assembly, are combined into one multi-skilled group in order to minimise the delay at hand-over between these two stages. This has close similarities with the use of different management philosophies seen in case one.

The principle performance measures used in the study was door to door time, however, there was a secondary goal of keeping labour utilisation at less than 70%. This relatively low figure was chosen to compensate for other tasks and operators unavailability, which were not included in the model. The use of learning curves for estimating assembly lead time is common in the aircraft industry where relatively short production runs and high dependence on worker skill mean that competence development and learning play a significant role.

Figure 3. Flowchart of the activities associated with the assembly line.
The "learning curve" equation in use at the company, which is different to that used in the first case study was used in the simulation model. (Parametric Cost Estimating Handbook, 1997-12-23):

\[ y = a \times x^b \]

where, 
- \( y \) = time per unit;
- \( a \) = time to complete the first unit;
- \( x \) = unit number and
- \( b \) = learning curve coefficient

The study used comparison between alternatives (Law & Kelton, 1991). The alternatives used were:

<table>
<thead>
<tr>
<th>Use of Learning Curves</th>
<th>Management Philosophy</th>
<th>No</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separate assembly groups</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Multi-Skilled assembly groups</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

**Results**

This study is still ongoing but some initial results can be presented. Table 2 shows a comparison between confidence intervals of door to door times (Hours) and shows that there is a significant difference between the four alternatives evaluated.

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>87.93</td>
<td>87.34</td>
<td>88.52</td>
</tr>
<tr>
<td>2</td>
<td>98.81</td>
<td>97.40</td>
<td>100.22</td>
</tr>
<tr>
<td>3</td>
<td>67.42</td>
<td>67.19</td>
<td>67.69</td>
</tr>
<tr>
<td>4</td>
<td>66.15</td>
<td>65.25</td>
<td>67.05</td>
</tr>
</tbody>
</table>

Table 2. Comparison of 95% confidence intervals for the four different alternatives.

The most striking difference is seen in the simulation results with and without learning curve effects. (1-3, 2-4) The model covers manufacturing from the 31st batch onwards and the slope in the learning curve is rather flat but still has a significant effect. There is also an indication that the spread in door to door time decreases when using the separate assembly groups. (1-3)

The study will be extended in order to develop the model to include limited resources in the form of jigs and also storage space. Neither of these were included in the present study. Another improvement is to increase the quality of the data, for instance accuracy of operator competence profiles.

The results obtained thus far, as well as those from further research, will be used by management to decide how to proceed in the real system.

**Conclusions**

This paper presents two case studies which demonstrate the effects of operator and team skill development and the need to include these characteristics when using simulation modelling in order to obtain a realistic evaluation of advanced semi-automated manufacturing systems.

In both case studies technical as well as organisational factors were modelled; technical factors being related to automated activities and organisational factors related to learning curve effects as the number of times that task is carried out increases.

From these studies it can be seen that simulation modelling including learning theory is important when modelling manufacturing systems characterised by frequent re-configurations and where productivity is directly effected by the organisations ability to adapt. Including technical as well as organisational factors is of great importance for understanding the effects of human/machine interaction on the overall system performance.

The most important application area for this technique is to support development of
manufacturing systems consisting of highly automated main processes and organisational oriented supporting process as found in Case Study 1. Traditional project management associated with this type of manufacturing system is usually very technically oriented and often neglects supporting process. Nevertheless, overall performance is often highly dependent on the performance of the supporting process.

Case study two shows that even systems which are well established can behave in what might appear an unpredictable manner when subjected to change.

Future research will include more sophisticated output analysis methods which will allow an increased number of factors to be considered and thus allow more complex competence development patterns to be studied. Another important area of research is the integration of financial modelling to support a realistic and dynamic life cycle cost analysis of the different systems.

Acknowledgements

The work presented here was carried out as part of the PIDUS research project, which addresses the design, implementation, commissioning, management and maintenance of production system. The authors would like to thank Eur.Ing. David Legge, other co-workers in the Department of Manufacturing Engineering and the industrial partners used for the case studies. Special thanks must go to the Swedish National Board for Industrial and Technical Development (NUTEK) for funding this work.

References


Paper V

Modelling the impact of supporting processes on manufacturing system performance – experiences from an industrial case study.
Paper V: Modelling the impact of supporting processes

Torbjörn Ilar
Modelling the impact of supporting processes on manufacturing system performance – experiences from an industrial case study.

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Abstract

This paper presents a modelling method which supports project management, evaluation and performance prediction in manufacturing systems where the interaction of the main process with supporting processes is significant. The method uses process mapping and discrete event simulation to develop a common understanding of system functionality amongst the project group rather than simply for measuring or predicting system performance. The method has been applied in an industrial case study and the results of the case study have shown the significant impact of the supporting processes on the overall system performances. Further, a learning factor has been introduced in the discrete event simulation model and has shown a great importance in achieving reliable predictions of actual system performance resulting from changes in organisation.

1. Introduction

The “Next generation manufacturing systems” (NGMS) which are being built today place increasing demands on flexibility which can be achieved through technological solutions such as reconfigurability and the use of automated systems. (Gaines et al. 1994). In line with increasing dependency on technology, the importance of humans and organisational structures as “technology enablers” is also increasing. The absolute productivity of NGMS are determined by the synergetic interaction of main (technical) process and supporting (human / organisational) processes.

Although the importance of organisational and human factors on system productivity long been known and investigated (Lehtinen et al. 1998; Finch and Luebbe 1995) these factors are still seldom taken into account in any performance evaluation related to proposed changes in existing systems or implementation of new systems. This often lead to a drastic over estimation of the productivity of the system.

Production (discrete event) simulation is commonly used for decision support in this kind of project. The scope of simulation is also usually limited to evaluating the relative technical merits of alternative system configurations. Not unsurprisingly, there is more often than not a poor correlation between the performance indicated by the technology oriented model and the real system which consists of both technical AND non-technical factors. For simulation to provide valid data for decision support both technical and organisational processes must be included in simulation models.

2. Industrial case study

The case study described here has been carried out at an SME ‘make to order’ manufacture. The study investigated a semi-automatic manufacturing system whose layout
consists of five independent product manufacturing areas. Each product area has dedicated operators with responsibility for all the activities within the main process and most of the supporting processes.

In the early 1990’s the company had few customers generating high and predictable yearly order levels. These orders were such that demands for flexibility within the manufacturing system were general low. The present layout and organisation date from this time when it was very well suited to handle the market situation at that time.

Since then, the company’s customer base has changed and it now faces problems. The company’s current market consists of larger numbers of customers who place smaller orders. This has made significant demands on the manufacturing system as far as flexibility and set-up frequencies are concerned. Efficiency of the system has drastically reduced due to long waiting times for activities within the main process due to shortcomings in the supporting processes. These can be attributed to poor organisation.

The study has focused on alternatives ways of organising the supporting process and initially focused on gaining an understanding of the current situation and in particular the supporting processes. In order to achieve an accurate time estimation for these processes, the operators assisted in collecting data over a four week period, as well as through a number of interviews.

The processes of interest to this study are outlined in figure 1. It is important to note that the sequential nature of the processes is due in part to the present organisation. The components manufactures are produced using conventional machine tools. The tool handling process is concerned with preparation and collection of fixtures. Raw materials and documentation must obviously be collected for each batch of work. The “disturbance” process in figure 1 refers to situations where tooling, documentation raw material etc. is not available or there are problems associated with them.

Figure 1, Main process and supporting process for one product group. This process structure is common for the five product groups in the study.
3. Simulation Experiments
The second step in the study consisted of translating the main and supporting processes into a discrete event simulation model.

The simulation study investigated two new organisational alternatives which were compared to the present organisation. The main performance measurement used for this was the percentage of waiting time within the main process for the five different manufacturing groups. The different organisational structures considered were:

1. Present organisation: Operators work solely within one manufacturing group and are responsible for both main and supporting process.
2. Common supporting processes: Operators are tied to the main processes within their manufacturing group but have joint responsibility for supporting processes with operators from the other groups.
3. Supporting process expert: As alternative 2, but with the addition of an extra person who sole responsibility is for the supporting processes for all five product groups.

To be able to model the ‘learning’ or increase in operator skill associated with working with the supporting processes over a period of time, a skill profile and learning curve was included in the simulation model.

In the simulation model, the skill index for each operator was updated according to a learning curve based on the time constant model (Naim and Towell 1993) each time s/he performed an activity. In broad terms, the model allows twice as long for a new operator to carry out a supporting process as it does for an experienced operator.

The simulation study used product batch sizes as a driving input. Two levels of batch size were run, the present level and a batch size only half as big which is the expected situation within two or three years.

4. Results
The results from the study are summarised in table 1 and are based on the simulation of 20 weeks stable production preceded by a 10 week stabilisation period.

The study indicated that the greatest efficiency is achieved by complementing shared operator responsibility for the supporting processes with a supporting process expert.

As there are always problems related to new organisational structures. The main role of the supporting process expert is to ensure that the organisation develops good routines related to the supporting processes.

Once these routines are established, it is expected that there will be few problems for the operators carrying out the supporting processes. This implies that the extra resources provided to assist with developing the supporting processes need only be a temporary thing and can be removed after about 20 weeks without any substantial effect on the system efficiency.

<table>
<thead>
<tr>
<th>Organisation Alternative</th>
<th>Without learning</th>
<th>With learning</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Min</td>
</tr>
<tr>
<td>Present situation (Reference value)</td>
<td>20.9</td>
<td>18.2</td>
</tr>
<tr>
<td>Common support</td>
<td>21.8</td>
<td>18.9</td>
</tr>
<tr>
<td>Expert resources</td>
<td>16.6</td>
<td>13.8</td>
</tr>
</tbody>
</table>

Table 1. Average capacity losses: mean, min, and max based on 95% confidence interval with present batch sizes.
The effects of the reduced batch size scenario are summarised in table 2. As expected, the resulting increase in number of set-ups required would reduce efficiency considerably if the present organisation were kept.

The common support organisations are both better able to provide the increased flexibility necessary. As before, the effects of the supporting process expert diminish over time.

<table>
<thead>
<tr>
<th>Organisation Alternative</th>
<th>Mean</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present situation</td>
<td>30.9</td>
<td>28.7</td>
<td>33.2</td>
</tr>
<tr>
<td>Common support</td>
<td>11.1</td>
<td>8.6</td>
<td>13.8</td>
</tr>
<tr>
<td>Expert resources</td>
<td>7.6</td>
<td>5.4</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Table 2, Average capacity losses: mean, min, and max based on 95% confidence interval with 50% batch sizes reduction.

5. Discussion

The industrial case study presented here reflects a common problem within Swedish industry with changing market demands causing significant pressure on manufacturing managers. Whilst the importance of the human involvement and organisation to the overall efficiency of manufacturing system has long been recognised in Sweden, knowledge about the quantifiable impact and optimum organisational structures is often very limited. The use of any analysis tool or method for the design of supporting process is still uncommon. In most cases existing organisations are grafted onto new systems and allowed to develop organically rather than being designed from the outset.

The modelling method described in this paper is ideally suited to handle the problems which are outlined above. In addition to gathering technology related information, human and organisation factors are also investigated.

The discrete event models developed from this gathered information allows for the evaluation of the overall system performances and for development of alternative configurations.

As always, success is very much dependent on close co-operation with the operators to achieve accurate process description and data. This requires trust to be built up between the operators and the staff carrying out the study, especially if it is known that organisational or other changes have been mooted.

The use of the simulation models as a means of communicating the simulant’s understanding of the current methods of working to shop floor staff increases their involvement in the project and allows feedback from this valuable source knowledge and supports the general acceptance of any proposed changes.

6. Conclusions

This paper presents a modelling method which supports project management, evaluation and performance prediction in manufacturing systems where the interaction of the main process with supporting processes is significant. The method uses process mapping and discrete event simulation to develop a common understanding of system functionality amongst the project group rather than simply for measuring or predicting system performance.

The results of the case study have shown the significant impact that organisation can have on supporting processes. Including technical as well as organisational factors in any simulation study is therefore of great importance in allowing understanding of human/machine interaction on the overall system performance to be obtained.

Modelling supporting processes can drastically improve the quality of the predicted overall system behaviour. Using this method will thus significantly increase the usefulness of production simulation to help develop solutions that are both technically and organisationally sound. Furthermore, mapping the supporting processes through operator participation in
the project work increases involvement and gives valuable feedback in the development of the system.

The introduction of learning factors in the discrete event simulation model is also of great importance in achieving reliable predictions of actual system performance resulting from changes in organisation.

The method can be extended to be able to fully support development of new manufacturing systems. Future research will include further industrial case studies where more significant system changes or investments are involved.

An important step in projects involving more significant changes or investments is the evaluation of a number of alternatives. Possible tools for this include analytic hierarchy process (Lin and Nagalingam 1997) and axiomatic design (Suh et al. 1998).

Another important area of research is the developments of methodologies which address the need of quickly develop production models (rapid modelling) as well as the integration of financial modelling to support a realistic and dynamic life cycle cost analysis of the different systems alternatives.

7. Acknowledgements

The work presented is based on research within the PIDUS project; which is concerned with developing techniques to improve the design, implementation, commissioning, management and maintenance of production systems. This project is funded by the Swedish National Board for Industrial and Technical Development (NUTEK). Additional work has been funded by the Luleå CIM Institute.

The authors would also like to thank Eur. Ing. David Legge and other co-workers in the Department of Manufacturing Engineering as well as the staff at the company used for the case study.

8. References


Paper V: Modelling the impact of supporting processes

Torbjörn Ilar
Paper VI

The effect of process interruption and scrap on production simulation models
Paper VI: The effect of process interruption and scrap

Torbjörn Ilar
The effect of process interruption and scrap on production simulation models
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Abstract:
This study shows that, for many manufacturing processes (such as welding and injection moulding), a machine breakdown will result in the scrapping of a component, and goes on to explain the effect that this can have on process simulation models. Breakdown related scrapping events are ignored by commercially available process simulation packages and this reduces their usefulness in decision support. This paper explains the different types of breakdown/scrapping dynamic possible and provides equations which can be used to describe them in future generations of simulation software. This work clearly demonstrates the scrapping dynamics effect on one of the major performance measures in LEAN based manufacturing systems, namely the Overall Equipment Effectivness.

Keywords: Simulation, Manufacturing, Breakdown, Scrapping, OEE

1 Introduction

The main aim of any production simulation software is the accurate representation of real situations. It is also highly desirable that process engineers with limited programming skills should be able to perform the modelling process (Chick S et al., 2003). From such modelling exercises, the engineer and management can make strategic decisions about capital investments and staffing levels etc. Eriksson (Eriksson U, 2005) has reported on a number of surveys which suggest that decision support is, and will be, the most important application of production simulation. There are, however, some risks involved in modelling if the programmer who designed the software fails to interpret the process accurately. One area where confusion can arise is that of machine breakdowns and any associated scrapping of components.

The effect of machine breakdown and the scrapping of components is usually over simplified in simulation models and this can have a serious effect on the accuracy of the model. Many processes that involve hot or molten metal, as well as some mechanical deformation techniques, fall into the category of being non-interruptible. Non-interruptible processes require special consideration if accurate production simulation is to be achieved because, in this case, most machine breakdowns will result in a scrap component. As we shall see later in this work, many commercially available production simulation packages do not link the scrapping of components to machine breakdowns. In future generations of production simulation software a distinction should be made between manufacturing processes which can be re-started on a component (after interruption) and those which are non-interruptable.
An example of a process which could be interrupted by a machine breakdown and then successfully re-started, would be the punching of a matrix of holes in thin sheet steel. If the punching machine broke down in the middle of a punch cycle the component could generally be completed after the repair was carried out (although this is not always the case).

On the other hand there are a considerable number of manufacturing processes which cannot be re-started on a component after interruption. For example; the bending of steel is a dynamic process which must be completed in one stroke. If the process is interrupted and then re-started, the result will differ from that produced by a single stroke. During the initial, partial, bend, the material will become harder and stronger by a process known as work hardening. After the breakdown is repaired the bending machine will be dealing with a work piece which is in a different shape (partially bent) and also stronger. It is therefore not surprising that the final bent product will be different from items which were bent in one smooth operation.

Welding is another important example of a process which can be badly affected by interruption. Figure 1 presents a view of an interrupted weld which has been continued by re-starting the process. It thus contains a start-up anomaly which will not have the same properties as the standard weld produced in one single welding operation. Anomalies of the sort can be a source of mechanical weakness, porosity or cosmetic disruption in the finished component.

![Fig. 1. An interrupted weld which has been continued by restarting the welding process; the start up anomaly may be a source of mechanical weakness or cosmetic disruption to the finished product.](image)

Methods for applying simulation to the modelling of production disturbances and breakdowns have been discussed by several authors (Selvaraj N et al., 2003; Shin F et al., 2004; Williams EJ et al., 2005). For example, Ingemansson et al (Ingemansson A et al., 2004; Ingemansson A et al., 2003) have reviewed a number of cases where production simulation was applied to the problem of optimising system performance. This type of work often includes machine breakdowns and in some cases part scrapping, but any possible links between machine breakdown and scrapping are ignored.

One of the most important development trends within industry is the implementation of LEAN manufacturing strategies (Holweg M, 2006; Shah R et al., 2003). LEAN manufacturing implies, among other thing, the use of a multifunctional team with shared responsibilities for the different processes involved (Holweg M, 2006). Realistic simulation
models of LEAN based manufacturing systems therefore require the modelling of shared resources (Shah R et al., 2003). The implementation of TPM (Chand G et al., 2000; Wang FK et al., 2001), Total Productive Maintenance, is also a crucial strategy in LEAN manufacturing and this has lead to the development of a performance measure called the Overall Equipment Effectiveness (OEE) (Chand G et al., 2000; Wang FK et al., 2001). The OEE is a measure of the value added to production through equipment. This is a function of machine availability, performance efficiency and the scrap rate (Wang FK et al., 2001).

Production simulation software is widely used to support decisions in the fields of manufacturing layout, organisation and process planning (Eriksson U, 2005). The quality of the decisions taken clearly relies on the accuracy of the simulation model. Wrong assumptions and inaccurate simulation results can therefore lead to the wrong decisions being made.

It is the aim of this paper to demonstrate that the accuracy of production simulation models is often dependant upon a correct interpretation of the breakdown/scraping relationship of the production system involved. This is a point which has been largely overlooked by the producers of commercial production simulation software.

2 Different types of breakdowns and their related scrap dynamics

Figure 2 graphically illustrates the comparison between zero breakdown production and three different types of breakdown, each of which results in different levels of productivity (indirect measures of operational availability). The graph shows the situation between to setups and does not include other disturbances (i.e. lack of material and operators).

Type A production involves no breakdowns and no scrap (the ideal situation) and therefore 100% productivity and is used as a reference for comparison in this investigation. Identical breakdown intervals and repair times have been assumed for the three types of breakdown (B, C and D) in order to keep the discussion as clear as possible. In all cases a breakdown takes place after exactly 5.5 process cycles and the repair time is taken as equivalent to 2 cycles.

Type B breakdown dynamic assumes that the manufacturing process can be continued after the breakdown repair and so no parts are lost. An example of this type of process might be the tapping of holes in mild steel, as this process could (generally) be restarted. In this case only the time of the repair is lost.

Type C breakdown dynamic assumes that the item is scrapped during the machine breakdown but that the item cannot be removed before the machine has finished its cycle. An example of this type of process could be bending or painting. Type C breakdown imposed scrapping is, in most cases, not directly offered by commercial software packages, but is quite easy to model using a standard simulation program feature; the routing percentage of a particular operation ie. If the relationship between breakdown and scrapping is understood a percentage out the machine output can be ‘routed’ to a scrap container.

Type D breakdown dynamic assumes that the item is scrapped during the machine breakdown and is removed from the machine as part of the repair. This means that production can start immediately after the repair. Examples of this type of process could be welding or sheet metal forming. Type D breakdown/scrap dynamic (which is likely to be the most common in industry) is, according to our knowledge, not considered in commercial software
codes and would require editing of the core code of the simulation software to obtain the desirable scrapping behaviour.

<table>
<thead>
<tr>
<th>Type</th>
<th>Productivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE A: No breakdown; No scrap</td>
<td>100%</td>
</tr>
<tr>
<td>TYPE B: Breakdown; No scrap</td>
<td>73%</td>
</tr>
<tr>
<td>TYPE C: Breakdown; Item scrapped but must be left in machine until cycle is complete</td>
<td>60%</td>
</tr>
<tr>
<td>TYPE D: Breakdown; Item scrapped but remaining cycle time is available</td>
<td>67%</td>
</tr>
</tbody>
</table>

**Fig. 2.** The ideal production situation (100% productivity) and the three different types of breakdown dynamics for the case of breakdown after 5.5 operations (cycles) and repair time of 2 cycles (\(\checkmark\) = acceptable product quality, \(X\) = product scrapped, \(R\) = repair taking place).

It is clear from figure 2 that the interpretation of breakdown dynamics has a substantial effect on productivity levels. In the example shown, the Type B model produces 9% more products than Type D and 22% more than Type C. In situations where breakdowns are more frequent or cycle times are longer, the differences between the four dynamics would be even greater.

As we mentioned earlier, the importance of breakdown related scrap is overlooked in commercially available simulation packages. For example, a review of three commercially available production simulation packages revealed that two of them (Simul8 and Enterprise Dynamics) offered no connection between breakdowns and scrapping events. In the case of the third software package (Extend) it was possible to link breakdowns to scrap but this lead to the bizarre consequence that the operator would also be ‘scrapped’. It is clear from these observations that, within these packages, breakdowns are generally considered to be a separate variable to scrapping events, and that all processes are assumed to be interruptible. The clear link between breakdowns and scrapping events for most manufacturing processes requires an improvement in simulation models of this type if they are to be used to make commercially viable decisions.

### 3. Analytical modelling of breakdown imposed scrapping

The following section of this work presents some analysis of the effect of breakdown imposed scrap on productivity levels. A first step in this analysis is the calculation of the percentage of scrap parts produced by a machine involved in a non-interruptible operation.
3.1 The breakdown imposed scrap percentage equation

The percentage scrap ratio PSR [%], is given by the ratio of the total number of parts scrapped (PS) to the total number of parts produced (TP), over a time period T.

\[ PSR = \frac{PS}{TP} \times 100 \]  

(1)

In the interests of simplicity the following analysis will assume that parts are scrapped only as a result of breakdowns. If this is the case, the total number of parts scrapped over a time period T for a Type D breakdown/scrap dynamic (see Figure 2) is given by:

\[ PS = \frac{T}{MTTF + MTTR} \]  

(2)

Where;

\[ MTTF = \text{Mean Time To Failure} \]
\[ MTTR = \text{Mean Time To Repair} \]

The total production (TP) over a time period is given by;

\[ TP = \frac{T \times MTTF}{MTTF + MTTR} \]  

(3)

where PT is the process time for the station involved.

Combining (1), (2) and (3) gives;

\[ PSR = \frac{PT}{MTTF} \times 100 \]  

(4)

The results of this calculation are given in figure 3 for a range of process times and it is clear that scrap related breakdowns can have a serious effect on productivity. This is particularly true if the process time is large. This is because each breakdown event becomes more significant at longer process times.
3.2 The overall equipment effectiveness (OEE) for breakdown/scrap dynamics type A to D

Although it is of some interest to monitor scrap levels, the most important measure of performance is productivity. One way of quantifying productivity is by analysing the Overall Equipment Effectiveness (OEE).

The Overall Equipment Effectiveness (Wang FK et al., 2001) as a percentage can be expressed as:

$$ OEE = PE \times A \times QR \times 100 $$

(5)

where:

- **Performance Efficiency (PE)** is given by:

  $$ PE = \frac{TCT \times AP}{OT} $$

  (6)

  where TCT is the Theoretical Cycle Time, AP is the amount produced and OT is the Operating Time.

- **Availability** (the proportion of time that the machine is not being repaired) is given by:

  $$ A = \frac{MTTF}{MTTF + MTTR} $$

  (7)
The yield (the proportion of components which are not scrap) is given by:

\[ Y = 1 - \frac{PSR}{PT} \quad (8) \]

For the case of breakdown imposed scrapping, Eqs. (4) and (8) give:

\[ Y = 1 - \frac{PT}{MTTF} \quad (9) \]

Combining Eq. (5), (6) and (8) gives:

\[
OEE = \frac{MTTF}{MTTF + MTTR} \times \left( 1 - \frac{PT}{MTTF} \right) \times 100
\]

(10)

For Type A breakdown dynamic MTTF = infinity and MTTR=0 which gives from Equation (10):

\[ OEE_A = 1 \times 1 \times 1 \times 100 \quad = 100\% \quad (11) \]

For Type B dynamic there is, by definition, no scrap, and, from Equation (10):

\[ OEE_B = 1 \times \left( \frac{MTTF}{MTTF + MTTR} \right) \times 1 \times 100 \quad (12) \]

Equation (10) will exactly represent Type C dynamic so the OEE for Type C is given by;

\[
OEE_C = 1 \times \left( \frac{MTTF}{MTTF + MTTR} \right) \times \left( 1 - \frac{PT}{MTTF} \right) \times 100
\]

(13)

For Type D strategy, with breakdowns happening, on average, PT/2 into a particular cycle, we will gain production time equal to PT/2 for each breakdown event compared to the Type C dynamic. The increase in productivity of the Type dynamic D compared to Type C is given by:

\[ \Delta PT_{D,C} = \frac{PT}{2(MTTF + MTTR)} \quad (14) \]

Combining (13) and (14) gives:

\[
OEE_D = \left( 1 \times \left( \frac{MTTF}{MTTF + MTTR} \right) \times \left( 1 - \frac{PT}{MTTF} \right) \frac{PT}{2(MTTF + MTTR)} \right) \times 100
\]

(15)
4 Results and discussions

4.1 The effect of scrapping dynamics on OEE

Figure 4 compares the OEE associated with the four breakdown strategies as a function of process time with MTTF = 23 minutes and MTTR = 2 minutes. This figure once again demonstrates the serious effect which breakdown associated scrapping can have on the OEE of a machine. Figure 4 also supports the point made in figure 3 that longer process times result in reduced OEE if scrap is related to breakdowns. It is also important to note that the results from the different types of breakdown dynamic diverge rapidly as the process time increases. In this case, for example, the difference between types C and D is only 5% when the process time is two minutes but this rises to 14% at a process time of five minutes.

![Graph showing OEE as a function of process time for different breakdown strategies.](image)

**Fig. 4.** The OEE associated with the four production breakdown dynamics (A-D) as a function of the process time (MTTF = 10 min, MTTR = 2 min).

Figure 5 illustrates the impact of the three main time variables PT, MTTF, MTTR on OEE levels when we consider breakdown strategy D. Note that figures for Type C would show similar trends, while Type A is the ideal breakdown-free case and Type B is not realistic for breakdown imposed scrapping. Importantly, the Type D dynamic is the one which is most likely to be encountered when dealing with a real engineering process of the non-interruptable type.

The first pair of graphs in figure 5 show the linear relationship between process time (PT) and OEE which would be expected from equation 15. Productivity levels can drop to as low as zero as MTTF, MTTR and PT converge. The remaining four graphs in figure 5 demonstrate that, for a type D breakdown/scrap dynamic, the relationship between OEE and MTTF or MTTR is not simply linear. It is also clear that OEE is more sensitive to changes in MTTF than MTTR (within realistic limits).

The graphs in figure 5 illustrate the importance of an adequate understanding of the breakdown/scrap dynamics when trying to obtain performance measures (in this case OEE) with some accuracy. An inappropriate assumption about breakdown/scrap dynamics could have a catastrophic effect on the subsequent decision making process.
4.2 The influence of different modelling approaches on performance measures

To further investigate the influence of the different breakdown/scrap dynamics (Types B, C and D) on OEE, the relevant OEE equations were incorporated into a discrete event simulation model of a manufacturing system. This example demonstrates a typical application for production simulation as a decision support tool. The system chosen consists of two stations with two parallel machines which are served by three operators with shared responsibilities, see figure 6. The bottleneck in the system, in this case Process II, has been given the highest priority for the operators. The process parameters used are given in Table 1. The commercial simulation software used was ‘Enterprise Dynamics’. The results are based on an 8 hour simulation time with 20 replicates.
Fig. 6. The system modelled in the comparison

Table 1. Parameters employed in the simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival</td>
<td>Unlimited</td>
</tr>
<tr>
<td>Process time /</td>
<td>Triangular distribution with mean 120, min 60 and max 180 sec.</td>
</tr>
<tr>
<td>Process I</td>
<td></td>
</tr>
<tr>
<td>Process time</td>
<td>Triangular distribution with mean 180, min 90 and max 270 sec.</td>
</tr>
<tr>
<td>/Process II</td>
<td></td>
</tr>
<tr>
<td>MTTF</td>
<td>540 seconds - exponential distribution</td>
</tr>
<tr>
<td>MTTR</td>
<td>Triangular distribution with mean 60, min 30 and max 90 sec.</td>
</tr>
</tbody>
</table>

Generally, the performance measure of greatest interest is the output per day and these results can be seen in Table 2. The hierarchy of productivity of the various breakdown/scrap dynamics is similar to that presented in Figure 2 where the relative values were 100%, 90%, 53% and 64% for Types A-D, respectively.

Bearing in mind that breakdown/scrap dynamics A and B are generally unrealistic, it is important to note that, in this example, there is a difference in production yield of 21% between Type C (which is easy to use in the software and would normally be chosen) and Type D (which is more realistic in real production environments). The implication here is that the more commonly used scrap/breakdown scenario (Type C) would often give an inaccurate analysis of a production situation and would therefore be a source of incorrect management decisions.

Table 2. Performance measure OUTPUT/DAY (yield) with 95% confidence intervals.

<table>
<thead>
<tr>
<th>Model</th>
<th>-95%</th>
<th>Average</th>
<th>+95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>284.1</td>
<td>285.2</td>
<td>286.3</td>
</tr>
<tr>
<td>Type B</td>
<td>255.2</td>
<td>256.7</td>
<td>258.2</td>
</tr>
<tr>
<td>Type C</td>
<td>147.4</td>
<td>151.7</td>
<td>156</td>
</tr>
<tr>
<td>Type D</td>
<td>180.4</td>
<td>183.7</td>
<td>187</td>
</tr>
</tbody>
</table>
The scrap per day performance is also important to our understanding of the system as well as to the overall costs. The scrap per day output from the simulation is shows a difference of less than 2% in scrap volumes for scrap/breakdown dynamics Type C and D. This may seem surprising as the production yield of the two differs by over 20%. This behaviour can be explained as follows: Although both dynamics involve a similar number of breakdowns, the Type C breakdowns all result in a greater loss of useful production time (and in turn of output) as the production cycle must be completed after the repair.

5 Conclusions

- Many manufacturing processes (like bending or welding) cannot be interrupted in mid-cycle and then successfully continued by re-starting the process. When such non-interruptible processes experience a mid-cycle breakdown, a component will be scrapped.
- This linkage between breakdowns and scrap is not a feature of commercially available production simulation software. This can result in the software supporting inappropriate conclusions when comparing systems or machines.
- Breakdown/scrap dynamics of types A, B can be incorporated into existing production simulation quite easily. Type C can be introduced by a skilled software user using existing options. However, there are many non-interruptible processes where dynamic D would be most appropriate to the model. It is extremely difficult to incorporate the type D dynamic into existing commercial simulation software. The lack of availability of the type D dynamic can lead to inappropriate decisions being made when comparing machines or systems.
- For all three types of breakdown (B, C and D), equations which describe the relevant Overall Equipment Effectiveness (OEE) have been developed. These equations could be incorporated in future editions of production simulation software.
- It has been demonstrated by example that, when using production simulation software, the correct choice of breakdown dynamic (A, B, C or D) is essential if the results are to be useful in decision support.

The present authors consider it a matter of some urgency that the providers of production simulation software should address the phenomenon of breakdown related scrapping events and incorporate Type D as a standard feature in their programs. Without this option the existing software packages are in many cases inaccurate, misleading or difficult to use by production management personnel.

6 References


Simulation of production lines involving unreliable machines; The importance of breakdown statistics and the effect of machine position.
Simulation of production lines involving unreliable machines; The importance of breakdown statistics and the effect of machine position.

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Abstract

This paper demonstrates the importance of choosing the correct values and statistical distributions for breakdown frequency and duration when simulating production line productivity. Statistical distributions with a wide range tend to reduce the productivity of the line but this trend can be disrupted by poor choice of mean values for the variables in question. Also, it is demonstrated that the productivity of a production line can be improved simply by re-arranging the order of unreliable machines in the line. If the line consists of similar or exchangeable machines, productivity can improved if the most unreliable machines are placed towards the end of the line. The paper also demonstrates the risks of reduction of the standard deviation to obtain a more deterministic model.

Keywords: Simulation; Manufacturing; Breakdown; Statistic distribution; Scrapping.

1. Introduction

Some of the effects of machine breakdowns on productivity are modelled in commercially available simulation software. However, as earlier work by the present authors suggests [1], the treatment of machine failure is often oversimplified and this can lead to misleading simulation results. For example, simulation models do not generally link the scrapping of components to machine breakdowns. In real production situations however, the item being produced when the machine breaks down is often scrapped. This is because many engineering operations (casting, welding, bending, etc.) cannot be completed successfully once they have been interrupted. This paper demonstrates that a useful mathematical analysis of the breakdown behaviour of a machine must be supported by a carefully chosen statistical description of that behaviour in the context of the production line.

The application of computer simulation for modelling production disturbances has been discussed in several papers [2,3,4,5,6]. For example, the work of Ingemansson et al [7,8] often includes references to machine breakdowns and part scrapping but the two phenomena are not directly linked. The importance of the correct interpretation of breakdown characteristics in achieving high model accuracy has also been demonstrated [9]. However, this interpretation only effects secondary performance measures (i.e. buffer size and product lead time) and not, as in our approach, the main performance measure – productivity.
The reduction of standard deviation in the statistical distribution applied in the model is method to perform validity tests of the model [10] or in general to obtain a deterministic model to increase the interpretation opportunities.

2. Simulation experimental work

Production simulation software packages offer a range of statistical distributions for input variables. These statistical approaches are intended to give a realistic model of the behaviour of a system.

In this investigation a production simulation tool (Enterprise Dynamics) was used to analyse the productivity of the production line shown in figure 1 using chosen mean values for Mean Time To Failure (MTTF), Mean Time To Repair (MTTR) and Process Time (PT) for the various stations. In order to compare the results of various statistical distributions the mean values were employed in three ways; 1. As a fixed value, 2. As the mean of a triangular distribution and 3. As the mean of various Gaussian distributions.

Table 1 describes the parameters used in the simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fixed Mean Time</th>
<th>Triangular</th>
<th>Gaussian</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival</td>
<td>Fixed; no constraints</td>
<td>Fixed; no constraints</td>
<td>Fixed; no constraints</td>
</tr>
<tr>
<td>Process time / Station 1 and 4</td>
<td>10.0</td>
<td>T(10.5,15)</td>
<td>G(10.5)</td>
</tr>
<tr>
<td>Process time / Station X and Y</td>
<td>10.0 Fixed; 10 minutes</td>
<td>Fixed 10 minutes</td>
<td>Fixed 10 minutes</td>
</tr>
<tr>
<td>Process time / Station Q</td>
<td>8.0 Fixed; 8 minutes</td>
<td>Fixed 8 minutes</td>
<td>Fixed 8 minutes</td>
</tr>
<tr>
<td>MTTF Station X (85% ok)</td>
<td>40.8 Fixed; 40.8 minutes</td>
<td>T(40.8,20.4,61.2)</td>
<td>G(40.8,20.4)</td>
</tr>
<tr>
<td>MTTR Station X (85% ok)</td>
<td>7.2 Fixed; 7.2 minutes</td>
<td>T(7.2,3.6,10.8)</td>
<td>G(7.2,3.6)</td>
</tr>
<tr>
<td>MTTF Station Y (95% ok)</td>
<td>57.0 Fixed; 57.0 minutes</td>
<td>T(57,28.5,85.5)</td>
<td>G(57,28.5)</td>
</tr>
<tr>
<td>MTTR Station Y (95% ok)</td>
<td>3.0 Fixed; 3.0 minutes</td>
<td>T(3,1,5.4)</td>
<td>G(3,1.5)</td>
</tr>
<tr>
<td>MTTF Station Q (99% ok)</td>
<td>237.6 Fixed; 237.6 minutes</td>
<td>T(237.6,118.8,356.4)</td>
<td>G(237.6,118.8)</td>
</tr>
<tr>
<td>MTTR Station Q (99% ok)</td>
<td>2.4 Fixed; 2.4 minutes</td>
<td>T(2.4,1.2,3.6)</td>
<td>G(2.4,1.2)</td>
</tr>
</tbody>
</table>

Table 1: Parameters employed in the comparison of different distributions (all times are in minutes)

1) eg; T(10.5,15) Describes a triangular distribution with a mean of 10 minutes; min 5 minutes and max 15 minutes.
2) eg; G(10.5) Describes a Gaussian distribution with a mean of 10 minutes and a standard deviation 5 minutes.

The situation being considered is as follows; Stations X and Y are identical machines carrying out similar operations (eg weld 1 and weld 2). Both machines are somewhat unreliable but machine X breaks down more often than machine Y and also takes longer to repair on each occasion. The management of the company in question are considering replacing one or both machines with faster, more reliable machines (Q).

The simulations were carried out for 400 hours with 5 replicates. The availabilities for Stations Y and Q were set to 95% and 99% respectively, the availability of station X was initially set at 85% although other values are used for comparison later in the discussion.
Figure 2 gives the result of the simulation for three different types of statistical distribution;

a. Fixed Mean Times (FMT) - No statistical distribution – mean values only.

b. Triangular (triang) – In this case we have triangular distributions with the same mean times as above but a minimum of half the mean and a maximum of one and a half times the mean.

c. Gaussian (Gauss) – In this case we consider Gaussian distributions with the same mean values as above and standard deviations of half the mean value.

These three types of distribution were compared against each other for all possible combinations of the machines; two new machines (QQ), the replacement of either of the old machines with a new machine in all the arrangements possible (QY, YQ, QX or XQ) and both arrangements of the old machines if no replacement takes place. In figure 2 the results have been presented in order of decreasing productivity.

Figure 2. The relative productivity of different arrangements of the stations.

The availability for station X is 85%, Y is 95% and Q is 99%.

Figure 2 demonstrates several points, two of which are obvious and others which need some discussion:

The obvious points;

1. Replacing both X and Y with new machines gives the highest productivity.
2. Replacing X with a new machine improves productivity more than replacing Y.
The more interesting points;

**A. The order in which two similar machines appear in the line affects productivity if the machines are of different reliability:**

Close examination of figure 2 reveals that the order in which the stations are arranged has an effect on line productivity. This effect can be seen more clearly in figure 3 which shows, for example, that changing the machine order from XY to YX improves the productivity of the line by over 2.5% for the triangular distribution and by over 1.5% for the Gaussian. This point, that line productivity improves if the more reliable machines precede the unreliable ones, is confirmed in figures 4 and 5 which consider the same production line if the availability of machine X is reduced to 67% (MTTF; 35mins, MTTR; 17.5 mins). In this case we can see that the productivity of the line increases by almost 10% for the triangular distribution if machine X follows Y rather than preceding it. The sensitivity of the line to machine order is reduced if more reliable machines are considered. For example, for the QY/YQ comparison, productivity changes by less than 1% for all the distributions examined in figure 5.

![Relative position effect (station X = 85%)](image)

*Figure 3. The changes in line productivity achievable if the less reliable machine is placed later in the line rather than earlier; e.g. The YX/XY value is calculated by dividing the line productivity if the machines are arranged 'Y then X' by the productivity of the 'X then Y' arrangement (Y being the more reliable machine). Results are given for each of the statistical distributions presented in table 1.*
Figure 4. The relative productivity of different arrangements of the stations if the availability for station X is reduced to 67%.

Figure 5. The changes in line productivity achievable if the less reliable machine (X machine – with an availability of 67%) is placed later in the line rather than earlier; e.g. The YX/XY value is calculated by dividing the line productivity if the machines are arranged ’Y then X’ by the productivity of the ’X then Y’ arrangement (Y being the more reliable machine).

The clearest way to explain the effect of machine order on line productivity is to describe what happens if both X and Y machines break down at the same time. We will, in the interests of clarity, use fixed mean values from table 1 for the following discussion;

XY machine order - simultaneous breakdown;
X takes 7.2 minutes to repair and Y takes 3 minutes. As X is before Y in the line, production on Y must wait until a part arrives from X. From the start of the breakdown machine Y must
wait 17.2 minutes before starting work – and the component arrives at station 4 (see figure 1) 27.2 minutes after the breakdown.

YX machine order – simultaneous breakdown; 
Y takes 3 minutes to repair and can begin processing a new component after this time. The repair to X continues whilst Y is operating and is finished before Y completes its process. In this case the second machine of the two (X) begins work after 13 minutes and the item arrives at station four 23 minutes after the breakdown began (a saving of 4.2 minutes production time compared to the XY case).

This ability of an unreliable machine to ‘starve’ subsequent machines of work is the reason why the positioning of the most unreliable machines towards the end of the line improves productivity. Of course this deliberate arrangement of the machines is not always possible, but it should be considered whenever similar or exchangeable machines are part of a production line.

One more minor reason why productivity can be improved if the more unreliable machine is placed later in the line is demonstrated in figure 6, which graphically represents the performance of machines X and Y in both their combinations. In this case the reliability of machine X is 75% (MTTF 40.8 mins, MTTR 13.6 mins) and that of Y is 95% (MTTF 57 mins, MTTR 3 mins). Figure 6 shows us that if machine X is placed before machine Y, then the full effect of breakdowns on both machines limits productivity. If, on the other hand, machine Y precedes machine X, then the machine Y breakdowns do not have much effect on productivity because they happen during the times when machine X is being repaired. Obviously the parameters have been chosen here to present an extreme case, but it is possible to have short breakdowns which do not affect production if they happen during longer breakdowns on other machines. This effect will become more noticeable for very unreliable machines where breakdown overlap will be more common.

B. Different statistical models using the same average values give different productivity results;

For each machine combination shown in figure 2 there is a hierarchy of productivity for the different types of statistical distribution; Fixed mean times generally give the best productivity followed by the triangular, then the Gaussian distributions. As all these
approaches involve the same mean values for MTTF and MTTR, this hierarchy requires some explanation;

If the triangular and Gaussian distributions describe a long period of production this will include shorter periods of high and low productivity for each machine (as the frequency of breakdowns and time to repair change temporarily). For the statistical distributions involved here, there will, of course, be an equal amount of matching high and low productivity periods centred around the mean values for MTTF and MTTR. However, when the whole production line is considered, the high and low productivity periods for the individual machines do not cancel each other out. A temporary increase in breakdown rate for a particular machine is likely to reduce the production rate of the line but a temporary decrease in breakdown rate for a given machine will not always increase production. In this case for example, a period of exceptionally poor performance by machine X will probably result in X becoming the rate determining machine. However, a period of unusually good performance by machine X may be simultaneous with a period of poor performance by machine Y. If this happens machine Y might become rate determining and the balancing effect of X’s improved performance will be lost. The difference in productivity between the triangular and Gaussian distributions shown in figure 2 is due to the wider spread of MTTR and MTTF values allowed by the Gaussian distribution (see fig 7) – the occasional periods of very high breakdown rate or longer repairs possible for individual machines in the (broader scope) Gaussian distribution will restrict overall productivity. This point, that a wider statistical distribution of MTTR and MTTF results in lower productivity, is supported by figure 8, which compares productivity for a Gaussian distribution with different standard deviations.

![Figure 7](image_url)

Figure 7. A comparison of the spread of values available for the triangular and Gaussian distributions being considered in table 1.
C. The importance of careful choice of mean values

Although figure 8 indicates that productivity decreases as the spread of possible values of MTTF and MTTR increases (i.e., as the standard deviation increases), this trend can be disrupted by, for example, small changes in MTTF and MTTR;

Figure 9 presents results of the relative performance of the production line (with machine Y before X) as a function of increasing standard deviation (of MTTF and MTTR) for three different percentage availabilities for machine X. It is clear that, in general, the productivity of the line decreases with increasing standard deviation – as in figure 8.

Figure 9. Although the general trend is for decreasing performance with increasing standard deviation, this trend is not always reliable – see figure 10.
Figure 10 however, demonstrates that, in the 75% availability case at low standard deviation, it is possible to decrease the relative productivity of the line from 72% to 55% simply by changing the values of MTTF and MTTR from 41 and 14 minutes respectively to 39 and 13.

On the face of it this is an astonishing result but it is easily explained as follows;

First of all we can make the assumption that the item in the machine at the time of the breakdown will be scrapped and the time spent on processing it up to the breakdown will be wasted. Earlier work by the authors [1] has established that this is a reasonable assumption for most engineering processes (because most engineering processes cannot be interrupted). We have a unit time (PT) of 10 minutes. If the machine breaks down after 39 minutes of production then it will have produced three good pieces and one scrap piece - which has involved 9 minutes of wasted production time. If the machine breaks down after 41 minutes it will have produced four good pieces and one scrap piece - which has only involved only one minute of wasted production time. It is clear from this that the 41/14 MTTF/MTTR combination will be far more productive than the deceptively similar 39/13 one if the system runs on fixed mean time values.

In the case of the 39/13 minute combination, the productivity of the line is low at small values of standard deviation (see figure 10). This is primarily as a result of the unfortunate relationship between PT and MTTF described above. At larger values of standard deviation the 39/13 and 41/14 lines converge because the spread of results increases until the two mean values become indistinguishable i.e. at very low values of standard deviation MTTF and MTTR are effectively fixed values, and in this case, 39 minutes will always coincide with the final minute of production of a part. Similarly, 41 minutes will always be associated with the first minute of production of a part. As the standard deviation increases, the values for either 39 or 41 might be any where between, say 36 or 44 – so either mean figure might involve a failure at the beginning or end of a production operation.
D. Unexpected results

As a result of the interplay of the variables involved we can occasionally get unexpected results such as those shown in figure 11. This figure demonstrates the effect of XY/YX machine order on line productivity for different X machine availabilities over a range of standard deviations. As well as the conflicting trends given by the choice of mean value (discussed above) there are numerous unexpected ‘kinks’ in the lines on the graph – some of which are counterintuitive (particularly in the 75% 41/14 case). It is not the intention of this paper to investigate such ‘kinks’ in detail – we simply want to draw the attention of workers in this field to the difficulties involved in identifying reliable trends.

![Deviation - XY versus YX - Gaussian distribution - Different std dev.](image)

Figure 11. Results such as these reveal the difficulties inherent in the identification of reliable trends in the detailed behaviour of production simulation models.

3. Conclusions

1. The modelled productivity of a production line is highly dependent on the statistical distribution type assigned to each breakdown variable (e.g., Gaussian or triangular distributions of MTTF and MTTR). Statistical distributions with a broad range (such as Gaussian) will tend to result in low productivity. This is because occasional periods of low productivity will not necessarily be balanced by occasional periods of high productivity if the whole line is considered.

2. Although an increase in the range of MTTF and MTTR will generally result in a decrease in productivity, this trend can be severely disrupted at small values of standard deviation or if fixed mean values are used. If fixed or almost fixed values are used it is important that the values are selected very carefully to avoid setting up breakdown ‘rhythms’ which could result in unrealistically high or low productivity results. For the same reason fixed or small standard deviation values cannot necessarily be used to validate the performance of simulation models (This technique of variation reduction for model validation is in widespread use).

3. The modelling of any engineering system must consider whether the process involved at each step can be interrupted and later continued to produce a usable component.
Many engineering processes such as casting, welding or painting cannot be interrupted and any mid operation breakdown will result in a scrap component.

4. The productivity of a production line involving unreliable but interchangeable machines is improved if the less reliable machines are positioned towards the end of the line. This effect diminishes as the reliability of the machines in question improves. The magnitude of this effect is strongly dependent on the statistical distribution type assigned to the breakdown parameters.

References