On Reduction of Production Disturbances in Manufacturing Systems Based on Discrete-Event Simulation

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Improved efficiency in manufacturing systems to achieve increased output and thus reduced production disturbances is a vital area. Discrete-event simulation can be used to visualize and study the dynamic issues related to total efficiency in manufacturing systems. A methodology for production disturbance reduction is presented. Manufacturing companies are the basis of a country which many other activities rely on. Different production improvement techniques, for example TPS (Toyota Production System), have been shown to smoothe production flows and raise overall quality.
The presented methodology is based on three main stages: 1) planning and data gathering, 2) analysis and implementation, and 3) continuous improvement. Planning and data gathering initiate the DES work. In the analysis and implementation stage the work will be based on experiments and then implemented in the manufacturing system. Continuous improvement of the proposed methodology includes improvement in model design, studies of production improvement techniques, training of operators, follow-up of implemented changes, investigations in measurement of production disturbances and key figures. With feedback various variables can be altered and the DES model and thus the manufacturing system can be improved in several phases.
The potential of the methodology was shown in several case studies. The industrial case studies showed improved performance of 6%, 12%, 14%, 18%, respectively. The suggested methodology may enable an increase of total output in a manufacturing system if it is applied.

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Summary

Improved efficiency in manufacturing systems to achieve increased output and thus reduced production disturbances is a vital area. DES (Discrete-Event Simulation) can visualize and study the dynamic issues related to total efficiency in manufacturing systems. A methodology for production disturbance reduction is presented. Increased performance of manufacturing systems means not only enhanced value for the company but in the long run for the society as a whole. Manufacturing companies are the basis of a country which many other activities rely on.

Different production improvement techniques, for example TPS (Toyota Production System), have been shown to smoothe production flows and raise overall quality. Implementation of production disturbance reduction ideas must be conducted according to all basic rules of manufacturing. Contemporary production improvement techniques based on supply chains between different suppliers and limited products in stock make it necessary to focus on production disturbance reduction.

The presented methodology is based on three main stages: (1) planning and data gathering, (2) analysis and implementation, and (3) continuous improvement. The planning stage includes project plan, goal and objectives of the study, definition of production disturbances, gathering of input data and logics and the conceptual model. The analysis and implementation stage comprises DES model translation, verification, validation, and experiments. The experiments are based on alternative tests in production disturbance reduction to increase equipment efficiency. The enhanced results in the model should be verified before they are implemented in the real world.

Continuous improvement of the proposed methodology includes improvement in model design, studies of production improvement techniques, training of operators, follow-up of implemented changes, investigations in measurement of production disturbances and key figures. The improvement process is a continuing

procedure. A model is seldom so good that it yet can not still be improved. With feedback various variables can be altered and the DES model can be improved in several phases.

The potential of the methodology was shown in several case studies. The industrial case studies showed improved performance of 6%, 12%, 14%, 18%, respectively. No larger investments were needed to increase the performance. The suggested methodology may enable in increase of total output in a manufacturing system if it is applied.

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Lund, 10 June 2004

Arne Ingemansson

List of Acronyms

CBS . . . . Corporate Business Systems

DES . . . . Discrete-Event Simulation

DT . . . . DownTime

ERP . . . . Enterprise Resource Planning

FMS . . . . Flexible Manufacturing System

HMI . . . . Human-Machine Interface

JIT . . . . Just-In-Time

MRP . . . . Manufacturing Resource Planning

NC . . . . Numerically Controlled

OEE . . . . Overall Equipment Effectiveness

PD . . . . Production Disturbances

PDM . . . . Product Data Management

PLC . . . . Programmable Logic Controller

RCM . . . . Reliability-Centered Maintenance

SMED . . . . Single-Minute Exchange of Die

SQC . . . . Statistical Quality Control

TBDT . . . . Time Between DownTime

TPM . . . . Total Productive Maintenance

TPS .... Toyota Production System

TQC........... Total Quality Control

TQM .... Total Quality Management

WIP .... Work In Progress

WT............ Waiting Time

Contents

Chapter 1

Introduction

1.1 Background

Competitiveness in manufacturing is a concern for everybody. Manufacturing of products is essential for a sustainable development of a country. All other sectors are based on the manufacturing industry. Improved equipment efficiency in manufacturing systems is necessary for a company to stay competitive. Simulation is one way to study the behaviour of a manufacturing system. DES (Discrete-Event Simulation) makes experiments in a virtual environment and thus a tool for increasing performance of a manufacturing system.

Increasing performance of a manufacturing system is a key area in the manufacturing industry of today. Decreased amount of production disturbances may contribute to more reliable and robust manufacturing systems and better overall efficiency of the manufacturing industry. Production disturbances may occur in all system levels in manufacturing and a more systematic approach to increase overall productivity of a system is needed.

1.2 Research Objectives

The main research objective of the thesis is to present a methodology for reducing production disturbances based on DES. Manufacturing systems tend to become more and more complex. Therefore, there is a need to take a more systematic approach to reasons for production disturbances occurring in a system. Adequate production improvement techniques should be used together with DES.

The DES model allows methods and techniques to be applied on a virtual manufacturing system. Reduction and elimination of production disturbances in manufacturing systems can be tested accurately. Both the operator and the machine and their interrelation can also be studied. Besides the numerical data, the methodology will include modelling of human interaction and to some extent the organizational aspects used in the manufacturing systems.

Furthermore, the goal is to find an applicable methodology to improve equipment efficiency in a manufacturing system with sufficient accuracy. An actual improvement should be possible to implement in the manufacturing system when the methodology is used. The suggested methodology should be useable both for academic and industrial areas. Finally, the increased performance of the system should be able to be measured when the methodology is applied in the real-world manufacturing system. Both further prevention and elimination of production disturbances should be considered.

1.3 Limitations

Certain issues related to the field of production disturbances in manufacturing are not covered in the thesis. Issues not included are, among others, the linkage to the design of the products for reduced production disturbances in a manufacturing system. Introduction and ramp-up of new products in a current system are not fully covered in the thesis; the methodology is based on relatively stable systems.

Seasonal or fluctuating demands and other outside conditions are also not included in the report. Production disturbances inflicted by the MRP (Manufacturing Resource Planning) system are not included in the study. Finally, the supply chains and their availability to deliver in time, correct amounts of products and with sufficient quality are implicit in the thesis.

1.4 Research Methodology

1.4.1 Scientific method

The methods of scientific work will help to produce a more reliable knowledge. In research some formalized frames are the base of the research process. The methods should help to gain the work and express the information in an understandable way. There are two main alternatives in research; deduction or induction (Patel & Tebelius, 1987). Inductive science originally means that the investigator should make observations, conduct experiments and record results; then make generalizations and gradually work up to hypothesis and theories (Hacking, 1995).

The scientific quality is determined by the patterns in the collected information in inductive research. There are some conditions that have to be met if inductive inference from observed facts should be changed into laws (Chalmers, 1999). It may be that the number of observations must be large, the observation must be repeated under a different variety of conditions, and no accepted observation statement should conflict with the derived law. These conditions may be met for case study research.

1.4.2 Qualitative versus quantitative research

Qualitative methods for research are useful for understanding and explanation. There are however some concerns, one of the more frequent criticisms is that it appears hard to generalize qualitative findings to settings other than those studied. There are not any great disadvantages although there are things researchers can do to strengthen their case (Firestone, 1993). The researcher asserts a conclusion that cannot be fully proven. Three arguments are (a) analytic generalization or extrapolation from sample to population, (b) analytic generalization or extrapolation using a theory, and (c) case-to-case translation. The strongest argument for generalizing is usually thought to be extrapolation from a sample to a population.

In analytic generalizations, the investigator is striving to generalize a particular set of results to a broader theory (Yin, 1994). There are four criteria for generalizing a case study often applied by judges to compare precedents to a current case. Firstly, there are material facts that must fit from the case study. Secondly, there is appropriateness that requires making value judgments about the fairness. The third criterion is the reason for the decision. Finally there is the generality of the decision to take into consideration.

The difficulty with the sample-to-population argument is that it is difficult to sample all events and issues that need to be sampled to draw some general conclusion or generalization. Undetected and uncontrolled interactions can lead one to falsely believe that observed main effects are significant and can also mask potentially important ones. The problem is that the cases are normally too small to allow some universal conclusions from them.

The researcher is looking for and would like to describe phenomena and understand things that are happening around us. The scientific knowledge is formulated as either a theory, model or hypothesis. The theory includes normally more than the hypothesis and also assumptions and conclusions (Wallén, 1996).

1.4.3 Case study methodology

The main approach to my research work is case studies. Case studies are the preferred strategy when "how" or "why" questions are posed, when an investigator has little control over events, and when the focus is on a contemporary phenomenon with some real-life context. Case studies could be used for exploratory, descriptive or explanatory purposes. Strengths of case studies are the ability to deal with a full variety of evidence, such as documents, artefacts, interviews and observations (Yin, 1994).

There are some prejudices against case studies: The case study investigator has been "sloppy" and has allowed equivocal evidence or biased views to influence the direction of the findings and conclusions. A second common concern is that they provide little basis for scientific generalization.

The advantages of case study inquiry can be summarized as follows:

- copes with the technically distinctive situation in which there will be many more variables of interest than data points from the case,
- relies on multiple sources of evidence, with data needing to converge in a triangulating fashion, and
- benefits from the prior development of theoretical propositions to guide data collection and analysis.

After definition of the case study, other clarifications in the unit of analysis become important. The immediate topic of the case study has to be distinguished from those outside it. There are some important steps to take under consideration such as: time boundaries are needed to define the beginning and end of the case, compare findings with previous research, linking data to propositions, and criteria for interpreting the findings and finally the logic linking data to propositions. The research undertaken here may be more linked to applied than experimental science. There is often a problem ready to be solved in the different case studies in the industry. Many of the ideas described are relevant in the search of the "truth" in my own field.

Some characteristics of case studies that lead to the strengths will also lead to weaknesses. The use of empirical data can yield theory which is overly complex (Eisenhardt, 1989). There is a temptation to build a theory which tries to capture everything. The result may be a theory that is very rich in detail, but lacks the simplicity of overall perspective.

Different persons in an organization have different views and would often like to influence the results of a case study in a certain direction. Being impartial under all circumstances can be difficult. In all performed case studies there are always some decisions made on value judgments. Unfortunately this is more or less unavoidable.

1.5 Ethics of Science

Ethics of science is connected to morality, actual customs in a society or cultural relativism. Ethics itself could be described in some kind of rational morality (Mårtensson, 2000). It is important that research is conducted according to scientific rules. The work should be recorded correctly. Responsibility should be taken for results far-reaching from the current field and other effects related to the research area.

Positive ethical aspects of my research follow: Production disturbances are a considerable issue in the industry of today. Previous research in the field has shown that up to 50% of all planned production time is used for production and the rest is wasted. Studies have shown that if production disturbances are reduced, operators at manufacturing companies can work on other issues than production disturbance handling. The manufacturing process will run more smoothly and it will be less stressful for the operators. Other studies have shown that a high amount of production disturbances will lead to more work hazards. When actions should be taken to restart the manufacturing process there is a high risk of injury. In the environmental field improvement in the manufacturing systems leads to products with higher quality and produced in right time and will therefore create less waste.

Negative ethical aspects in my study could be that increased productivity might lead to more stressful working environment for the personnel. More and more sophisticated equipment could also result in problems for the personnel, who need more education and training. Scientific results should be made available to engineers working at manufacturing companies as well. There is always a risk that the results can be misinterpreted and misunderstood. Finally, there are also some company-based issues in a macro perspective concerning ethical aspects. Companies will benefit from the results; in a global perspective it is necessary to be competitive to obtain a high standard of living.

1.6 Disposition

Chapter 1, *Introduction*, (this chapter) defines the background, research objectives and limitations. A brief description of research methodology and ethics of science is also included.

Chapter 2, *Frame of Reference*, summarizes previous and current research in the field connected to the research question.

Chapter 3, *Industrial Case Studies*, describes the results from the case studies.

Chapter 4, *Methodology*, describes a methodology of production disturbance reduction together with discrete-event simulation.

Chapter 5, *Results*, summarizes the methodology.

Chapter 6, *Discussion*, a discussion on the methodology.

Chapter 7, *Conclusions*, presents the most important conclusions from the research study.

Chapter 8, *Future Research*, suggests future research in the subject.

1.6.1 Description of appended papers

All papers have been reformatted to fit the printing requirements for the thesis.

A1: Reducing bottlenecks in a manufacturing system with automatic data collection and discrete-event simulation.
Contents: The automatically collected input data enabled an elaborate model to be created.

A2: Improved efficiency with production disturbance reduction in manufacturing systems based on discrete-event simulation.
Contents: An improvement method for increased performance in a manufacturing system using DES and step by step alteration based on two case studies.

A3: Increasing performance efficiency in manufacturing systems with production improvement techniques and discrete-event simulation.
Contents: The combination of production improvement techniques and DES is necessary for a beneficial project.

A4: A survey of the use of the discrete-event simulation in manufacturing industry
Contents: 80 Swedish companies were investigated in their use of DES.

A5: Increase the total input when disturbances are reduced in a manufacturing system.

Contents: Two of the case studies are further described in detail.

Chapter 2

Frame of Reference

2.1 Manufacturing Systems

Manufacturing is a key concern for all countries. The ultimate basis for all job creation is and must be the manufacturing industry. All other services are in one way or another based on the manufacturing industry. Some nations have successfully gained a competitive lead due to monopolistic growth in certain manufacturing sectors. Sophisticated industries are the backbone of any advanced economy (Porter, 1998). A nation does not inherit but instead creates the welfare. Even though the workforce involved in manufacturing is shrinking, especially in the more developed countries, this is the backbone of a welfare state.

An example of the importance of the manufacturing industry is the work within the EU (European Union) to create the common market for different products. Products should be the same for the whole market and do not have to be adjusted to specifications for each country within the EU (European Union, 2002). Thus, it enables the European companies to be more competitive in a global perspective with a larger domestic market. Among other countries, Japan and the U.S. have used the method to create global brands and products. One advantage for the EU, among others, is the ability to negotiate with other trading countries to open their markets.

By nature, manufacturing has in many sectors become more and more sophisticated. The investments in new facilities and manufacturing lines are for every time increasing in cost and complexity. Therefore, it is necessary to have a competitive approach to make the investment profitable. A systematic model for design of the manufacturing with the help of powerful computer programs, such as DES

(Discrete-Event Simulation), may be one way to perform high overall productivity. An example may be to build a virtual copy of the manufacturing line before it is assembled in the real world.

2.1.1 Manufacturing and service sectors

There has been loss of work in the manufacturing sector in the last few years. Thus, the trend in many countries has been to increase the effort to create new jobs in the service sector. Few service industries feature high entry barriers compared to the manufacturing industry. Therefore, the service sector is generally not as significant as the manufacturing sector. There is also a linkage between the service sector and the manufacturing industry (Cohen & Zysman, 1987). Many services are in close proximity to the manufactures. If manufacturing disappears, the connected service roles will be moved to the new manufacturing site, maybe also in another country.

2.1.2 The manufacturing process

Manufacturing is much more than a pure material transformation from raw material to a product ready for distribution. The manufacturing includes areas related to the actual material transformation process, see Figure 2.1. The first basic need involves the customers' activity. The products manufactured must be attractive and possible to sell on the market. Product design is more important when the product cycle matures. Focus must shift to production planning, distribution and service logistics to achieve competitive costs according to Hitomi (Yien & Tseng, 1997).

Quality and delivery of manufactured products are significant factors for customer satisfaction. Time to market and service response are included as a part of the manufactured system. Total production cost is another performance measure vital for manufacturing systems. Flexibility in the systems has also drawn more attention. The systems should be designed with production capability and routing alternatives in mind.

2.1.3 The interaction between machine and operator

The interaction between machine and operator has been studied in previous research. Small-scale learning, how experiences are conveyed, and how operators can be seen to generalise their understanding within the work task have been in-

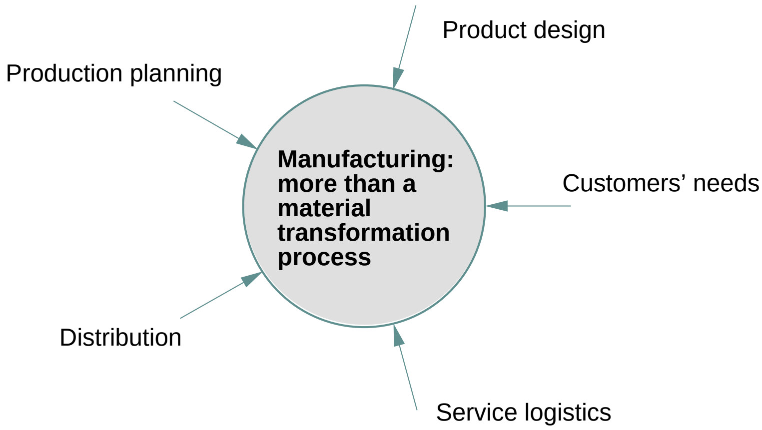

Figure 2.1: *Areas closely linked to the manufacturing process according to Hitomi (1997).*

vestigated (Döös, 1997). What is considered abnormal or normal in the task is dependent on whose perspective it is viewed from. Production disturbances in manufacturing systems are an early occurrence in the chain of events leading to an actual accident. The operator has appeared to be a "fixer" of immediate problems, rather than an inventor of long-term solutions to production problems. Enriched work tasks and work for the promotion of safety seem to go hand in hand. Production disturbances could be handled in a manner that promote development and learning for operators. At the same time, work environment and safety must be in focus.

Many engineers fail to consider the operator a system component. The lack of design for the human user is one of the reasons why so many machines and systems are unsafe, difficult or inconvenient to use (Chapanis, 1996). The physical, functional and operational view can describe the system. The physical view, also called the architectural view, focuses on what the system contains, e.g. design and crew. The functional system focuses on what the system does. That is what the system must do to produce the required operational behaviour. The operational view focuses on how the system will serve its users. This view is establishing operating requirements for the system, how well and under which conditions the system must operate.

Adoption of cellular manufacturing should not be viewed merely as a technical and engineering dominated problem. It is also a change process where the people element is involved (Wemmerlöv & Johnson, 1997). It is therefore suggested to involve personnel, in addition to their technical competence, with an understanding of human resource issues, project planning, and change management. A survey in the U.S. established the view that besides strategic dimensions such as manufacturing lead-time, customer response time and quality, it involves and affects the organizational and human aspects of the manufacturing firm. Cellular structures often require changes in the employee selection, job design, measurement and compensation systems, planning and control procedures, costing systems, reporting structures and vendor relations.

2.1.4 The human representation of data and the learning process

There are certain limits to human process models in cognitive learning (Bainbridge, 1997). Firstly, there is no distinction between inner and outer worlds. Various researches have shown evidence that a person's inner representation of a task is not the same as the data represented. A person's inner view of the world may not be the same as the outer world as agreed by other observers' views. Secondly, human information processing modelling is situation specific and it is impossible to produce a general model of human cognition.

The cognitive processes can be listed (Bainbridge, 1997):

1. Information may not be available about the state of some parts of the system. Information which is available about the state, and the actions on it is often ambiguous.

2. The person is expected to keep under control one or more independent dynamic entities.

3. The dynamic entities may have several variables to be controlled, or there may be inter-dependencies.

4. Most of these tasks are sufficiently complex and it is not to be possible (at least in practice) to anticipate beforehand all the possible situations which might arise.

It is difficult to put a number on human processing capacity limits for at least three reasons: equipment design, expertise and working methods available. Different tasks can require different mental or physical effort depending on the equipment. When a person becomes more of an expert, they can do a task with less mental effort, or inversely, they appear to have increased mental working capacity. In other words, they have developed a skill.

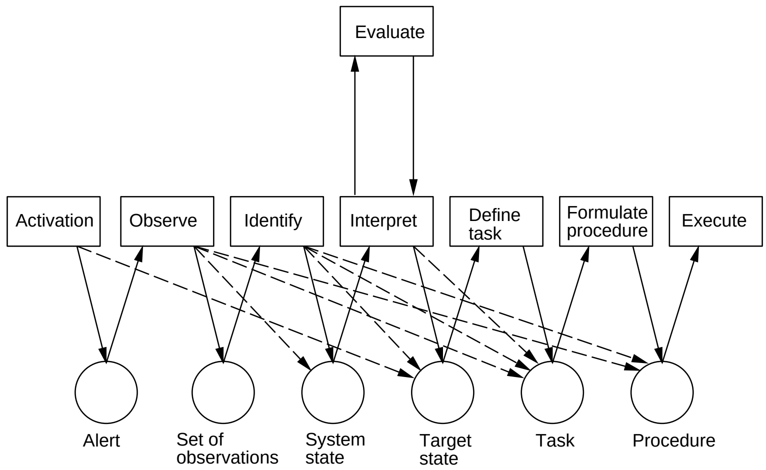

Figure 2.2: *The actions of human operator in control system including intermediate states described in a box diagram. Short cuts in dotted lines represent tasks in which some of the processes are not used (Bainbridge 1997).*

In human engineering a common model of a cognitive process consists of a set of sequence starting with reaction and ending with execution. A box diagram describing the actions of human operator in control system including intermediate states is shown in Figure 2.2. All operations are not needed in all operations and therefore some short cuts are added in dotted lines. Models are often missing the knowledge part of a task. A person acts and responds to a situation that is more likely to their known knowledge. Finally, it has been shown that the different work shifts, for example the night shift, also can affect the responding time.

A number of researchers have tried to identify the process by which companies select methods for improving the performance of their operations. There are two main alternatives of learning: in-process or off-line (Upton & Kim, 1998). In general the learning is still passive and takes place when a production disturbance happens. The learning process in manufacturing improvement involves among other things reducing uncertainty in decision-making when an actual production disturbance has already taken place. Perhaps it is wishful thinking to hope that more preventive actions are to be taken.

2.1.5 Cooperative decision making

The designer, the operator and the automatic control system must be considered together (Rasmussen & Goodstein, 1986). There is a dynamic allocation of decision functions between the partners with appropriate feedback and communication facilities between them. The designer can not possibly foresee the essential control responses for all possible production disturbances. There is a need to an elaborated dialogue between the designer and the operator of the problem to achieve the best possible interface for the operator.

Previous experience of manufacturing the same or similar products should be considered, whether it is a new system or not. System design of today is based on proven technology and is more an update of previous design. It would be more wisely to base the system design on a thorough analysis. Studies have shown that the information needed to control execution of pre-established procedures is typically not adequate for error detection and recovery.

2.1.6 The organizational aspect

An appropriate organization is necessary to support the manufacturing system. The organization should besides manufacturing products handle and tackle production disturbances, maintenance, improvement work and other related issues to the manufacturing system. Many of the production disturbances can be traced to the behaviour of the organization according to the author's opinion. The organization of the company is more or less a "fixed" structure. There is usually resistance to reorganization. Individuals are by nature against new changes in an organization. Most threatened are the groups of low-level supervisors and operators. Reluctance to change structures may give overall consequences for the company in the long term such as decreased yield.

The structure of the labour market with more and more temporary workers may explain some of the new things that can obstruct production disturbance reduction in a manufacturing system. The short-term workers will not develop enough skills before they are replaced. A profitable, forward-looking company would use the recession as an opportunity to train the staff for better times to come.

There is also a tendency to use information technology systems, for example MRP (Manufacturing Resource Planning) systems that may be considered "high-risk" systems. Companies have gone out of business following its MRP or ERP (Enterprise Resource Planning) systems (Mendelson, 2000). Boeing was forced to shut down two of their assembly lines and take charges against earnings in 1997 due to their complexity of their computer systems. Information technology used in an organization is determined by decisions the organization makes and not by the technology itself (Osterman, 1999). Some of the most successful production systems, e.g. TPS (Toyota Production System) has chosen to not rely on sophisticated computer systems.

2.2 Design of the Manufacturing Process

Systematic design of manufacturing systems in all parts is seldom seen. Systems are often built in different steps without any strategic planning. In general, not far-reaching planning is considered for new future products in the same product family and for easy increase in production capacity, e.g. new parallel stations. Many manufacturing systems can be considered “patchwork” built in different sections at different times. There is a need to find more systematic approaches and techniques for overall design of manufacturing systems. One proven way is to decompose the manufacturing system into subsystems of more manageable sizes. Of vital importance is to dedicate resource requirements for layout design, material handling and production planning subsystems. An overall framework of manufacturing systems and their design and evaluation, with particular emphasis on systems analysis, systems design and systems methodology have been suggested (Wu & Ellis, 2000). Manufacturing system design specifies physical, human, organizational and finally information and control architecture as principal areas in design of manufacturing systems.

Many attempts can be seen in improving performance of a manufacturing system. A generic capability unit is suggested as one solution. In this case it is possible to move functions from one unit to another (Gindy & Saad, 1998). The nature of competition is gradually changing in the industry due to information technology. The advances in information technology are changing the industry structure (Porter, 1998). Information technology is a lever that companies can use to create competitive advantage. Finally, information is spawning completely new businesses. Companies that anticipate the power of information technology gain a competitive advantage if it is used in an appropriate way.

2.2.1 Automation in manufacturing systems

Automation may expand rather than eliminate problems with the human operator (Bainbridge, 1983). The classic aim of automation is to replace operators with machines. This is, however, seldom completely fulfilled. The designer’s view of the human operator may be that the operator is unreliable and inefficient and should be eliminated from the system. The irony that Bainbridge discusses is that designer errors of a manufacturing system can be a major source of operating problems. The more advanced a control system is, the more crucial the contribution of the human operator will be. Furthermore, a second irony is that the designer who tries to eliminate the operator leaves the person to do the tasks that the designer cannot think how to automate. The most successful automated systems, with rare need for manual intervention, may need the greatest investment in human operator training. An example of this may be a nuclear power plant.

Automation of a system means often from an operator's point of view that the most important work tasks disappear (Kidd, 1995). The remaining tasks are often characterized as more supportive and could be activities such as filling up material and handling production disturbances. The problems can also be aggravated by poorly designed HMI (Human-Machine Interface). More and more sophisticated computerized systems have in many cases led to tighter connection between human and machine instead of the opposite as intended. The issue, which needs to be addressed, is why technology is designed in such a way to produce unsatisfactory work for people. This kind of work creates so many problems in the workplace. The work task has been given to the robot and the job of the operator has become totally unskilled, trivial and machine-paced. There was an earlier technological development that brought about the unsatisfactory job in the first place.

The production system is much more than the equipment (Brödner, 1991). The system also includes the work force, its skills and the allocation and the sequences of working tasks. The relations among all these elements determine the performance of the production. The combined resources of technology, work organization, and skill profiles must be well suited to each other. The principle of "organization first, technology second" is also asserted. The development and use of technology is the result of social relations and interests that set the conditions and objectives under which technology develops.

The fast development of the manufacturing systems increases the demand for a systematic approach to the design of both systems and products. The product must be appropriate for manufacturing in a suitable manufacturing system. The development continues to obtain an improved system with a high overall output with low tendency for production disturbances. Finally, the information management must be able to give indications if any problems occur. A good manufacturing system is a combination of human interaction and production techniques. Some selected production improvement techniques that may help to achieve it, are further described in Chapter 2.5 and appended Paper No. 3.

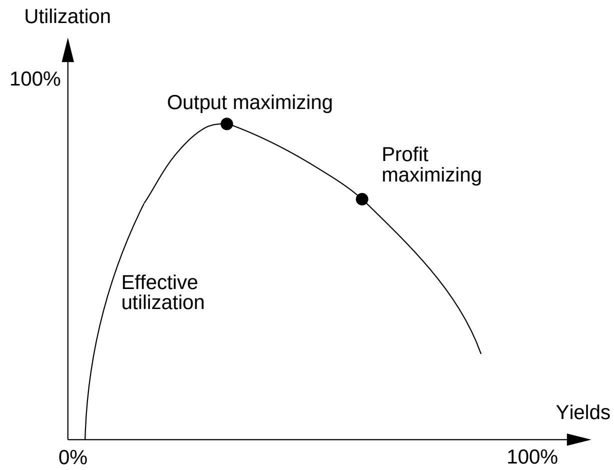

Figure 2.3: *Utilization versus yields in a ramp-up phase, based on Terwiesch and Bohn (2001).*

2.2.2 Production ramp-up

The market window has shrunken for many products in the sectors of telecommunications and consumer electronics. This means that the production ramp-up process has grown more and more important. This creates trade-off between experiments and production (Terwiesch & Bohn, 2001). A new product's ramp-up can last a significant part of the product life cycle. Yields and production rates will gradually increase when learning of the process increase, see Figure 2.3. The two points of output maximizing and profit maximizing are the most endeavoured points to be reached. If the products can be sold and the manufacturing system is robust, this can make the difference for a company to be profitable. The area of production ramp-up is increasing in importance due to the trend toward shorter product cycles. It is a great idea to apply DES in this area. However, the simulation methods and tools are not often well integrated in the development process (Klingstam & Johansson, 2000).

2.3 Production Disturbances

A concern in the input data phase is the classification issue. In-depth studies at machine cells with staff such as operators, maintenance personnel, production engineers and production managers have revealed a great deal of difference in what can be regarded as a production disturbance. The results showed a remarkable variation. This gives the person working with DES (Discrete-Event Simulation) problems; the classification needs exact data for the simulation model.

It is vital for a DES project to have a definition of what can be considered a production disturbance. The comparisons of production disturbances between different manufacturing systems are difficult to achieve as the design and the structures have an impact of production disturbances in a system. No standard classification of what can be regarded as production disturbance exits (Kuivanen, 1996). Each company has to set up their own rules to performance measure the manufacturing productivity. The difficulties in structuring production disturbances are one major drawback seen today. A simulation project is dependent on input data so it is critical to find a structure for it. If the input data is not sufficient structured it is hard to achieve reliable results from a simulation model.

Production disturbances in manufacturing systems can partly describe the current need for inventories. No facility can fully rely on the production system and products are piled up in advance in different places, stocks. The trend, however, has especially for the multinational companies been for the last decade to produce leaner and leaner with reduced stocks. This combined with a globalization and an outsourcing trend has resulted in more semi-finished products to be shipped to different production sites across the globe.

One research project has tried to take a broader view of reduction of production disturbances (Bellgran, Gullander & Harlin, 2002). The aim of the project was to take a wider perspective of improving performance of a manufacturing system. Hard facts as well as organizational questions to different people in the organization and work improvement have also been considered in the project. The complex nature of production disturbances has been shown in the project. There seem to be no “easy” formula to increase the equipment efficiency. It is more of a struggling never-ending project that has to be taken in incremental steps.

There is the problem of scheduling in practice too. Production disturbances can also occur due to MRP (Manufacturing Resource Planning). The disturbances can be categorized in three categories (Stoop & Wiers, 1996): Firstly, there are production disturbances due to the manufacturing system. Secondly, there are production disturbances due to orders such as express orders. Thirdly, there are differences between pre-calculated and actual processing time in the MRP (Manufacturing Resource Planning) system.

This thesis has focused on production disturbances in the actual manufacturing system and not those inflicted by the MRP system. However, it should be noticed that production disturbances can be created outside the manufacturing system and those can later show up more or less unexpectedly in the actual manufacturing process.

2.3.1 Reporting of near miss incidents

Near miss incidents are often related to working with production disturbance reduction. Accidents in manufacturing systems are often connected to production disturbances. The original cause of production disturbances in descending order is operator failure, technical failure, organizational failure and unclassifiable events (van der Schaaf, 1995). There is a tendency to loosen the safety-related work after several years of production without any accidents. A system of near miss reports may help keeping the grip on the safety work. Near misses are also more numerous than actual accidents and can give a hint of where measures may be taken. Furthermore, money is to be saved both for the company and the society if an actual accident may be avoided. For example aviation industry has been successful in avoiding accidents due to incident reports.

2.4 Definition of Formulas

External effectiveness deals with measurement of customer satisfaction. Service level and quality measures are often used for measuring external effectiveness at companies. Internal efficiency is used for measuring performance of a function (Jonsson & Lesshammar, 1999). To decrease the complexity of the overall measurement system it is therefore suggested to use some selected measures of internal efficiency.

Commonly used and according to the author best suitable for a semi or fully automatic manufacturing system is the measurement of OEE (Overall Equipment Effectiveness), see Equation 2.1. OEE and its formulas are modified from the TPM concept (Nakajima, 1988; Prickett, 1999). There are a variety of different definitions. The definitions used here are also valid for all performed case studies. Figure 2.4 is describing the relation between the different components in the equation.

$$OEE = Availability \cdot Performance\ \ rate \cdot Quality\ \ rate \tag{2.1}$$

Where the following definitions are used for availability, performance rate and quality rate:

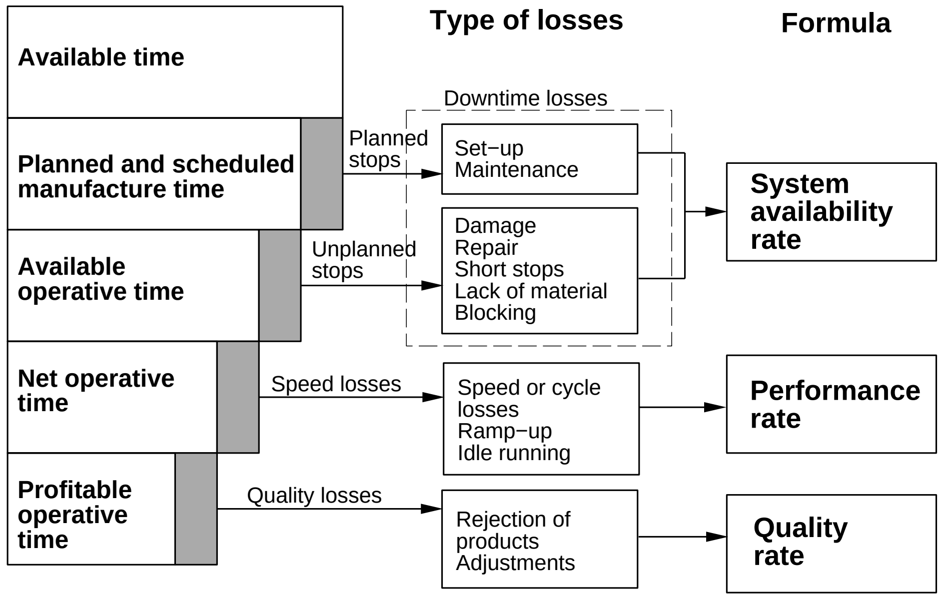

Figure 2.4: *The components of the OEE (Overall Equipment Effectiveness) formula, based on Nakajima (1988) and Prickett (1999).*

$$Availability = \frac{Available\ \ time - Downtime}{Available\ \ time} \tag{2.2}$$

$$Performance\ \ rate = \frac{Theoretical\ \ cycle\ \ time \cdot Produced\ \ amount}{Operative\ \ time} \tag{2.3}$$

$$Quality\ \ rate = \frac{Produced\ \ quantity - Defective\ \ quantity}{Produced\ \ quantity} \tag{2.4}$$

The key component in the OEE formula is the system availability rate or more commonly named availability, see Equation 2.2. In this equation the production disturbances are included in the factor of DT (DownTime). DT refers to the time frame when a production disturbance starts until it ends. Previous studies have shown that WT (Waiting Time) for any action may in many cases be as long as 90% of total downtime, see also appended Paper No. 5 for further reading. The long waiting times are often due to organizational issues according to the author's observation. Accuracy is also a key in the measurements. Automatic data collection enables more accurate data to be measured.

Performance rate, see Equation 2.3 is an assessment of losses arising owing to the operation of the machine tools at reduced performance levels (Prickett, 1999). The performance rate is for example depending on speed or cycle losses, idle running and ramp-up during the actual cycle time. However, theoretical cycle time can be improved. For example, new tool design and material may shorten the theoretical cycle time.

Quality rate, see Equation 2.4 and Figure 2.4, includes the quality related losses of the manufactured products. The products are either rejected or require adjustments. The quality rate can be different from company to company and can also change over time. For example, the requirement for car painting is much higher today compared to the early days of car production.

Based on experience (Nakajima, 1988) the OEE figure of 85% is possible to achieve and the goal should be to surpass it. Furthermore, the ideal conditions based on Nakajima (1988) are:

- availability greater than 90%,
- performance rate greater than 95%, and
- quality rate greater than 99%.

Target values are one thing. However, the experience is that many companies are well below the target. A study based on nine different manufacturing systems at five companies has shown a mean OEE of 50% (Ericsson, 1997). Case studies performed by the author, see appended Papers Nos 1-5, indicated the value to be about the same, from 40% to 60%. Increased and improved measurement will raise the potential of improvement and working with DES is a way of achieving it.

The concept of PD (Production Disturbances) is defined as the time when the manufacturing system is down. That is when the manufacturing system is not producing anything. PD can also involve prolonged cycle time or product quality deviations. Thus, in many cases and in this thesis it is the same as DT. There can always be a discussion what can be included in the figures. The most common idea is to divide DT in planned and unplanned production disturbances. Example of planned production disturbances are maintenance and set-up, and example of unplanned stops are damage, repair, lacks of material, blocking and other stops. Measurements of the different components are necessary in order to improve the manufacturing system's OEE and availability.

Cycle time is the total time needed to perform the necessary operations for processes at each machine or station. In real life, cycle time can be longer than tact time since variances in operating time are not considered. In most cases, however, tact time is much longer than cycle time mainly due to various production disturbances. DES may be used as a tool in studying the phenomena. Finally, quality rate shows percentage of approved products compared to scrapped and by other means adjusted products.

2.4.1 Measurement of production disturbances

There is confusion about the terminology and definitions in the area. An exact definition of production disturbances and what should be included have not been found. One definition describes production disturbances as an unplanned or undesirable state or function of the system (Kuivanen, 1996). However, at a company it is more important to measure something and then there can always be a discussion of how the production disturbances should be categorized.

There is the same problem with adjacent terminology. Definitions such as quality and reliability suffer from the same confusion (Lee, Katz & Hillman, 1998) and the same is valid for dependability, error, failure and fault (Prasad, McDermid & Wand, 1996). There is no consensus and the definition of production disturbance has to be tailored for each company's need according to the author's view. An advantage is that it also starts an interesting discussion on the subject. A survey has been conducted in Sweden of 80 companies showing that the idea of what is regarded as a production disturbance varies considerably, see appended Paper No. 4 and Ylipää, Harlin & Ingemansson (2002).

There can be debate on what should be regarded as production disturbances, both in the academic and industrial world. In real life, however, it is more necessary to find a workable definition. Today this is made on a company level or even from manufacturing cell to cell and it has to be decided on a case to case basis. In all case studies performed by the author the unplanned downtimes are the primary key to improved performance. The other losses in planned downtimes and cycle and quality losses also exist. However, the potential of performance increase in the system is less compared to working with unplanned production disturbances according to the author's views.

If production disturbances should be registered or measured, it seems logical to define the concept of production disturbance first (Smet, Gelders & Pintelon, 1997). However, this is not always done according to the author's experience which is further described in the case studies. It would be wise to achieve at least a company standard of what is regarded as a production disturbance.

Different production systems have a different approach in defining productive time. TPS (Toyota Production System) is reducing costs by eliminating waste (Monden, 1998). Waste is anything that adds cost without adding value. The waste can be invisible of various reasons, for example when a new machine or change of material has made some operations unnecessary (Robinson & Schroeder, 1992). Waste can become normal and necessary part of the process. A failure to update measurement of upgraded manufacturing systems has been noticed by the author.

A more direct linkage between OEE (Overall Equipment Effectiveness) and actual cost is a way of showing the importance of measurement and its effects (Hansen, 2002). If the actual cost can be shown it is easy to justify the improvement work also. The key figure OEE may be used as a business strategy. The pay-back time for the actual improvement project can also be calculated to motivate projects.

When a change in the manufacturing system occurs there is always a risk of introducing a new source of waste. Detecting and eliminating invisible wastes are one of the important jobs of the production manager. In many cases waste can become a "normal" or "necessary" part of the process. It could be called perspective-based invisible waste, since it is exposed if observed from a different perspective (Robinson & Schroeder, 1992).

2.5 Techniques for Improving Manufacturing Systems

There are many production improvement techniques. The methods mentioned here have been established by some of the most profitable companies worldwide. A brief presentation will describe some of the methods. Some of the methods are implemented in the case studies presented. The main techniques used in the case studies are lean production, supply chain management, TPS (Toyota Production Systems) and TPM (Total Productive Maintenance). For a more comprehensive description, see also appended Paper No. 3.

Studies have shown that small plants are slower than larger to adapt manufacturing innovations. For example a survey based on over 1000 US manufacturing plants disclosed a difference in manufacturing technologies (Swamidass, 2003). The technologies include JIT (Just-In-Time), TQM (Total Quality Management), MC (Manufacturing Cells), and SQC (Statistical Quality Control); any new equipment is not essential to their use, but may enhance effectiveness.

An investigation studied three companies in the diesel engine sector in the US (Pagell, Newman, Hanna & Krause, 2000). The companies have different approach to manufacturing. One result seen from the study is that the long-term

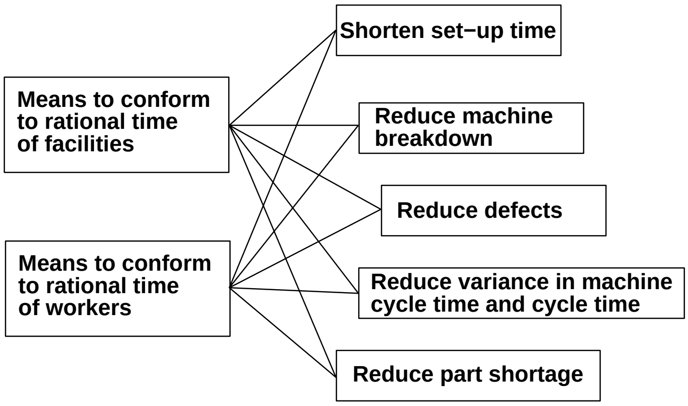

Figure 2.5: *Improvement in the workable rate of facility and worker according to Monden (1998).*

implications of using buffers may actually be lower performance as their use may create costs and even more uncertainty through negative feedback loops.

2.5.1 Toyota Production System

One of the most competitive manufacturing systems is TPS (Toyota Production System). Many of its elements have been spread around the world as state-of-the-art of manufacturing. The main idea is to reduce costs by eliminating waste in different dimensions (Monden, 1998). Waste can be found everywhere in production operations, for example excessive production resources, overproduction, excessive inventory and unnecessary capital investment. The work has to fit together with three other intermediate goals: quantity control, quality assurance and respect for humanity. All together it will make the TPS.

Overproduction is a result of continued work when essential operations should be stopped. Excessive inventory allocates resources for more manpower, more equipment and more floor-space both for transport and stock for the inventory. One of the basic concepts in the Toyota Production Systems is “kanban”. The main idea is to take control of the material flow and smooth the production flow by using physical cards. Demand variations of around 10% can be handled by changing only the frequency of Kanban transfers without changing the total number of cards.

The continuous improvement work in the TPS is shown with the following example, see Figure 2.5. To improve the workable rate, the bottleneck among fa-

Table 2.1: *Assembly plant productivity, weighted average. Volume producers include the three biggest American companies, Fiat, PSA, Renault, and Volkswagen in Europe; and all companies from Japan (Womack and Jones, 1990).*

Owner and location	Productivity (hours/ vehicle)	Quality (defects/100 vehicles)
Japanese-owned plants in Japan	16.8	52.1
Japanese-owned plants in North America	20.9	54.7
American-owned plants in North America	24.9	78.4
American- and Japanese-owned plants in Europe	35.3	-
European-owned plants in Europe	35.5	76.4
Plants in Mexico, Brazil, Taiwan, and Korea	41.0	72.3

cility and worker must be identified. Investigating and eliminating the causes of unworkable time leads to shortening actual hours. Five probable causes of unworkable time are: excessive set-up time, machine breakdown, defects, variances in machine and overall cycle time, and parts shortages.

2.5.2 Lean production

Flexible manufacturing, shorter product lifetime and a shorter product cycle have changed the ideas of manufacturing. The concept of “lean manufacturing” has altered the way of manufacturing (Womack, Jones & Roos, 1990). It can be best described in the difference between mass and lean production. Mass production consists of interchangeability of parts, simplicity of attaching them to each other and marketing and management techniques. Lean production, on the opposite, focuses on small batches, mistakes to be shown up instantly, continuous and incremental improvement process called “kaizen”, five why’s, supply chains and JIT system utilizing for example Kanban.

The lean plant transfers the maximum number of tasks and responsibilities to those workers actually adding value to the product. Furthermore, it has in place a system for detecting defects that quickly traces every problem, once discovered, to its ultimate cause. The automotive industry has been an early adopter of lean manufacturing and lean product development especially of the Japanese companies. To view the productivity and quality defects of lean manufacturing, see Table 2.1. The Japanese automotive industry has taken a lead in productivity and low quality defects. However, there is also a difference in subassembly between different automotive companies.

2.5.3 Supply chain management

Work with supply chains may centralize production units and reduce lead-time. The suppliers' role is widened from only pure manufacturing to e.g. distribution logistics and design (Mattsson, 1999). What makes matters more difficult is the overall change in the market with shorter and shorter product life cycles. The more different competing companies in the area and the longer backwards from the product market the more difficult it is for the company to react on the changes and the shorter time is available for any reaction, see Figure 2.6. It is common to adjust the demand too much (Forrester, 1961). This causes unnecessary fluctuations in the manufacturing process. To adjust to a new level will often take some time.

Despite the implementation of supply chain management, there has been a sharp increase in inventories in the recent downturn in the economy (The Economist, 2001). The only change from previous recessions is that everything is happening faster. Regardless of the extended communication there is often insufficient use of it. The second reason for the increase is the responsibility of the supplier to have the inventory and the obligation to deliver on a very short notice.

It has been shown that demand of products is more erratic and harder to predict due to the option of placing orders via Internet. Orders are placed at a later stage and delivery has under many circumstances been more important than cost for many components. Especially the back-end supply chain can barely handle the huge unpredictable orders. Manufacturers need to overhaul their procurement process and the order information must be shared on an earlier base with the supplier. When products are changed the suppliers must be warned for changes. One can assume these are some of the drawbacks with the current outsourcing trend (Stolle & Fryer, 2001).

There may be a risk for lack of creativity in the development process at a company if all products are outsourced (Harvard Business Review, 2004). Two major trends can be seen so far. First, the production can be moved to a country with low labour cost. Second, the site can also be moved very close to the major customer, for example subcontractors in the automotive industry. There are signs of the trend going in reverse. A Japanese company shifted production back to Japan. Specially trained workers, low defect rates and lean processes increased production flexibility and reduced inventory costs (The Economist, 2004).

2.5.4 Total Productive Maintenance

TPM (Total Productive Maintenance) is an idea to get a wider perspective of the

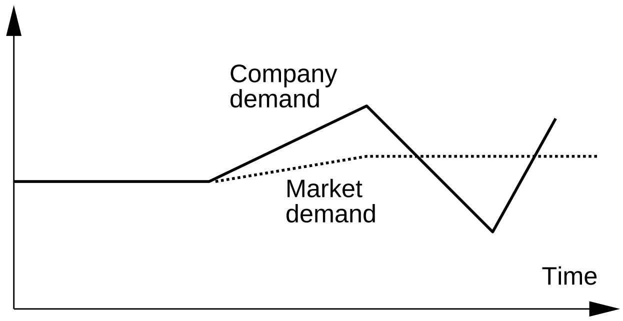

Figure 2.6: *The company has to adjust the produced demand faster than the real demand. It may cause unnecessary fluctuations.*

maintenance function. Maintenance should be shifted from a separate department to become everyone's responsibility. TPM includes all employees. Like TQC (Total Quality Control), TPM is maintenance of equipment performed on a company-wide basis. The goal is zero breakdowns and zero defects. Maintenance depends heavily on human input and TPM involves total participation of all staff. Much waste can be avoided if engineers co-operate more and close the gap between maintenance and design technology (Nakajima, 1988).

Challenges to an implementation of TPM are to overcome the staff's resistance and change the organizational structure. These issues can be found when a new culture is established, after changing attitudes, creating new work environments or accomplishing paradigm shifts. The top managers need to make maintenance a high priority and allocate sufficient resources. One suggested method is mathematical models to increase the effects of TPM (Lawrence, 1999). Thus, four different mathematical models for easier implementation of TPM in the organization were suggested. These describe the benefits in the maintenance and production departments respectively, benefits for cooperation for the organization and benefits for the organization's customer. TPM programs have a tendency to fail due to resistance from maintenance personnel or production personnel.

Products and processes must be integrated (Yamashina, 2000). The future of competitive manufacturing is probably more oriented towards human-integrated production. The basic requirements for world-class manufacturing are to be outstanding in applied research, production engineering, improvement capability and detailed shop-floor know-how involving good maintenance and to integrate them together as a system. A suggested development of TPM in different steps from 1960 onwards is shown in Figure 2.7. The development of TPM is a never-ending process. The nearest future of TPM may focus on RCM (Reliability-Centered

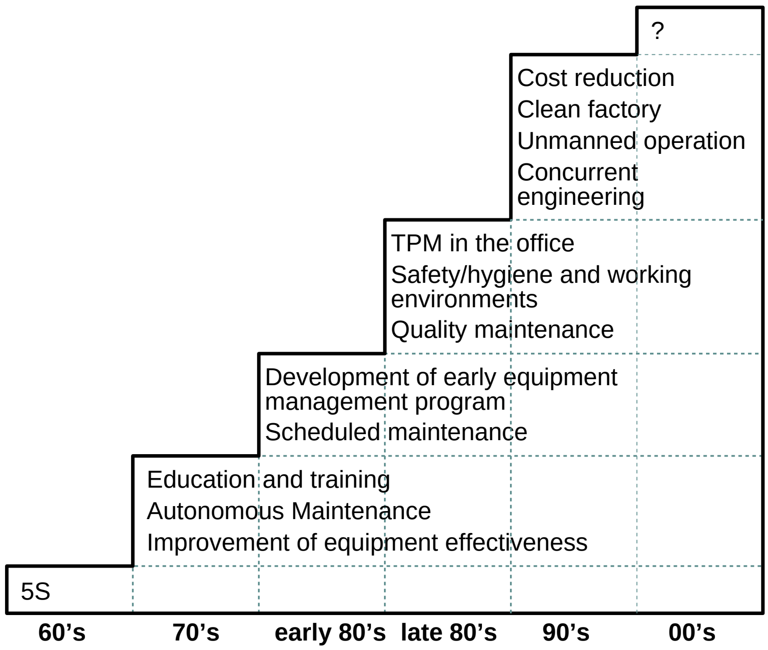

Figure 2.7: *TPM development based on Yamashina (2000).*

Maintenance) and "Condition Monitoring". In addition to OEE, more mathematical models for measurements may also be used.

2.6 Discrete-Event Simulation

DES (Discrete-Event Simulation) is an imitation of a proposed or a real-world process. A DES model enables a study of experiments of a complex system in a virtual world. One advantage with DES is to study the dynamic interactions in a manufacturing system and thus the capabilities of a machine can be determined. By compressing and expanding time, the DES model can speed up or slow down the phenomena such as bottleneck studies. The model can also be used as pedagogical device for different persons in an organization (Banks, 1998*a*), managers as well as operators.

2.6.1 The person responsible for the DES models

The model builder is the person who is responsible for the DES model. The best choice would be the production engineer to also be in charge of the DES model. Production engineers are the main beneficiaries of a DES model. However, the tool of DES requires extensive training before it can be used in an appropriate way. Today's software is adapted to be used by programmers. It is easy to get stuck in applying the logics of the system in the DES model. This combined with the input data issue require often a full-time work to come up with some useable results that may be implemented in the manufacturing system.

In the best of worlds, the production engineers should be able to handle the case study. However, the production engineers often have many different work tasks. The DES software requires almost daily use if the simulation model should be developed in an efficient way. A specific department takes care of DES activities in many larger companies today. Smaller companies often use consulting companies for DES work.

It is a delicate issue because the model builder needs knowledge in both programming and production improvement techniques. There are several features of model work to take under consideration. One is to understand the tool comprehensively; a second is to translate the studied system into a workable model. The time to prepare a useable model is in many cases underestimated. Not only should the model be created, a successful DES model will be used for a considerable time. If a separate department or a consulting firm is taking care of the DES project there is a risk that the model is not updated and used in the same way as an in-house project. The main key to an improvement project, in the author's view, is that the people who build the DES models need to have knowledge about production improvement techniques, too.

2.6.2 Level of simulation methods

The different methods of simulation suitable in a manufacturing company are shown in Table 2.2. The table illustrates the various simulation tools available for improvement work in different dimensions at a company. Depending on the use of a simulation model it has to be built accordingly (Bley, Olterman & Wuttke, 2000). DES is a tool that should be used when it is appropriate compared to the benefits and costs. Today DES is mainly used for manufacturing systems and independent cells. The experience is that equipment efficiency will increase in a manufacturing system when DES is used. This will be shown later in this thesis. Several DES software packages exist, generally they have many things in common. To

Table 2.2: *Level of simulation methods according to H. Bley et al (2000). Different tools are used for different situations at the company.*

Planning level	Content	Method
Company	Business process Information flow Order	Business process Modelling
Production system	Plant layout Material flow Control strategies Job organization	Material flow Simulation
Cell	Cell layout Sequencing NC programming Cycle time Collision check	Movement Simulation
Component	Operations Process parameter Tools Auxiliary means	FEM-simulation

compare, the same model was built in both in Quest and Automod by the author. There was no significant difference in the results of the two models.

Reduction or deletion of certain production disturbances for later implementation in the real manufacturing system have shown to be beneficial. One of the main benefits to use DES is the visualization of the dynamic effects. However, in some cases other methods may be applicable, for example spread sheets or common sense. DES is a powerful method and should be used together with production improvement techniques for best results. In all projects, costs and benefits should be evaluated too.

2.6.3 Conceptual model

Documentation is necessary throughout the DES design phase. The conceptual model is a written version to describe all relevant input data such as layout, logics between elements and other numerical data, including production disturbances, time-to-repair and cycle times. All components in the system should have logical names and characteristics. The conceptual model will be the log of what have been inserted in the simulation model. The amounts of settings in today's software are numerous. Therefore, it is recommended to log the incremental development of the model in a separate document. Furthermore, the conceptual model is valuable when reverted back to the model for revision or for possible fault detecting. It will then be easy to go back and check what has been actually done in the DES model.

Practitioners seldom use any formal model representation method according to a survey (Schorman & Perera, 1998). In case they use any representations it is a simple flowchart. The structuring of the model in a more comprehensive way needs a conceptual model. In the development of a more general simulation model useable for different projects there are certain issues to take under consideration (Randell, 2002). The model should be modularised and adjustable with logical names, everything documented in the conceptual model. Time utilized to build simulation models is in many circumstances easy to underestimate. It is therefore recommended to allocate enough resources in advance to fulfil the project goals. One way of doing this is to use a conceptual model.

2.6.4 The validation and verification process

The DES model should be sufficiently accurate compared to the real world. The accuracy is dependent on the need and purpose of the model. However, the model has to be both verified and validated. This could be enabled in terms of models details: conceptual model validity, verification, white-box validation and data validation and the overall validity, also mentioned as black-box validation (Robinson, 1997). Verification ensures that the model is correct to the conceptual model, while white-box validation ensures that the content is correct according to the real world. In this way it is an indirect form of conceptual model validation. In black-box validation the overall behaviour of the model is considered. Confidence is to be placed in the model when it is running under the same conditions as the real world systems.

Verification is concerned with building the model *right*. It asks the questions (Banks, Carson, Nelson & Nicol, 2000): Is the model implemented correctly? Are the input parameters and logical structure of the model correctly represented? The accuracy of transforming a problem formulation into a model specification or the accuracy of converting a model representation in a micro flowchart into an executable computer program is evaluated in model verification.

Validation is concerned with building the *right* model. It is achieved through the calibration of the model, an iterative process of comparing the model to actual system behaviour and using the discrepancies and insights to improve the model.

Model validation is substantiating that within its domain of applicability, the model behaves with satisfactory accuracy consistent with the studied objectives (Law & Kelton, 1991).

2.6.5 Data collection

There are different methods to obtain input data to a DES model. The data have to either be collected manually, automatically or a combination thereof. Integration of data collection is the future of simulation (Robertson & Perera, 2001). Adequate quality of the input data is necessary both for the actual simulation and to draw logical conclusions from the DES model. Case studies performed by the author indicate a lack of logging of production disturbances, see appended Papers Nos. 2, 3 and 5. A fully automated collecting system is the best but not yet a cost-effective solution according to the author's view. In case study No. 1 data are collected from a fully automated system. The study is also further described by Lundin (2003). Among other things, the data must be easy accessible in a "ready to use" state. The data should more or less be collected and inserted directly in the DES model. The whole idea with automatic data is that it should be easy accessible and useable for different applications.

To implement an automatic data system is a major undertaking and a long-term project. One investigation indicated the time for implementation of shop floor management and control system takes from one to three years (Bauer, 1995). Even though it is not exactly the same thing there are many parallels. There are some standards in the field of machine interface, for example ISO 9506 (2000). However, the collecting software often needs to be customized in the interface between the machine and the program. Up to today there is no translation module for input to the DES software either. One of the case studies (No. 1) has utilized automatic data. In this case study, translation work was performed before the data could be used in the DES model.

A semi-automatic system is seen as the most appropriate data collection system today. In any case, a limited number of production disturbances should be logged. Ten different production disturbances are suggested by the author. The different classes should be well distinguished from each other. Furthermore, the unclassified events must be lower than 10%. If the unclassified events exceed this figure, the category of not known production disturbances will be too distinguishable in the overall work. A workable method is to have automatic time collection and manual production disturbance logging for each registered stop. However, it is a toilsome method.

Duplicate data sources may sometimes be a problem. At some occasions there are multiple data sources for the same machine or manufacturing system. The best possible data have in that case to be selected. Data can be collected in different ways according to a survey (Robertson & Perera, 2001). The different methods to take care of the issue are to use the following: most recent data, most reliable data, most local to source/origin, obtain team knowledge, and/or based on personal experience.

2.6.6 Model development and analysis

The obtained facts and figures about the manufacturing system are considered one of the major advantages in DES studies. Common measurements, such as cycle time and set-up time, are often well known but other data are not. However, there is often need to update the information about the manufacturing system. The data may be obsolete due to changes in the system. In many cases the total performance of the system is not known and is also very seldom documented. Unfortunately, production disturbances and the different background causes to these are most unlikely to be recognized in the organization of a company without further investigation. DES is one way to raise the question.

There is an investment in computers, software and training of personnel before the DES tool can be used. The software requires one to be updated with all kinds of features in the software including the knowledge of how to customize programming of specific routines. The requirements for the person working with DES is high. The provider of the DES software tries to develop a program suitable for all different kind of DES models. This has resulted in a somewhat unstructured and large number of instructions and commands. DES programs usually include a unique software language, which further complicates the issue. Compatibility problems between the different versions of the same program have also been experienced.

Some basic rules can be used in selecting the best distribution available. It is recommended to fit as many standard distributions as possible, e.g. uniform, triangular, exponential, gamma or Weibull. Use a reasonable set of criteria to rank the goodness of fit of the actual distribution. According to investigations the most frequently employed distribution of the failure process is the negative exponential distribution (Lie, Hwang & Tillman, 1977). The log-normal distribution seems to give a better fit to the repair time distribution. The only problem is to have input data that is possible to transform to distributions. Both own calculations and commercial software (Expertfit) were utilized to test distributions. In the performed case studies actual data were used in the models as no distributions were

Table 2.3: *The amount of time of the entire simulation project spent on a particular effort based on W. J. Trybula's experience (1994).*

Task		Proportion
Problem definition	approx.	10%
Problem analysis		10%
Data gathering and validation		10-40%
Model development		10-40%
Model verification and validation	approx.	10%
Model experiments		10-20%
Analysis of results	approx.	10%
Conclusions and recommendations	approx.	5%

recognized in the goodness-of-fit tests more than in a few cases.

2.6.7 Experiments and results

The experiment and analysis phase is one of the main phases. Various alternatives should be tested for relevance to find a suitable solution to improve performance of the model. The strength of the DES software is that many variants of a model may be tested. A considerable amount of time should be used here. One recommendation is to change things gradually in the model. It is better to start with a smaller model and then add on new features (Pidd, 1996). The output data of the experiments should at all times be checked for relevance. The experiments will be the base for the later implementations in the real world manufacturing system.

2.7 General Experiences from DES Work

In a perfect world, each activity in a simulation project is concluded before the next step is started. In practical life with tight deadlines it is rather difficult to achieve this order. The pressure to present results pushes the model designer too quickly past the input data gathering and model development phases. Risks of neglecting the initial phases with problem definition and problem analysis are easy to understand. If the problem is not defined accurately there is a risk that the whole task has to be revised. The result may be that the project will be delayed, more expensive and with possible imperfections because the project has to be rushed during later stages. In Table 2.3 estimations are made of the time spent on different stages in a simulation project (Trybula, 1994). Other investigations indicate that the step of model building requires less investment of time than either gathering its data or conducting experiments using the model (Williams, 1996). It

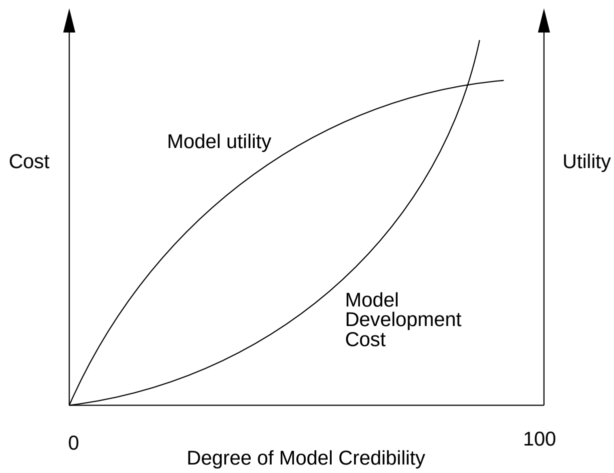

Figure 2.8: *Model credibility versus cost and utility (Balci, 1998).*

must be emphasized the need to allocate enough time to each task in a simulation project to make the project successful.

The general experience from the described case studies validates the amount of time spent in different phases in a simulation project. An important issue is to obtain relevant input data. It is a very time-consuming process and allocated in all case studies one third of the total project time. The experience is that the input data gathering phase has to be done in different stages. When the models were developed lacks were discovered even though a conceptual model was made. Even if the intention is to gather all input data at one occasion it is seldom made in a real world.

It is preferable to develop a model describing the real world with the built-in functions of the DES software as far as possible. The author's opinion is that it is easy to get stuck in programming issues and lost sight of what the real intention of the project is about: to increase equipment efficiency of the studied manufacturing system. The input data phase was about 30% of total project time, as earlier mentioned. Estimated time of model development was also one third of the time. The time spent on the other activities such as problem definition and analysis is 10%, verification, validation and other experiments is 20%, analysis, conclusions and recommendations is 10% as a rough estimation.

Assessing the accuracy of the model is usually difficult, especially if the model is describing a non-existing equipment or line. The model is an abstraction of reality and perfect representation of it may never be expected. There is also a correlation between the accuracy of the model and time spent on it. Therefore, the accuracy of the model must be valued in the simulation results. A suggested comparison of credibility versus cost and utility is shown in Figure 2.8. The figure indicates that there is a limit when usefulness of improving the model is not worth the cost. The limit varies from simulation case to simulation case and it could be useful to evaluate how suitable time is spent. There is a taxonomy that classifies the verification, validation, and testing techniques (Balci, 1998), many of those checks to be done instinctively when building the model.

2.8 Summary

Sustainable manufacturing is a key concern for all countries. To keep pace with other competing companies all over the world is a daunting task. However, DES is a beneficial tool to benchmark progress in equipment efficiency of a manufacturing system. Different components are necessary to study in order to achieve a progress in equipment efficiency of a current or new manufacturing system. The different production improvement techniques should be included in the work. The most successful manufacturing companies should be studied and experiences learned from them, e.g. TPS (Toyota Production System). If these production improvement techniques are used together with DES, a considerable toolbox is available. The DES software is comprehensive and with some experience it is a powerful tool. The case studies in the next chapter will further show the potential of the combination.

Chapter 3

Industrial Case Studies

Four case studies have been accomplished to study the possibilities for production disturbance reduction in manufacturing systems by using DES combined with the goal of implementing improved overall manufacturing efficiency. Three of the four case studies are also further elaborated in the appended papers. All performed models were designed according to best practice in simulation model design. The DES software, QUEST (Delmia, 2004), has been used for the different DES models and the DES models built in case study Nos. 1, 2 and 3 showed all good correlation with the real world.

The purpose of the case studies has been to analyze the manufacturing systems and to develop a methodology adaptable for a general manufacturing system. The methodology, which is using DES, has the aim to increase the equipment efficiency in the manufacturing system. To protect the anonymity of the four companies they will be referred to case studies No. 1, 2, 3 and 4.

3.1 Case Study No. 1

3.1.1 Background

A manufacturer of engine blocks at a multinational company has equipped a manufacturing system with an automatic data collection system. Different sets of data were logged at each machine such as DT (DownTime) and TBDT (Time Between DownTime). The reason behind each DT was also included automatically from the status of each machine as far it was possible.

There are 11 NC (Numerically Controlled) machines and six other stations includ-

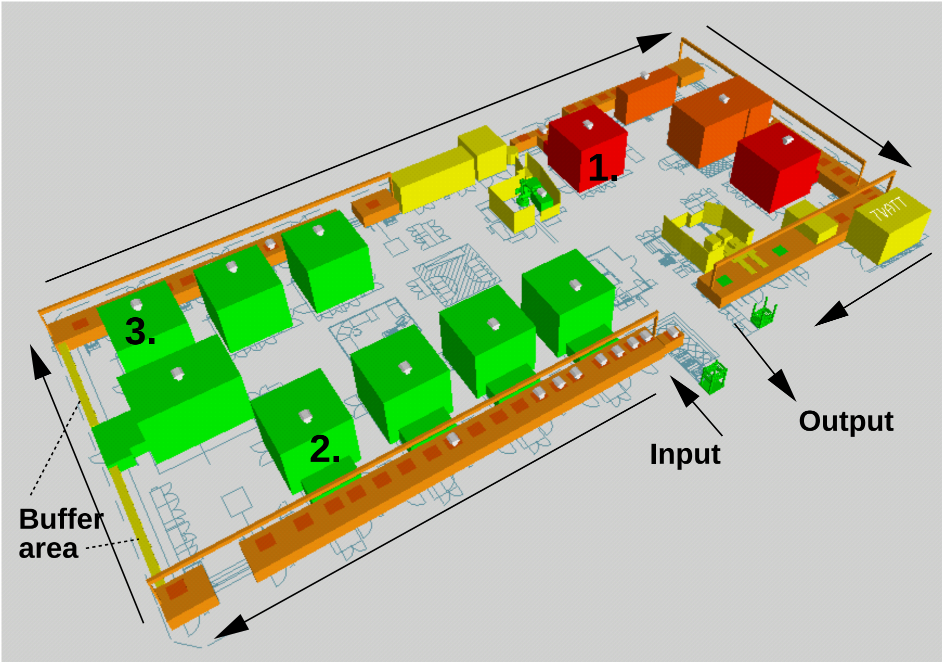

Figure 3.1: *Layout from a case study with automatic data collection at company No. 1. The different colours of the machines indicate the status; green for busy, yellow for idle, red for failure and orange for blocked.*

ing assembling, washing and cleaning, and quality control in the manufacturing system, see Figure 3.1 for a schematic layout. A casted block was inserted at the beginning of the line. Machining takes place in different process stages. The NC machines were used for milling, drilling, lathe tooling and quality control. At the end of the line the engine block was ready for the assembly line; see "Output" in the same figure. For further information about the case study, see also appended Paper No. 1.

The automatic data system enabled time data to be collected in an accurate way of the manufacturing system. All stops were logged from the shortest DT in seconds to the longest in hours. The system performance was easy to measure at each machine and also the overall performance of the system. There are no major set-ups in the system. Other types of engine blocks with other number of cylinders are produced by other manufacturing lines.

3.1.2 The model

The manufacturing system is dependent on the subsequent and preceding machines. It is interesting to observe how the machines in the manufacturing system are interacting. Different experiments were carried out according to appended Paper No. 1. The system has been studied three times with new input data, one year between each sample.

3.1.3 Production disturbance reduction

DES is suitable for studying performance improvements in a bottleneck study in a manufacturing system. Experiments in the DES model indicated that one operation was the current bottleneck in the system. In Figure 3.1 the first three bottlenecks are shown. For example, the number (1) in Figure 3.1 shows the first bottleneck studied. The bottleneck was identified by studying the simulation runs and was verified by the statistics from the model. Improvements of this single NC machine were shown to improve the whole system.

The NC machine that was assumed to be the manufacturing bottleneck in the DES model was further checked in a comprehensive real world study. The manual study was used to log the different types of production disturbances with the help of the operators. The manual logging study was carried out in parallel with the automatic system in order to fully check the behaviour of the machine. A drawback with the current automatic system is that there are too many unclassified events. As a result, the reasons for the different production disturbances are not fully known and the real-world study was necessary. The experience of the operators was also considered and this is a main advantage with manual logging.

The DT was reduced in this single NC machine by one third from 22.5 to 15 hours a week. This was accomplished by reducing the tool exchange time by 50%, which was a feasible task. The new tools have longer useful life and consequently longer replacement intervals. Not considered in the initial study was the possibility to increase cutting speed too. The new tools were later implemented in the other machines in the manufacturing system also. When the proposed changes were implemented the overall output of the manufacturing system increased by 3% annually. The decreased amount of DT enabled smoother production and better working conditions as well.

A new simulation was carried out one year later with new data from the automatic data collection system. On year to year basis the model indicated an improvement of 6% of overall output in the manufacturing system. At that time, one year later

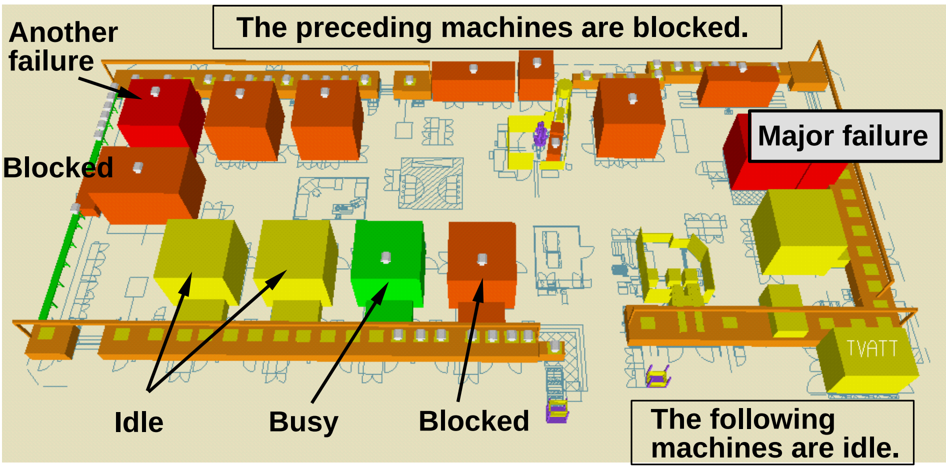

Figure 3.2: *A major failure in one single machine in a manufacturing system without any larger buffers reduces the OEE of the system. The machines preceding a machine with a longer failure are blocked and the machines following a machine with a longer failure are idle.*

from the project start, two different bottleneck analyses were concluded and one was ongoing. The results from the bottleneck analysis on one machine were implemented on other machines as well. The investments in equipment to improve the system have been relatively low, approximately €2000 to 3000. In addition, engineering time has been invested in simulation, analysis and implementation of the improvements.

Two years later than the initial study, a third simulation was carried out. At that time, five different bottleneck studies from the project start have been accomplished. The new data showed an improvement of the system of 12% from the project start. Yet there is one suggested proposal that has not been implemented. The DES model shows that the input path of the system is a critical part. There are only three buffers before the first NC machine. With a cycle time of about 20 minutes the system has to be filled with new material every 60 minutes. An easy way to increase output must be to keep the input path full at all times. The simulation model showed that the system may be possible to fill with more material.

It was clearly shown as a result in the DES model that the downtimes caused blocking and idle times in the system. Four to six machines were observed in the model to be affected when one single machine was down. At rare occasions, even more machines were influenced which showed a clear decrease in overall output.

An example of a major failure and the consequences is shown in Figure 3.2. It is a delicate problem to decide the suitable number of buffers in a manufacturing system. Too many buffers will lead to a high cost if something in the manufacturing process goes wrong and the manufactured parts have to be altered or discarded. There is also the question about how much capital should be tied in the products. Moreover, it will hide the real problems from being discovered in due course. Several production improvement techniques such as TPS try to minimize the amount of buffers in order to highlight the actual problems at an early stage.

3.1.4 Results

The case study showed the benefits of an automatic data collection system. The best measure is the hard facts. In two years the output of the system has increased by 12% without any major investments. The data makes it possible to study many different changes in the manufacturing systems. The automatic data logging system facilitated tests to be undertaken in an elaborate way. Each real-life alteration could be further explored in the simulation model too. Conversion of data from the automatic data collection system to the simulation model is an area that could be further improved. In the study a time-consuming translation of data had to be carried out. This issue may be solved by script routines and standard interfaces.

3.1.5 Discussion

Many advantages are seen in an automatic data collection system combined with a DES model. One is the exactness, this accuracy in time measurement is not possible in a manual or semi-manual system. Another advantage is that the measurement is unaffected by subjective judgments. The experiments showed that an improvement in availability of one single machine may significantly improve the total system's performance. A change in the system can be systematically investigated in the simulation model. One disadvantage that could be seen with automatic data collection systems are the relevance of all collected data. The studied system logged all signals from the PLC system of the different machines. It gave an accurate picture of the system. However, the exactness provided the author with a great deal of data. For example, seven weeks of collected data in 2003 resulted in 158,000 rows of data. On average, a single NC machine logged about 10 events an hour. It is hard to filter out relevant data and a routine must be established to obtain data for the actual simulation model. Preferably it should be done automatically.

The classification of production disturbances chosen by the system is important, as this will be the basis for all improvement measures. The degree of automation must be chosen in the system. If the system is fully automatic and indicates both time and real cause of production disturbances it is vital to select the appropriate causes of production disturbances. This requires analytical work to be done with the data. In a data collection system intended for production disturbance reduction it is important to classify the different background causes in relevant categories. Some general categories applicable on almost all manufacturing systems may be: set-up time, maintenance, repair, and lack of material. Other more specific categories related to the studied manufacturing system may be: casting related issues, deviation issues, and sequential errors. Unclassified data must be less than approximately 10% according to the author's experience. If one category expands it may be split into several new ones to make it easier to analyze.

The combination of an automatic data collection system and DES is a suitable way of analyzing production disturbance reduction. The main advantages with the combination seen in the case study are: objectiveness of data, accuracy of time measurement, and the opportunity to classify production disturbances in relevant categories. Finally, the amounts of data are beneficial for different experiments time wise. If a special event occurs in the manufacturing system the data can be selected for analysis.

3.2 Case Study No. 2

3.2.1 Background

The company in case study No. 2 manufactures forklift trucks for warehouses. The company has been expanding in volume over a longer period and at the same time with continuous growth in profit. Investments in new production equipment have been extensive to keep pace with increased production output. Production is based on customer orders with flexible manufacturing techniques. The components produced in the studied cell of the case study consisted of two main articles, frames. The fabrication of these frames is divided into some standard lengths and many directly customized lengths. The system is operating 24 hours a day, 5 days a week and also on two shifts in the weekend. For further information about the case study, see appended Papers Nos. 2 and 5.

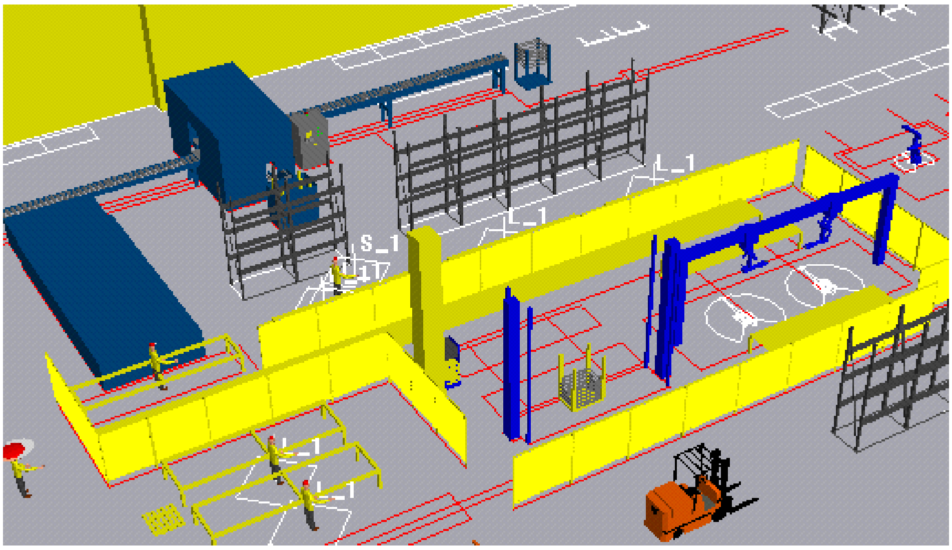

Figure 3.3: *Case study at company No. 2. The case showed an improvement of 14% in performance when a major production disturbance was removed.*

3.2.2 The model

The model was updated, modified with changes and the station worked after verification and validation like the current existing real-world system. Input data, automatically logged from the PLC system were not adequate to production disturbance studies. This data collection system only logged longer breakdowns and showed no stops less than 15 minutes. Manual logging was carried out by the author during a week to observe actual failures and to obtain a thorough overall view of the system. The manually logged data combined with interviews were the basis for input data modelling. The model is illustrated in Figure 3.3. Even though some data have to be estimated the model was reliable and evaluated to be accurate.

3.2.3 Production disturbance reduction

The availability of the studied system was 49%. The reduction of a major production disturbance, online programming, was considered to be the most important to reduce. The online programming was due to a considerable amount of different lengths of the frames and subsequent re-programming in the station. Waiting time was separated from production disturbances and sorted out as a single production disturbance more related to the organizational area. The online programming was selected as the most important to reduce and the increase of output when this cause of production disturbance was removed was 14%.

3.2.4 Results

The human effects of production disturbances were also studied in the case study. According to the operators and the production supervisor the smoothness of the production flow was improved when production disturbances were removed or reduced. Less production disturbances will improve the material flow both before and after the cell. The case study showed that production disturbances longer than two hours have in many cases a multiplying effect at the company.

3.2.5 Discussion

Knowledge of production improvement techniques is essential, in this case lean production in combination with the measurement technique, OEE (Overall Equipment Effectiveness). In the case study it was shown that a queue in front of the bottleneck in the manufacturing cell increased performance in the manufacturing system. It was clearly shown that the best results in a DES project is a combination of DES and production improvement work. See also appended Paper No. 3 about the combination of production improvement techniques and DES.

A welding station is a challenging task to fully automate due to the welding process itself. This means there are many short stops caused by the welding process due to the tolerances of the frame. The disadvantage of these short stops is that the operators are closely linked to the station. One conclusion from the case study is the necessity of training the personnel. Adequate training can achieve significant improvement in performance of a manufacturing system. The case study was a team project that involved many disciplines in the company.

3.3 Case Study No. 3

3.3.1 Background

The company in case study No. 3 produces equipment and machines to the window blind industry. The production unit in Sweden employs some 100 people. The company has a wide range of products in the product mix including both machines and consumer goods. The studied product, braided cords, is produced in

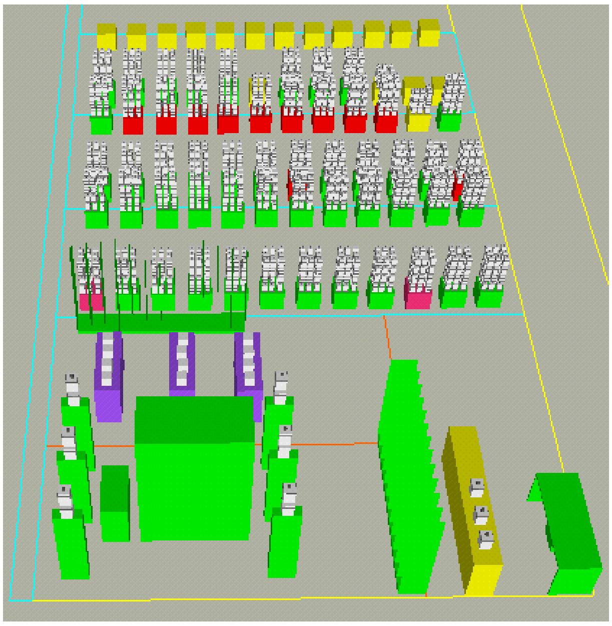

Figure 3.4: *Layout from a case study at company No. 3. Parallel changing was suggested to improve equipment efficiency at the department.*

72 different machines and each of the machines has two units making two cords independently. The machines operate 24 hours a day, 7 days a week and they operate unmanned as long as no production disturbance occur, up to some 100 hours. 60 types of the cords manufactured were coloured in a separate colour machine. As a final operation, both coloured and white cords are sales packaged before transportation to storage. For further information about the case study, see appended papers Nos. 2 and 5.

3.3.2 The model

Commonly in a case study, the problem in the data gathering phase was the lack of input data. The MRP (Manufacturing Resource Planning) system indicated some rough data on annually basis, unfortunately not adequate for simulation input. The data could, however, be used for later validation of the model. The system in current use for production disturbance gathering was a manual log-book. The historical data available were logged in different categories. Favourably, production disturbance data were logged in five different classes. However, actual times in production disturbances to take measures to reach normal production were not included at all.

A main source of input data was interviews with the personnel. It was possible to recognize working methods and obtain some solid times, e.g. minimum, mean and maximum times for the different activities. Frequent maintenance problems and times allocated for repairs with some parts of the equipment were also discussed with the maintenance staff. Two indicators with time documentation were placed on two different braiding machines to receive relevant production disturbance data for the model. The indicators logged a clock-time table for DT (DownTime) and TBDT (Time Between DownTime). The operators then manually added the different production disturbances to why the machines had stopped. A DES model was built of the studied production unit, see Figure 3.4. Selected bottlenecks in the system, such as the braiding department and the colour machine, were magnified in separate models for further experiments.

3.3.3 Production disturbance reduction

Production disturbances due to long waiting times before actions were taken to get the system back to normal state were considered to be significant to reduce. This was found around the braiding machines and also in the station where the threads were coloured. In the area of the 72 braiding machines the waiting times were more than 90% of the total DT. Tests were carried out with new working schedules for the personnel to improve the output. To easier show the status of the machines “andon” is suggested. This is a signal sign showing all relevant equipment for easy supervision of the status of the machines, e.g. working or not working.

In the experimental stage one type of production disturbance was removed and the changes were shown in the DES model. The results from the model were also confirmed in real-life tests. If parallel changing was introduced it showed an improvement of 18% of the time available for production. Tests were carried out and the working method showed a good conformity between the model and the real system.

The colour machine had a long set-up time, approximately two hours. The overall demand to reduce lot sizes makes it interesting to work with set-up reduction. A decrease of 50% to one hour means that the corresponding lot size can be reduced by half with equal total output and comprising smoother production. The company goal to reduce WIP (Work In Progress) also co-operates with the suggested proposal.

3.3.4 Results

This case study showed that different work organization could improve performance of a manufacturing system. A training programme in production flow for the staff may also be beneficial.

3.3.5 Discussion

In this case study the importance of the operator's knowledge was shown. Interviews with the operators at the manufacturing cell gave valuable information. The operators have also precious knowledge of the different machines and what faults and other problems may occur related to the manufacturing system. The information by the operators can be useful in the improvement work. The case study showed that by easy means, e.g. different working routines and preventive maintenance, improvements could be made with cost-effective means. The potential in the case study to increase output was shown to be 18%, which is considerable using existing machines and equipment.

Another point of interest in case study No. 3 was the issues regarding input data. Due to lack of data numerous visits and interviews were performed. For some data estimations such as extreme values have to be used to reach a reasonable result. All values were, however, validated to annual data logged in the MRP system. Interestingly, proper estimations may give reasonable accuracy to a model.

3.4 Case Study No. 4

3.4.1 Background

The company manufactures crankshafts for motor chainsaws in the studied department. Interviews were performed at the company about the knowledge of production disturbances based on a questionnaire and in-depth interviews. The company has also had some past experience in the DES area. A previous DES model study has been performed at the company (Stolt, 1999), see Figure 3.5. This described case study is somewhat different and will show the current situation at the company and the need to establish a standard for production disturbance reduction.

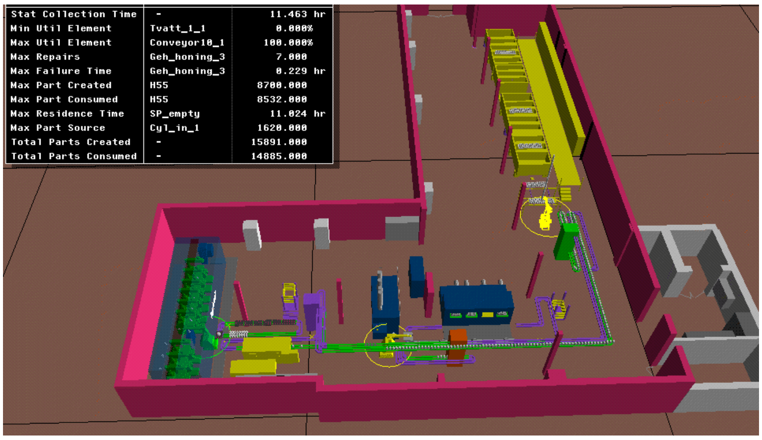

Figure 3.5: *Layout from a previous case study performed at company No. 4. The study is a project performed by Stolt in 1999.*

3.4.2 The study

The case study was based on interviews and gave an overall view of the complex problems in production disturbance reduction and performance increase at a company. A questionnaire with multiple-choice questions in a strict order was also distributed. The opinions of two different groups at two different manufacturing cells were studied at the company. The investigation was carried out in 2002-2003. Some of the main results in the study are published in Bellgran & Gullander (2003).

3.4.3 Production disturbance reduction

To identify production disturbances is a challenging task. There is a problem with frequent production disturbances according to 69% of the interviewed personnel. The actual cost of the production disturbances are known by few, 9%, according to the investigation. 23 employees at the company have answered those questions.

The questionnaire showed frequent production disturbances due to different reasons: delayed deliveries from other departments, lack of maintenance of machines. Furthermore there may be balance problems; the numbers of casted details are not same as the real number of details. There could also be other problems with the machines such as tool exchange problem, machine failure tolerance and machine problems. Furthermore, broken details, quality problems due to old tools, preventive maintenance have to be considered. Finally, staffing is also regarded as a problem.

The question is to find a suitable method to measure the manufacturing systems. A clear definition of what is regarded as a production disturbance is useful. Key figures should be measured and be used for follow-up. The potential to improve performance in the case study may be substantial if they are considered.

3.4.4 Discussion

A company that is working with measurements of their manufacturing systems have to consider a few points. Definitions have to be established of what can be regarded production disturbance in order to find a method of performance improvement. A recommended way is to divide those production disturbances in planned and unplanned disturbances and finally categorize these in a few groups for easy measurements.

Key figures should be measured for easy follow-up. Some advice for the best use: The key figures should be easy calculable and understandable for everyone at the company. Second, estimate a cost for downtime for each independent manufacturing system. Third, establish a working routine on improvements. Four, the measurement will also benefit the DES work in the future. Input data will be more easily accessible and may be used for DES models in the future.

3.5 General Experiences from the Case Studies

DES raises the issue of performance improvement in manufacturing systems. The issue of measurement has to be emphasized. A DES project also works as a process between different employees in the organization and many are involved from different departments. The main benefits may be: the graphical interface of DES highlights the issue of production disturbance reduction and performance improvement in a manufacturing system. The combination of production improvement techniques together with DES is beneficial. Some other points identified: the personnel working in the manufacturing system must be involved in the project and their experiences incorporated in the DES project. Finally, never underestimate the importance of adequate input data, time and costs.

3.6 Summary of Case Studies

The three first case studies showed that production disturbance reduction with the help of DES software is beneficial. In each case study the work resulted in increase of equipment efficiency. It was also shown that the efficiency of the manufacturing system could be increased by non-expensive means. The costs of the projects have been engineering time. The fourth case study indicated the importance of measurement in manufacturing systems. A solid foundation of measurements will benefit future DES projects.

The next chapter will describe a general method based on the case studies. According to the mentioned industrial studies a DES case that uses the proposed method will have a target of about 15% improvement on an existing manufacturing system if applied. However, the real potential of the estimations must be proved in each case study.

Chapter 4

Methodology

4.1 Introduction

The methodology should give a solution to the problems encountered in the case studies. Based on these facts the methodology should be more generalized. Thus, the methodology should be applicable to a general case study in the manufacturing industry according to the introductory chapter. There are DES methodologies already presented in a rather general manner, e.g. Banks et al. (2000). Other methodologies focus on the actual design process that is also valid on the manufacturing system itself, e.g. Pahl & Beitz (1996), and Jackson (2000). However, the methodology presented here is new in the respect that it combines production improvement techniques with DES. The suggested methodology may lead to performance improvement if applied on a manufacturing system.

4.2 Productive Simulation Studies

There are some basic needs in order to work with DES. Three subjects in productive simulation studies are presented in Figure 4.1. The first need is simulation know-how. The person responsible for the simulation model must be able to use the software in an efficient way. Due to the DES simulation software of today it is necessary to be properly trained to use it. It is assumed that useable software is chosen with accuracy and applicability to the problem. Vendor support should also be considered in the selection phase.

The second need is a comprehensive knowledge of production improvement tech-

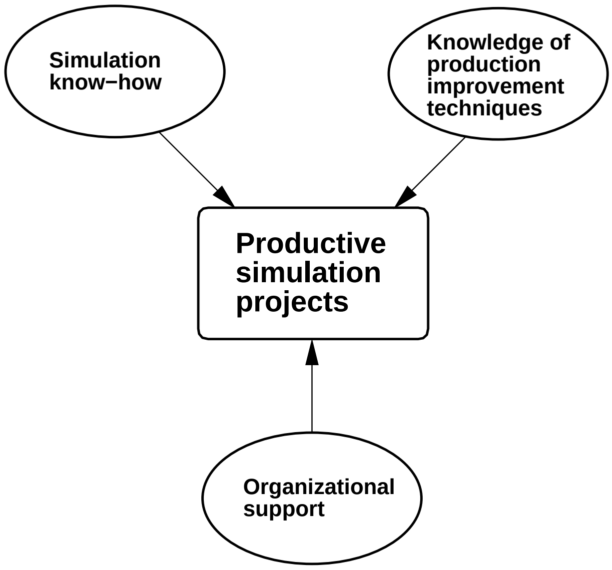

Figure 4.1: *Three subjects in productive simulation study. Simulation know-how, knowledge of production improvement techniques and organizational support are recommended to be combined.*

niques. Techniques known to produce results need to be known in order to improve performance of the manufacturing system, e.g. TPS (Toyota Production System) and lean production. Some of the production improvement techniques are presented in Chapter 2. Many lessons can be learnt from the most profitable manufacturing companies in the world and their production techniques.

The last point is an organizational support. The management must give their support to the project. A DES project includes many individuals in an organization and the full involvement of everybody concerned is necessary. In order to obtain relevant information many people may be involved in the study. This concerns for example operators, supervisors, maintenance personnel, managers and designers.

In the end, the purpose is to have a general DES model that is possible to scale, easily adaptable and effortless to update. Different modules such as machines, other equipment and personnel, should be possible to switch on or off in the model simultaneously. All the different parameters of production disturbances should be possible to adjust. The reduced production disturbances should be readily recognizable depending on the parameters used. Finally, another demand is that it must be easy to revert back to a simulation model after a time gap as work in a simulation study is often done in different stages.

One advantage in DES studies is the new knowledge obtained about the performance of the system. More common measurements, such as cycle time and set-up time are often known. Other significant data are not noted about the manufacturing system, such as availability, downtime and production disturbances. Therefore key figures, for example OEE (Overall Equipment Effectiveness), may not be fully known. In all improvement work it is vital to measure key figures to see the progress of the improvement work. Unfortunately, production disturbances and the different background reasons are most unlikely to be recognized if the manufacturing system is not measured in a proper way. The key figures are also useable to follow-up measurement on a week to week basis. Those figures may give a first warning if the manufacturing system is not working appropriately.

4.3 A Presented Methodology for Performance Improvement

A first methodology for performance improvement in a manufacturing system was presented in different steps in appended Paper No. 2, (Ingemansson & Bolmsjö, 2004), see also Figure 4.2. A short description of the methodology is included here: The methodology describes a DES study in different steps. Firstly, a suitable project should be identified. Secondly, the input data collection phase is initiated. The input data are documented in the conceptual model in case of later reference. Then the actual DES modelling begins, followed by experiments and the result analysis take place. The process of working with DES is based on Banks et al. (2000). The model should be modularized, adjustable with logical names, and everything must be documented in the conceptual model.

This is undertaken at the same time as the production disturbance analysis should be initiated. What are the reasons behind the production disturbances? The source should be found if possible. Elimination of the source will always be desirable and give the best results. Different techniques may be used, for example “5 why”. In short the technique is asking “why” until the source of the problem is found. Interaction with the personnel should benefit the process. Different production improvement techniques should also be used to improve the performance of the system.

The second main issue is about tests in the DES model. Based on different production improvement techniques evaluations of the best possible solution should be carried out in the DES model. The alterations are easily made in the model based on the techniques such as for example Lean Production, Supply Chain Management, Total Productive Maintenance, (SMED) Single-Minute Exchange of Die and (OEE) Overall Equipment Effectiveness. The linkage of the different case

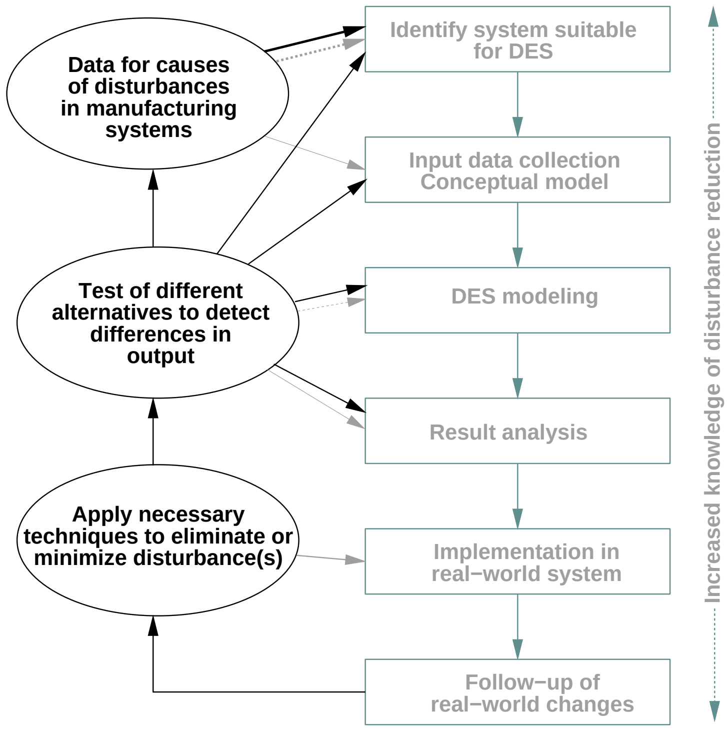

Figure 4.2: *A methodology for productivity improvement presented by Ingemansson, 2004.*

studies to the different production improvement techniques are further described in appended Paper No. 3.

The third main issue in the model is to apply the achieved results in the real-world system. The implementation may bring you back to the model several times for minor modifications. Unexpected events may occur in the real-world that will affect the DES model. A minor simplification in the model may suddenly give consequences in the real manufacturing system. At this stage it is recommended to work interactively between the DES model and the real manufacturing system.

4.4 Further Development of the Methodology

Figure 4.3 shows new details added to the development process of the methodology presented in this thesis. It was noted that some issues needed to be further emphasized, mainly supportive activities to the DES modelling. The cases studied

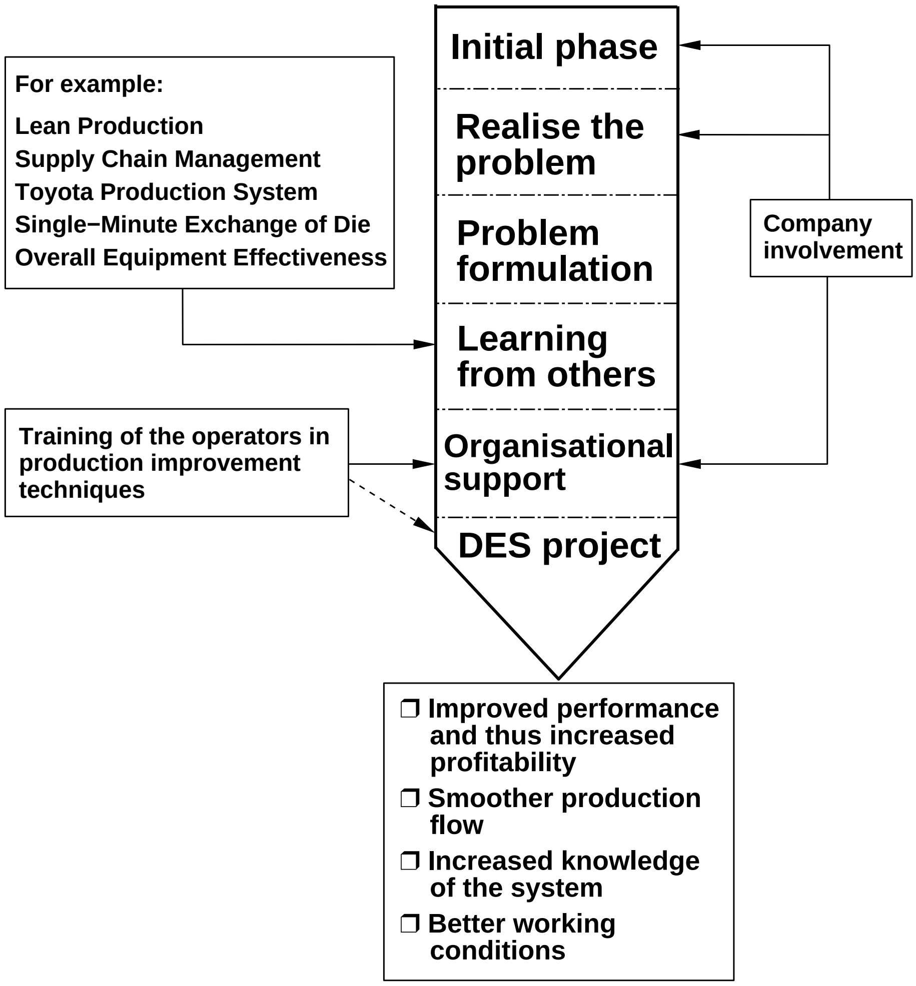

Figure 4.3: *A further development of the methodology presented in Figure 4.2. External factors are more emphasized. The main benefits of the proposed methodology are also visible.*

showed the importance of *operator training*. If there should be an improvement in the manufacturing system the operators must be aware of the measures to be taken. Some basic understanding of material flow, supply chains, etc., seemed to be necessary. Increased understanding about the manufacturing system will in most cases also motivate the operators. As a result both quality and produced quantity may increase in the manufacturing system.

Backup and support of the management and the other parts of the organization are also necessary. The study must be taken seriously by the company in order to achieve the best results. The DES study is rather often initiated by the management. Both time and costs are involved in a study. One of the companies in the case studies had, for example, a declaration to be world-class in manufacturing. This company use DES as a tool in achieving this goal.

The production improvement techniques are vital for successful studies. A company has seldom time to invent new methods itself. The most successful production improvement methods should be chosen to achieve the best results. Each improvement technique is based on a great deal of experience and has been developed over a longer period. To use the production improvement techniques are an efficient way to increase overall output. Consequently, both time and money are saved for the company.

The main results of the methodology are increased equipment efficiency in the manufacturing systems and thus in the long run higher profit for the company. Some other points may also be mentioned, see again Figure 4.3. The improved performance with shorter production disturbances will also lead to smoother production flow. It has been observed that lacks in subsequent departments have diminished. Training of the staff is beneficial. It may also be easier to adjust the manufacturing system if there is more knowledge about the system. Interviews have also indicated better working conditions as one major benefit when working with the methodology. The operators seem to be more comfortable with their situation when they have increased knowledge about the manufacturing system, their interactions and the possibility to reduce production disturbances.

4.5 A Production Disturbance Reduction Methodology

The investigated case studies and previous work have resulted in a methodology applicable on a manufacturing company. The company should have an interest in improving efficiency and thus reducing production disturbances.

The stages are divided into three sections, mainly due to readability of the meth-

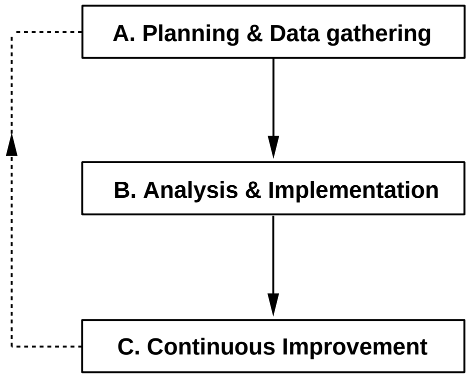

Figure 4.4: *The three main stages in the methodology.*

odology. The intention is that the methodology should be taken as a whole. The time frame of the suggested methodology may be at least three months. It would be preferable to calculate about six months. To illustrate the potential of long-term commitment one of the case studies (No. 1) has been ongoing for two years. Continuous work with the methodology can be beneficial. There are three main stages in the methodology, see also Figure 4.4 for their connections:

Stage A: Planning and data gathering

Stage B: Analysis and implementation

Stage C: Continuous improvement

4.5.1 The planning and data gathering stage

The first stage is called the planning and data gathering stage due to the work that has to be done before the actual DES modelling, see Figure 4.5. First of all a project plan has to be established. All involved people must agree that the correct problem will be solved. The goal and objectives of the project must be decided and documented. Unfortunately in the past, too many projects have solved the wrong problem. So it is wise to make some effort here. However, the goal and objectives can be revised later in a project if there is a need for doing so. The work with equipment efficiency also involves the definition of production disturbances. It is a crucial step and must be performed before the actual measurements take place. A recommendation is to divide the production disturbances into a maximum of ten categories. No individual class should dominate and the unclassified events

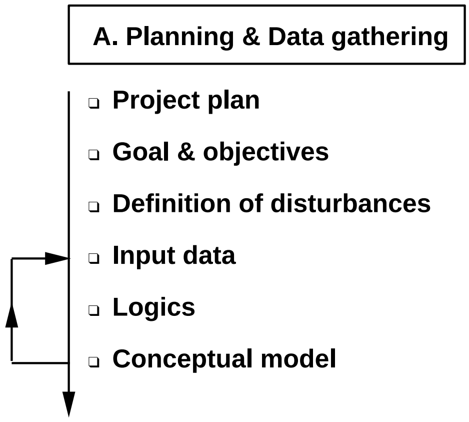

Figure 4.5: *The planning and data gathering stage.*

must be lower than 10%. This in order to work with the material in an appropriate way.

When all definitions are established the actual measurements can take place. Newer machines can be equipped with automatic data collection systems. If they are available, they should preferably also be used. The input data measurement and logics are documented in the conceptual model. Data, that are recorded, are suggested to be collected in a way suitable for the DES model. The conceptual model will be the log of what is performed in the case study. It is recommended to scrutinize the conceptual model and revert back to the steps of input data and logics. The more relevant information that will be collected in the beginning of the project, the better end-results will be useable of the model. The steps of input data, logics and conceptual model have to be repeated several times in order to build a DES model in the next stage as complete as possible. The conceptual model is also valuable for fault-tracing in the DES model. See also Figure 4.5 for the different steps in the planning stage.

The human interactions in the manufacturing system should also be included in the work as far as possible. The labour of the operator personnel may also be included in the simulation model. Their interaction and prioritization in work order is always of interest to study. Different work organization may be one way to increase performance in the manufacturing system. One vital issue in a manufacturing system is the interaction of the human and machine (Stahre, 1995).

4.5.2 The analysis and implementation stage

The analysis and implementation stage is the next stage, see Figure 4.6. Based on the input data and logics in the conceptual model the DES work can begin. However, when the model building starts, some data can be lacking and more input data and logics have to be collected. In that case one has to revert back to input data, logics and the conceptual model and collect the missing information. The findings indicate, based on the case studies, that the conceptual model should be well prepared in order to build an adequate model. Everything should be converted to a workable DES model. Mathematical distributions should be used where appropriate.

It is recommended to not get stuck in the DES model translation process. Simplifications in logics in the model may be a solution in some cases. There are anyhow uncertainties in the collected input data. It is better to start with a modest model and then gradually let the model become more sophisticated, as needed. The model has to be verified and validated once it is ready. Preferably the model should represent the real world within reasonable range. There is a cost of increased model accuracy. The production in the manufacturing system is suggested to be compared to yearly data. The experiments can start when all these steps are concluded.

The experiments should be based on knowledge in production improvement techniques. Experience from the most successful companies in the world and their improvement work should be used. Alternative tests in production disturbance reduction to increase efficiency may be the best way to see the difference in output and thus performance increase. This is a loop that has to be performed several times. Based on the experiments in the DES model the implementations have to be verified if they are possible to perform in the real world. It is also recommended to perform the necessary amount of simulation runs to avoid having statistical errors in the model.

The proposed alterations can then be implemented in the manufacturing line. Before the actual implementation it is suggested to discuss the changes with other people familiar with the manufacturing system. This will be an extra checkpoint before the actual implementation. Changes in the real world manufacturing system are best done in small steps according to the simulation model. The adjustments will change the behaviour of the system and the system must work in a stable state before the next alteration.

Other possible not previously foreseen alterations are at the same time verified in the DES model to prevent any unforeseeable changes in the real-world sys-

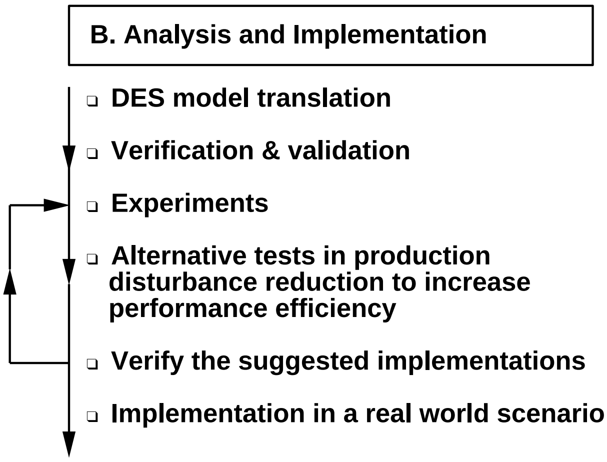

Figure 4.6: *The analysis and implementation stage.*

tem. The new changes must not create more problem than they solve. A reduced production disturbance is seldom uninterruptedly diverted to output, see also appended Paper No. 2 for further discussion on the subject. Some part of the gain is re-routed to other production disturbances. DES may give an early answer to understand the dynamic effects that arise in production disturbance elimination. This is a real advantage with the DES model. The verified changes of the manufacturing system in the DES model are carefully observed.

The reasons to why production disturbances occur must be investigated in the studied manufacturing system. Simultaneously, an educational phase is initiated to explain the importance of production disturbance reduction to all involved personnel. The outcome of the study is less likely to be successful if the operators are not fully aware of the planned implementations and their benefits. A creative discussion itself can increase the output of the manufacturing system even if the DES model is not designed at all.

4.5.3 Continuous improvement of the methodology

No methodology is so good that it could not be further improved, see Figure 4.7. Some examples are presented to illustrate this stage: The improvement can be made on different parts, such as improvement in model design of the DES. Translation of logics and input data can always be improved. Perhaps a library of ready-to-use logics can be created for future studies?

The field of statistical analysis both for input and output data can be studied. For

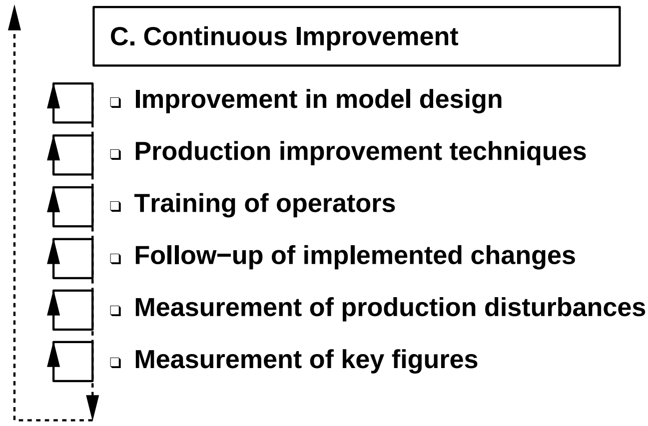

Figure 4.7: *The last stage, continuous improvement of the methodology.*

example, the use of different distributions to fit input data may be further investigated. The development of production improvement techniques can be further studied. One of the key ideas is to use the most successful production improvement techniques in the world. Training of operators in material flow and production improvement techniques are other tasks beneficial to future projects.

Follow-up of implemented changes to see if performance actually increased according to forecast is another task in this stage. This may be done over a longer period of time. Measurement of product disturbances and measurement of key figures are two other areas where there is a need for continuous improvement of the process. The amounts of not classified production disturbances should not increase; in that case a reclassification has to be initiated. Key figures are useable to get an indication if the manufacturing systems encounter some unforeseen problems. Comparisons of key figures on a week to week basis give an indication of the performance of a manufacturing system even if the figures are not defined in a best possible way.

4.6 Resource Planning

Resources and time are often critical at a company. However, enough resources for a project must be allocated if working with the suggested methodology. The length of a performance improvement project should not be underestimated. Experience from the case studies has shown that three to six months is an appropriate time for a case study. Besides the original case study one or several follow-up phases are also recommended.

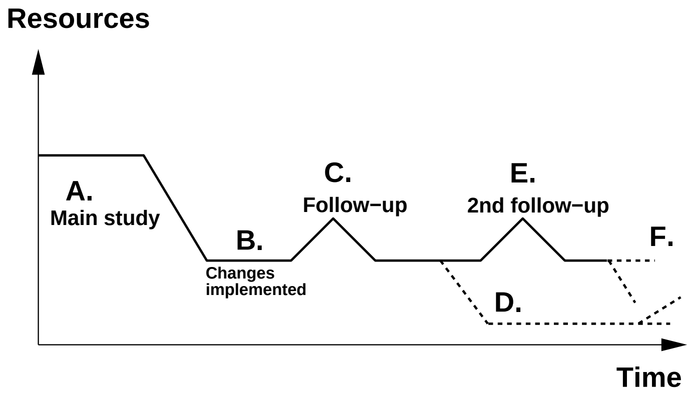

Figure 4.8: *Time resources needed in a study. The description is symbolic.*

Figure 4.8 shows the suggested resource allocation in a project working with the methodology. At (A) the maximum amount of resources is needed, from the project start until the first suggested improvements being implemented in the manufacturing system. At (B) the manufacturing system is running with the new changes. A follow-up simulation is suggested at point (C), perhaps three to six months after the implementations. If the results are satisfactory, the DES project could be concluded (D), alternatively the follow-up simulation is repeated again (E). The continuous improvement work can be repeated until expected results are fulfilled (F). When these results are fulfilled, the improvement project may start from the beginning again with a new goal.

Resource planning is a delicate issue. The simulation work should have strict deadlines and at the same time be continuous. New work tasks compete with older assignments. Experience has shown the difficulty in longer ongoing work tasks. However, increased performance in the manufacturing system will be seen in evaluations of the work and this will benefit the continuation of the work.

4.7 Evaluation of Methodology Based on Case Studies

Based on the performed case studies a validation of the methodology has been undertaken. The development of the methodology has been performed hand in hand with the actual case studies. In all case studies it has been shown that the combination of DES models and the use of production improvement techniques are beneficial in both increased performance of the manufacturing systems, better work environment and smoother production. For example, the manufacturing philosophy of lean production is sensitive to longer production downtimes. Therefore reduced production disturbances are beneficial in making smoother production flow.

Thus in the long run, the proposed methodology will also increase profitability of the company. Time and cost of engineering work should not be underestimated in the study. However, the performance increase in the different case studies did not need any major investments. Even if investments should have been added to the costs they should be reasonable to pay back compared to the increased performance.

4.8 Summary

The described methodology allows a more systematic process when working with production disturbance reduction and DES. It is necessary to be skilled both in the DES software and in production improvement techniques. The case studies have shown that the methodology was useful even when the actual methodology was in its development stage.

The case studies have shown that improved efficiency in a manufacturing system can be achieved by production disturbance reduction. The combination of DES and production improvement techniques is beneficial. Each case study has resulted in an increase of equipment efficiency. It has also been shown that the performance could be increased by inexpensive means. The goal of performance improvement of a manufacturing system using the methodology may be about 15%. However, this is a rough figure showing the potential of the methodology based on the performed case studies. Except for engineering time, all case studies have been improved without any larger investments. Time for DES work is often underestimated. It is therefore also recommended to allocate enough resources in advance to fulfil the project goals in time.

Chapter 5

Results

The combination of DES modelling and production improvement techniques has in the case studies shown to be beneficial to improve productivity of a manufacturing system. Manufacturing companies are the basis of a country which many other activities rely on, see Chapter 2. If the performance of the manufacturing system can be improved it means enhanced value not only for the company but in the long run for the society as a whole.

Production disturbances should be studied from a total efficiency viewpoint considered from both a human and technological aspect. The DES models locate and isolate the causes when production disturbances can be reduced or even eliminated. Furthermore, the findings show that increased performance of a manufacturing system is seldom uninterruptedly diverted to output. Some part of the gain may be re-routed to other production disturbances. This study indicates that DES may give an early answer to understand the dynamic effects that arise in production disturbance elimination.

Analysing a DES model will give ideas of reducing and eliminating production disturbances. The DES model can tell where the next bottleneck is in the system. It is considered an advantage to have this information at an early stage. The combination of production improvement techniques is recommended.

In real-world case studies time and cost are the determinant factors. Measures for improvement of manufacturing systems have to be taken in a short period of time and can in some cases be vital for a company's future existence. Quality of the DES model should, however, not suffer any loss due to lack of time or money. As previously mentioned, the performed case studies did not require any major investments. The main cost was engineering time. Thus, it is recommended to

Table 5.1: *The results of the case studies when working with the proposed methodology.*

Case study	Estimated project time	Estimated performance improvement
No. 1A	12 months	6%
No. 1B	24 months	12%
No. 2	3-6 months	14%
No. 3	3-6 months	18%

make a cost-benefit analysis of the work before it is started.

The case studies were performed in interaction with the development of the methodology. However, the main ideas have been included from the beginning. All results are based on applied research to show applicability on different case studies and to give basis for a theoretical framework. This framework should be seen as a working method for the more general case study.

The methodology has been developed on four different case studies and there is always a possibility that more case studies may have improved the methodology further. Table 5.1 shows the results when working with the proposed methodology. Case study No. 1 increased the performance with 6% in one year and 12% on a two-year basis. With an investment in input buffer there may be a further potential left to increase capacity.

The case studies Nos. 2 and 3 both showed an increase of 14 % and 18 %, respectively. An indicative figure of the potential of performance improvement working with this methodology is about 15%. The findings also indicate that the study is a long term project and the time frame should not be underestimated. However, future case studies will show the real potential of the methodology.

The allocation of resources in a study with suggested methodology must be considered too. Most resources are needed at the beginning in the start-up phase. All concerned parties at the company are recommended to be involved for the best possible outcome of the project. This type of work also involves many people in an organization. As soon as the data gathering phase is concluded it is of priority to create a workable model. For future discussion a model is valuable. However, the case studies showed that the initial investigation gave valuable results, too. Different departments at a company have solutions when they start to work together.

Once the initial improvement work is finalized, it is recommended to give sufficient resources to the continuation of the model work. Updating a DES model is often effortless compared to creating it. Sufficient resources should be maintained to keep the model alive and at the same time deadlines should exist so the DES work does not stagnate. The companies working with continuous improvement have also been shown to be the most profitable in the long run, for example Toyota. The improvement work of a manufacturing system is an endless activity.

Chapter 6

Discussion

DES and the production improvement techniques are a competitive combination. When the input data are collected, a conceptual model can be developed. At the same time different improvement techniques may be studied. The DES modelling allows different tests to be carried out together with the production improvement techniques. The experiments in the model will show different alternatives in output of the manufacturing system. Latest production improvement techniques should be included in the work. The DES model may give ideas of implementations in the real-world system. Different parameters in the DES model can be changed. This is a powerful feature. Thus, different types of production disturbances can be switched on or off. Various production improvement techniques can be tested off-line without any interference with current production. The different results can be shown quickly in the virtual model.

The proposed methodology is a way to get an overall view of the manufacturing system. Documentation and follow-up of relevant data from the manufacturing system are also raised in a DES project. The knowledge about e.g. availability, production disturbances and explanation of the reasons will increase at the company. This may lead to new information of why different production disturbances occur in the studied system. Sometimes the new knowledge can be used at other manufacturing systems as well.

The improvement project must be measured in terms of cost against the benefits of the outcome. The case studies showed that the main cost in the project was engineering time. All improvement projects were made without any investments in the manufacturing system. However, some projects showed a need for investments in the manufacturing systems. One of the case studies, case study No. 1, showed that an investment in a longer input path should be beneficial.

The DES model will illustrate the manufacturing system in a way that all personnel can understand. No comprehensive background knowledge of production systems and other techniques are needed for those who are studying the finished simulation model. The visualizing feature enables everybody to understand the model and the manufacturing system. The intricate design of the DES model is up to the model designer.

Experience from one of the case studies showed the benefits of the visualization feature. The operators experienced a more holistic perspective of the manufacturing system. A longer production disturbance will both block other machines as well as cause some machines to be idle. This gave new understanding for the personnel working with the manufacturing system. A DES study can prove invaluable to understanding how the manufacturing system really works as opposed to how everyone thinks it works.

A long period of time, for example a full year, can be compressed and the dynamic propagation of production disturbances can be shown. In a more sophisticated system, such as a longer supply chain, it is beneficial to study the different courses of events. This allows also the phenomenon, for example a specific production disturbance, to be scrutinized.

Time consumed in a DES project is often underestimated. Parallel activities may save some time. However, one single piece of input data may jeopardize the model. The model is then inadequate to draw any relevant conclusions from. Input data are seldom easily accessible in a DES study. The last missing data are often the most hard to obtain. Approximations have to be used, e.g. maximum and minimum values. There are anyhow so many uncertainties in the input data selection phase that minor simplifications in the DES model are acceptable.

Transformation of events from the real world to input data to the simulation model are the base of the DES project. Every measured piece of data record must be dealt with, included and relevant. Issues such as production disturbances are seldom fully considered in the phase of measurement. Lack of all relevant data, for example omission of downtime analysis produces an invalid model (Williams, 1994). Input data must often be cross-checked for relevance. The output data is directly linked to the input data.

Correct data are not obtained from the simulation models, unless enough relevant data are put in the simulation model from the beginning of the study. The results from the simulation model can in the worst cases be misinterpreted due to erroneous input data. It is therefore emphasized to evaluate input data so they are within reasonable limits. One way to investigate this is to check the shortest and longest possible time for each event.

The case studies also indicated other problems with input data for the DES models. The data may not be used as they include mixed information or not significant information. One case study indicated that the event had been recorded but not the time used for it. Another case study illustrated the opposite, the time is very accurate but the production disturbance causes are not. In addition to the issue of analysing output data there is the question of obtaining the best possible input data. In all case studies, manual data gathering have been necessary. The time of the production disturbances and their causes are necessary to obtain a full picture. Work in this phase will show to be beneficial throughout the project.

A good advice is to "keep the model simple". It is easy to get stuck in complex programming of not defined functions in the DES model. The opinion of the author is that the model is probably too complex if not predefined functions in the DES software can be used by default. In that case, measures should be taken to simplify the DES model. There are anyhow so many uncertainties in the input data selection phase that minor simplifications in the DES model are acceptable.

The phases of experiments and result analysis of the simulation model will decide the results of the DES project. A common mistake is to use too much time on the actual building, often due to programming tasks, and get short of time for the remaining phases in the study such as experiments and analysis. The results from the simulation model can in the worst circumstance be misinterpreted.

DES is a powerful tool and the results are often granted as "the truth" when they are presented. The person working with this tool must always state that there are uncertainties in a DES model. Example on inconstant values in a DES project: Firstly, missing quantity or quality in input data will change the results. Secondly, logics of the simulation model must be interpreted correctly. Two different persons can never design the layout of the same manufacturing system exactly the same way due to different interpretation on the layout, logics and selection of input data. Thirdly, statistical transformations in both input and output figures need consideration, too.

Development in DES software is a drawback of the current use. The software must be improved if the use should be spread from consulting firms and larger companies to small and mid-size manufacturing companies. The interface is regarded by many users as too complex. Special software language to build logics is according to the author's opinion a failure. The use of simulation software can never be significantly increased if the interface is not improved and includes all necessary options.

Until today, studies of efficiency and production disturbance reduction have mainly been undertaken at larger companies. In the current outsourcing trend it is consequential that the manufacturing companies that have taken over manufacturing can absorb the same techniques as the companies that outsource abandon. Normally, these companies that now will manufacture the products do not have the same resources. The companies are, in some cases, much smaller in size, e.g. turnover. They do not have the resources to implement this kind of projects. New manufactures must adopt beneficial production improvement techniques to become competitive in the long run and production disturbance reduction combined with DES may be a tool in this work. In some sectors, e.g. telecommunications, the subcontractors are larger.

Unfortunately there is a “fashion trend” in production improvement techniques. It is suggested to look beyond the shortest trends and have a more long-term perspective. Manufacturing companies that are profitable year after year have often adopted successful manufacturing techniques. It can be an idea to investigate those further. According to the author, the current outsourcing trend may be an example of a short-sighted trend. The connection between the design and production departments are more useful in the long run compared to decreased production costs in the short run.

It would be useful to have a general guideline of which production improvement techniques is most appropriate for each manufacturing industry. However, it is a daunting task. The guideline would in that case depend on a number of different decisions. For example, it depends on the company’s production policy, availability to deliver, the complexity of the manufacturing system, maintenance and repair. A more holistic perspective is suggested when a new manufacturing system is designed. For an existing system it is probably better to improve the system in small steps. A general guideline to improve efficiency in a manufacturing system has been written (Gullander, Bellgran, Lundin, Harlin, Ylipää, Ingemansson, Fjällström & von Axelson, 2004). One chapter in this book concerns DES as an improvement tool in the process.

The categories of production disturbances should be clearly distinguished from each other. Preferably, when the different categories are analysed there should not be any risk of misconception. It is proposed to use the most common categories from the OEE formula, and add on with specific categories according to the activities in the manufacturing system. From the OEE, see also Figure 2.4, set-up, maintenance, and repair can be chosen. The different case studies gave system specific categories, for example casting (Case Study No. 1), and welding (Case Study No. 2).

DES enables users to investigate totally different manufacturing concepts. The same manufacturing system may be studied with different production philosophies and then compared to the actual system. In a longer perspective it also gives hints of which future manufacturing system that is suitable for this working method. However, approximating the production disturbances of non-existing equipment is a problem. The suppliers of equipment have a tendency to exaggerate the performance of the equipment and the model builder has to take this under consideration and estimate more reasonable values that can be used in the simulation model.

Training of the staff working at the manufacturing system is necessary for best results. As mentioned before, the DES model can be considered a valuable tool in describing different production philosophies, for example the build-up of storage can be easily shown in the model. The different production improvement techniques will help avoiding waste and in the end it can increase the profitability of a company. Therefore, it is of value to combine the investment in DES with training of the latest available trends in production systems.

There is a possibility to simulate human involvement in the DES models. Human behaviour is to some extent difficult to measure. In more complex manufacturing systems the operator's skill will be developed after some time. It may be difficult to evaluate this skill in many cases. However, it is suggested that labour in the DES model should be included where appropriate. One way to evaluate the manual work time is to use time measurement, for example the method of MTM (Methods Time Measurement) (Wiklund, 1982). However, today's manufacturing system demands many complex tasks. Some of those may be a challenge to measure but worth an effort. It can also be a way to document the operator's work tasks.

Increased knowledge about production techniques may increase the productivity of the manufacturing system. Changed work organization can enhance productivity without any physical changes at all. The case studies indicated that changes of working methods are a cost efficient way of improving the performance of a system. Interviews with the staff also showed that smoother production resulted in better working conditions as well. Thus, the company will probably also increase the overall quality as well.

The automotive and aircraft industries are both working with methods to integrate several disciplines to shorten development time of a new product. One way to shorten time to market is to integrate product and process development. Thanks to information technology, new methods such as DMU (Digital Mock-Up) are possible to implement. The idea is to work parallel with product and process developments to reduce time and cost (Reinhart & von Praun, 1999; Bolmsjö, Lorentzon & Randell, 1999). Time saved can increase profitability for a company when new products are introduced. The ramp-up phase may also be shortened. However, the parallel work demands a great deal of coordination between the disciplines. This still needs to be improved.

Product design is also interesting to compare with DES. Some parts in the product design process can be learnt from the design departments. The PDM (Product Data Management) systems keep a record of different versions of files in a comprehensive way. It would have been seen an advantage if there is more support for this feature in current DES software. Another missing feature in current DES software is the possibility to move backwards in older versions of a file. Where PDM systems will be used on a larger scale, the integration of DES models will be natural.

The DES models were designed according to best practice in simulation model design. A conceptual model was at first formulated describing all relevant input data as layout, connections between elements and all other various data, for example production disturbances and cycle times. The conceptual model is a base on what data that have been inserted in the simulation model. All components in the system should have logical names and characteristics. Due to the many settings in the simulation program, it is vital to log the incremental development of the model in a separate document.

This is also necessary later when one is reverted back to the model for revision when anything has to be adjusted or for any possible fault detecting. A conceptual model embedded in the simulation model is another idea suggested by the author. There are so many possibilities of changes in the software and it easy to insert a value by mistake. One unintentional change in the model could be fatal for the results of the DES model. A log file describing all changes from normal values would be supportive for fault detecting and quality assurance of the model. Pharmaceutical manufactures have strict regulations of documentation; perhaps some ideas from there may be re-used.

Input values to the DES model are a great concern. The different figures are often measured at site and then later used in the model. One has to be really skilled to evaluate the measurements. In some machines, the system can itself measure and compensate if the measurements are outside the limit of tolerance. This means that the cycle time is not fixed. Commonly, all knowledge about the system is not given to the model builder. In all case studies values have to be adjusted in the DES models. In this respect the documentation in the conceptual model should by no means be neglected.

To work in a team is also a way to improve the results of a DES model. There are many uncertainties in a simulation project, for example there are possibilities to design a model or collect input data in different ways. To achieve more different views in the DES project it is suggested to work more in a team. This may provide a more holistic perspective on the project. In many companies today the DES projects are often seen as one single person's task. If compared to product design, a product is seldom or never developed by a single person. Surprisingly, a DES project is often solved in this way. Constructive discussions will enhance the results in most simulation studies.

The manufacturing method used in the manufacturing system should be more considered when the actual product is designed. Factors such as material, tolerances, strength, stress, fatigue etc. are decided when the product is designed. Those factors will also define the way the product is manufactured and thus decide the manufacturing system. To involve more production engineers in the design process may help prevent production disturbances.

A point to consider is that it is difficult to press creative, motivated and responsible employees into the prefabricated schemes of software packages (Wiendahl & Stritzke, 1998). The software itself is seldom a solution to the problem. The software, the tool for improvement, should support you in your effort to improve production performance of a manufacturing system. A drawback with all computerized tools is that they may moderate creativity.

So far the events of production disturbances have been studied at one manufacturing cell only. A future development may include several stations depending on each other. The study should also include the logistics as well as other information flow. The production disturbances could then be studied and how they propagate through a system. Bottlenecks and other obstacles could be more easily detected by the source. The DES model is suitable for combining all mentioned issues. The consequences of any alteration of manufacturing capacity could also be easily analyzed in the whole system.

Another research idea is to make a complete layout of a manufacturing facility in the DES environment. Accuracy, however, must be sacrificed in a model that will cover all complex tasks in all manufacturing lines. As suggested in Chapter 8, the future model must include all relevant input data and production disturbances to study the actual behaviour of the system. Finally, the model should be possible to keep up-to-date. It is a demanding task to update the model with changes that appear in disturbances and also in the system itself.

Chapter 7

Conclusions

The objective of the thesis was to find and use a suitable methodology for production disturbance reduction in a general manufacturing system. Work that increases overall efficiency due to reduced production disturbances also substantially increases profitability. Most companies constantly need to improve profitability in a competitive international environment.

The combination of a DES modelling and the real-life implementation make it possible to achieve increased equipment efficiency in a manufacturing system. The idea behind the proposed methodology is to have a useful technique and to apply it in the real world. Different experiments in production disturbance reduction can be tested before implementation.

The basic rules of different production improvement techniques, for example TPS (Toyota Production System) have also been proven to be successful for smoother production flow and high overall quality. Production disturbance reduction ideas must be implemented according to all basic rules of manufacturing. Contemporary production improvement techniques based on supply chains between different suppliers and limited products in stock necessitates a focus on production disturbance reduction.

The three main stages in the suggested methodology are 1) planning and data gathering, 2) analysis and implementation stages. This is also combined with 3) continuous improvement. The planning and data gathering stage includes project plan, goal and objectives of the study, definition of production disturbances, gathering of input data and logics, and the conceptual model. The second stage, analysis and implementation, comprises DES model translation, verification and validation, and experiments. The experiments are based on alternative tests in production disturbance reduction to increase efficiency. The enhanced results in the model should be verified before they are implemented in the real world.

Continuous improvement, the third stage, of the proposed methodology includes improvement in model design, studies of production improvement techniques, training of operators, follow-up of implemented changes, investigations in measurement of production disturbances and key figures. The improvement process should continue. A model is seldom so good that it yet can not still be improved. With constant feedback various variables can be altered and the DES model can be improved in several phases.

Experiences from implemented results need to be fed back into the system. This is valid both regarding production disturbance reduction in real life and simulation building. In real life, new products develop at a faster pace than ever. When these are produced in a manufacturing system, changes will be made to adapt the system to the new product. Both before and after such adaptations, it is natural to experiment and evaluate the performance of the manufacturing system.

Proper training of related personnel is also a step towards increased knowledge of overall efficiency. Significant gains can be made by non-expensive measures. Increased understanding of the related problems is a key to improvements. Training of the personnel must by no means be neglected and may be the key to overall efficiency for the company. The involvement of the personnel working at the manufacturing systems should never be neglected.

The presented work also shows the need for powerful tools such as DES combined with knowledge of production improvement techniques. The case studies all showed improved performance of 6%, 12%, 14%, and 18%. The suggested methodology may enable an increase of total output in a manufacturing system if it is applied.

Chapter 8

Future Research

For a more overall view of production disturbance reduction combined with the tool of DES several issues noticed in this report can be investigated further. More research is needed mainly by the software developers in developing the DES program to be an even better tool in production disturbance handling. It would be useful with some kind of more solid general guidelines valid for a variety of manufacturing systems when using DES.

Performance improvement and production disturbance handling is an area that can be further elaborated. There is always a discussion about what can be regarded as a production disturbance. A more general guideline is requested that could be used at a company level. This may help to classify the different types of production disturbances.

Measurement of efficiency in manufacturing systems must be carried out in a more elaborated way to structure further work in the area. Automatic production disturbance logging in the future will be more integrated in the PLC (Programmable Logic Controller) system of the manufacturing lines. Projects that connect PLC for production disturbance gathering have been studied in one of the case studies. Further work needs to be done here, for example data translation and production disturbance logging.

An interesting area is inclusion of several manufacturing cells where various production disturbances can propagate through the system. Parallel machining is another idea to improve performance of a manufacturing system. The study would, probably based on case studies, include the material flow as well as the information flow between the stations, from and to the outside of the system. All kinds of alterations in a manufacturing system could be easily analyzed.

Finally, further studies are needed when a completely new product is introduced in a current manufacturing system, the ramp-up phase. The new product itself creates production disturbances that possibly also infect other already existing products produced in the line or related lines. The design of new manufacturing systems is also an area that needs to be further studied.

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Paper I

Reducing bottlenecks in a manufacturing system with automatic data collection and discrete-event simulation

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Abstract

A methodology for working with bottleneck reduction by using a combination of automatic data collection and DES (Discrete-Event Simulation) for a manufacturing system is presented. In the DES model, the bottleneck was identified by studying the simulation runs based on the collected automatic data. A case study showed an improvement of the availability in one machine from 58.5% to 60.2%. This single alteration with a minimum of investment resulted in a 3% increase of the overall output in the manufacturing system consisting of 11 numerically controlled machines and six other stations. A new simulation run was performed one year after the first study in order to see how the improvement work has progressed with the suggested method. The method resulted in an increase of 6% in overall output. It could be assumed that machines in future manufacturing systems will provide automatic data. The data can then be used for DES models when identifying bottlenecks in a manufacturing system.

Keywords

Discrete-Event Simulation (DES), Manufacturing Systems, Bottleneck Reduction, Productivity Improvement, Production Disturbances (PD)

1 Introduction

Elimination of bottlenecks in a manufacturing system is a way to increase efficiency. The method facilitates studies of the most critical part of the manufacturing system. In this regard, it is interesting to work with automatic data collection in combination with DES (Discrete-Event Simulation). DES models provide the means to change different conditions and see the results in the model. A key issue is to combine production improvement techniques with DES. The potential of a tool like DES for analysis of equipment effectiveness in manufacturing systems is also of interest. Improvements of a manufacturing system are beneficial compared to the simulation costs. The increased production from the manufacturing system may be considerable.

Bottlenecks for one product are not automatically bottlenecks for other products in the same manufacturing line. This is due to process time for the different products in different machines. The reasons are varied from case to case. One study in the electronics industry has shown issues for processes such as suitable dispatching, batching, setup strategies, equipment dedication, hot lot policies etc. (Laure, 1999). According to various investigations, the reasons are often so differentiated that no specific production disturbance can be pointed out without subsequent investigation. Different products in one machine has to be compared with the same product is manufactured in different machines. With more than one machine for the same product there is a greater flexibility to handle production disturbances.

Studies from advanced manufacturing systems in manufacturing industry have shown that the OEE, is about 50% (Blanchard, 1997; Ericsson, 1997). The figure may even be lower during production setup (Ylipää, 2000). Production disturbances affect OEE, as well as the overall production efficiency during the life cycle of a manufacturing system. The disturbances may affect product quality as well as work safety, work environment and satisfaction of workers.

System improvement is important in terms of increased productivity in manufacturing. There are some fundamental performance improving attributes of manufacturing operations. Some previous research has linked the study of effective technological development with organizational learning theory. Existing learning studies relevant to operations improvement may be grouped into five general categories: learning-curve research, function-based learning studies, analytical learning theories, learning microstructure studies and organizational learning theory (Upton & Kim, 1998).

The analytical formalization is that learning in the manufacturing improvement process involves reducing uncertainty in decision-making. Managers gather more information and knowledge about the candidate improvement projects and update their estimates according to Bayesian principles. The improvement work would benefit from a more systematic viewpoint.

The main purpose of the performed case study is to show the improvement of a manufacturing system when automatic data collection is combined with DES. The findings indicate that the potential is considerable if the automatic data collection system works accurately and the data can be used as input data to the simulation model. The bottleneck analysis is one way to achieve increased performance in a manufacturing system.

2 Automatic Data Collection Systems

Automatic data collection systems are increasingly being used in manufacturing systems. One study used CBS (Corporate Business Systems) according to Robertson & Perera (2001). The input data from CBS and MRP may, however, under many circumstances be far too imprecise to be adequate for input data for the simulation model.

Production disturbances and mistakes are bound to happen under various conditions and it is important to find out what is actually happening. One benefit from a data collection system is that data are continuously logged in all circumstances and time. It is always possible to go back to see what actually went wrong. Another benefit is that measurements of the system are independent from human involvement. The logging will be the same even if the operators are working in different shifts. Thus, the system is able to objectively log all different activities of a manufacturing system. This is important when the same set of circumstances can provoke similar errors and downtimes regardless of the people involved (Reason, 2000). In an automatic system it is easier to categorize this type of problems.

It is important both from a productivity and safety point of view to get control of production disturbances in a system. Blaming individuals may be considered emotionally more satisfying than targeting the background reasons for improvement of the system. To survive in the long run, however, the improvement projects are among the most important to stay competitive and in business.

For example, aviation has incident reports to avoid possible future accidents. It may be wise to adopt a similar procedure both for incidents and production disturbance issues in manufacturing processes. Documentation may give the opportunity to categorize and find out fundamental reasons why production disturbances occur. It is then easier to tackle and avoid future production disturbances permanently. At the same time many of the production disturbances contain behavioural elements which were not thought to be possible in advance; these can only be solved by human involvement (van der Schaaf, 1995).

Machine developers are increasingly using a common protocol to connect different machines and other equipment to each other. MMS (Manufacturing Message Specification) is an international standard for communication between manufacturing equipment (ISO 9506, 2000). If the format is standardized it will be even easier to obtain data from the machines. However, developments are necessary in the software that handles and presents the information collected from the different machines. Modern control systems make it possible to collect various data from the manufacturing system. New options exist to measure the system's performance. It is also feasible to measure the efficiency of the different machines with high accuracy. For this purpose time measurements can be in any increment values.

Automatic data collection systems demand some consideration. First, the systems can collect a considerable amount of data and the data have then to be filtered or reduced to be usable. Second, the transfer of the data to input data for the DES model is important. Third, there is a need of categorizing the production disturbance data correctly. The data should be lucid and the amount of data must often be reduced considerably. The different causes of production disturbances that occur are also vital to include. There are two main alternatives; a fully automatic or a semi-automatic system. According to the authors' experience the semi-automatic system is the best alternative today. In any case the amount of undefined production disturbances must be restricted.

3 Measuring of Key Figures

The difference between tact and cycle time is important to take under consideration (Monden, 1998). From an overall sales perspective the tact time can be described, see equation 1.

$$Tact\ \ time = \frac{Regular\ \ operating\ \ hours}{Saleable\ \ quantity\ \ of\ \ products} \tag{1}$$

The tact time indicates the time needed to produce one unit considering the daily saleable quantity. The formula shows the perspective of the entire company. To get an adequate view of the manufacturing line the formula has to be decomposed. A suggested and well used measurement is OEE (Overall Equipment Effectiveness), see equation 2 (Nakajima, 1988; Prickett, 1999).

$$OEE = Availability \cdot Performance\ \ rate \cdot Quality\ \ rate \tag{2}$$

Performance rate is losses at reduced performance levels. Quality rate is about quality related losses. Based on experience (Nakajima, 1988) an OEE figure of 85% is possible to achieve and also possible to surpass. However, the experience is that many companies are well below the target and according to different studies, for example Ericsson (1997), and case studies performed by Ingemansson & Bolmsjö (2001), the value is more likely to be around 50%. Increased and improved measurement will raise the potential of improvement.

$$Availability = \frac{Available\ \ time - Downtime}{Available\ \ time} \tag{3}$$

The key component in the OEE formula is the availability, equation 3. DT refers to the time frame when a production disturbance starts until it ends. Previous studies have shown that WT for any action may in many cases be as long as 90% of total DT (Ingemansson & Bolmsjö, 2001). Accuracy is a key in the measurements. Automatic data collection enables more accurate data to be measured.

The concept of PD (Production Disturbances) may be defined as the time when the manufacturing system is not working properly. One definition describes PD as an unplanned or undesirable state or function of the system (Kuivanen, 1996). PD can also involve prolonged cycle time or product quality deviations. Thus, in many cases it is approximately the same as DT.

Measurements of the different components are important in order to improve the manufacturing system's OEE and availability. There can always be a discussion of what can be included in the figures. The most common idea is to divide DT in planned and unplanned production disturbances. A survey has been conducted in Sweden of 80 companies showing that the idea of what is regarded as a production disturbance varies considerably (Ingemansson, Bolmsjö & Harlin, 2002).

Cycle time is the total time needed to perform the necessary operations for processes at each machine or station. In real life, cycle time can be longer than tact time since variances in operating time are not considered. In most cases, however, tact time is much longer than cycle time mainly due to various production disturbances. DES may be used as a tool in studying the phenomena.

4 DES and Efficiency Improvement in Manufacturing Systems

Manufacturing systems often have difficulties to reach theoretical output in actually manufactured products. The calculations made at the planning stage before the lines are actually built are seldom in accordance with the actual output. In many cases the actual results are significantly lower than the estimated figures. There are examples of manufacturing systems, according to the authors' experience, that have allocated some 50% more working hours in real use than planned from the beginning.

The DES model depends on accurate data for its input. A sophisticated control program gives the opportunity to collect data in a more comprehensive manner. In the end the data will also yield a better and reliable simulation model. Input data issues are critical in making a usable model.

If a potential bottleneck can be eliminated the cost for the DES model is paid many times compared to the investment in equipment and design costs. Still, it may be difficult to allocate funds in a project plan, according to the authors' experience. There is a need for a new approach that includes DES in the initial planning of manufacturing systems.

Measuring of key figures is an important issue for continuous improvement of the manufacturing system. There can always be a discussion of how the data are measured. The authors' recommendation is easy understandable key figures such as OEE. The key elements in OEE are availability, performance rate and quality rate. To illustrate the importance of the key figures the link between OEE and financial statements are of great importance (Hansen, 2002). If it is possible to show increased profitability of the company it will be the greatest incentive of them all.

However, the issue is to obtain figures that can be compared to each other. The figures can rapidly indicate production disturbances that have to be reduced. The figures can also initiate a more comprehensive DES study. Shorter production disturbances can unfortunately be hidden in key figures. Those short production disturbances can be very annoying for the operators.

The combination of automatic data collection, measurements of key figures and DES modelling have shown to be beneficial. The industrial case study will describe the method and the potential to improve the system. The method combines the knowledge of the personnel around the manufacturing station together with acquired knowledge from the DES model. The potential to improve production efficiency in a manufacturing system together with DES has been shown to be considerable (Ingemansson & Bolmsjö, 2004). The automatic data enable better quality of input data and in the end better results of the overall study.

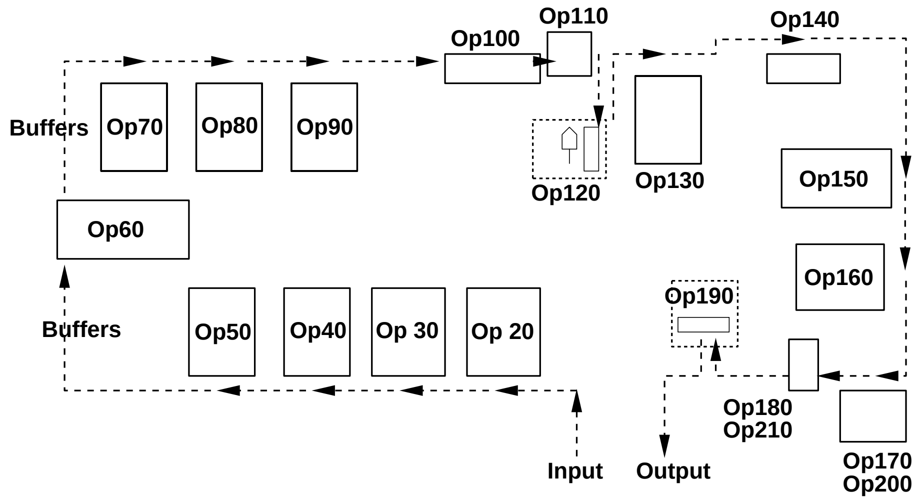

Figure 1: *Schematic layout of case study.*

5 Industrial Case Study

A manufacturer of engine blocks at a multinational company has been equipped with an automatic data collection system. Different sets of data, DT (DownTime) and TBDT (Time Between DownTime) are logged at each machine. The reason behind each DT is also included whenever it could be extracted automatically from the status of each machine.

The line consists of 11 NC machines and six other stations including assembling, washing and cleaning, and quality control, see Figure 1 for a schematic layout. A casted block is inserted at the beginning of the line. After insertion there are machines for different process stages. The NC machines are used for machining such as milling, drilling, lathe tooling and quality control. At the end of the line the engine block is immediately ready for the assembly line; see “Output” in the same figure.

The current automatic data system made it possible to collect data in a very accurate way. All stops were logged from the shortest DT in seconds to the longest in hours. This means that the actual system performance is easy to measure at each machine and also overall performance of the whole system.

There are no major setups in the system. Other types of engine blocks with, for example, different number of cylinders are produced at other manufacturing lines. The study was carried out in Sweden in 2001 and 2002.

5.1 Case Study Methodology

Input data to the simulation model were extracted directly from the data files of the collection system. Relevant data to the simulation model were then selected from the extensive amount of data stored in the different sets of files. The physical layout of the manufacturing area was used as a basis for the layout of the DES model to enable an accurate and realistic simulation model.

Interviews with personnel at the company were also carried out, mainly among operators, maintenance personnel and industrial engineers. The main reason behind the interviews was to understand the manufacturing process and the possible problems that can occur to achieve information about production disturbances. The operators and maintainers working with the actual system are often the most valuable resource. In this particular case, a study was performed to understand the work tasks of operators and maintainers. A questionnaire and semi-structured interviews were carried out; these are further described in Harlin, Ylipää & Fjällström (2002).

Case studies are used when the investigator has little control over events and when focus is on a contemporary phenomenon with some real-life context (Yin, 1994). Case studies could be used for exploratory, descriptive or explanatory purposes. Strengths of case studies are the ability to deal with a full variety of evidence, such as documents, interviews and observations. The complexity of the performed case study has limited the article to only one study.

5.2 Model Building

When the DES model was built, verification and validation were carried out to check the accuracy of the model. Actual yearly data were compared to simulation data and showed acceptable accuracy, less than 5% deviation from real values. The main idea of model verification is to ensure that the conceptual model is reflected accurately. For example, are assumptions on system components and system structure, parameter values, abstractions and simplifications accurately represented? A whole range of questions can be asked in order to achieve a necessary accuracy of the model. What happens if analysts change parameters, input variables, or modules of a simulation model? Is the simulation model an adequate representation of the real world system (Kleijnen, 1998)? Those issues were raised during the model building phase.

The following simplifications have been included in the DES model: The transfers of the engine blocks in a gantry system between the machines were not included.

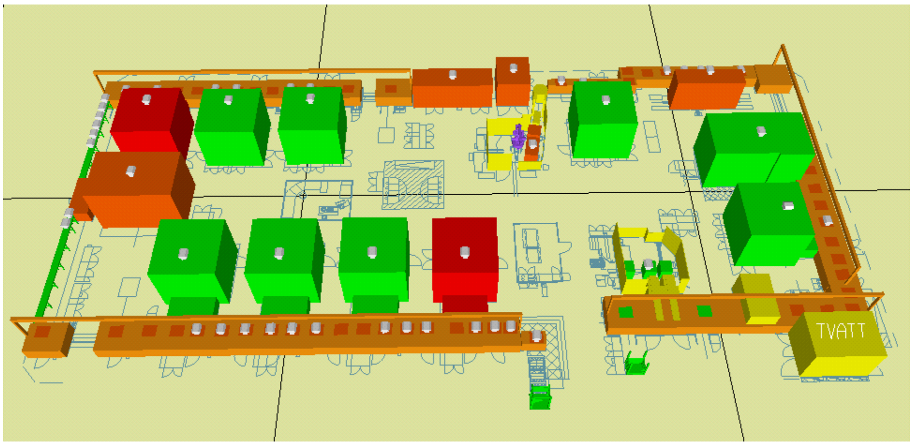

Figure 2: *DES layout of the case study. The operation modes of the machines are indicated by the different colours; green for busy, yellow for idle, red for failure, and orange for blocked.*

The time to transport the different engine blocks was much less than the production time of the system and can not by any means be seen as a bottleneck in the system. A normal cycle of the transfer took approximately 20 to 30 seconds compared to 9 to 23 minutes of the NC machines. Materials handling within the machine were not included. The machine time is set to a specific time when the detail was inserted in the machine and ends when the part is removed from the machine again. Internal movements of part and tools were included in the machine time. The simplifications saved time to be used on the main bottleneck studies.

The input in the manufacturing system was always supplied with engine blocks and caused no idle times in the studied DES model. Output was conveyed to the next station without delay and caused no blocking in the studied system. The DES software used in the case study was QUEST.

5.3 Experiments and Results

Many different experiments in the case study were carried out. To show the potential of combining DES with performance improvements a bottleneck study in the manufacturing system is described. Experiments in the DES environment indicated that Operation no. 130 was considered the current bottleneck in the system. The bottleneck was identified by studying the simulation runs and was verified by the statistics from the model. Improvements of this single NC machine were shown to improve the whole system.

The operation assumed to be the manufacturing bottleneck was further checked in a comprehensive real world study. The study logged different types of production disturbances. Manual logging was carried out in parallel with the automatic system in order to check the behaviour of the machine. A drawback with the current automatic system is that there are too many unclassified events. As a result, the reasons for the different production disturbances are not known. Therefore, supplementary manual logging was necessary to obtain the real causes of the disturbances. Another advantage with the manual logging was that the experience of the operators was included in the study.

The DES model was used for reduction of production disturbances when the model was verified and validated. The results are described in the following example and the figures are also presented in Table 1. The DT was reduced by one third from 22.5 to 15 hours a week. This was accomplished by reducing the tool exchange time by 50%, which is a feasible task. Availability increased in the operation no. 130 from 58.5% to 60.2%. The overall output of the manufacturing system increased by 3% annually with the proposed changes implemented. The decreased amount of DT will also enable smoother production and better working conditions as well.

In addition to the DT reduction at operation 130, other improvement areas were identified in the bottleneck study at the same operation. Today's cutting tools have longer useful life and the intervals of exchange can be extended. This decrease the need for planned production disturbances. The cutting data have also improved and consequently the cycle time of the different machines can be reduced. The alterations were later implemented on all operations in the manufacturing system with similar machining.

A new simulation was carried out one year later with data from the automatic data collection system. On year to year basis the model indicated an improvement of 6% of overall output in the manufacturing system. The figure was again verified to real production data. At this time two different bottleneck analyses have been concluded and one is ongoing. The results from the bottleneck analysis on one machine were implemented on other machines as well. The investments in equipment to improve the system have been approximately €2000 to 3000. In addition, engineering time has been invested in simulation, analysis and implementation of the improvements.

It was clearly shown as a result in the DES model that the downtimes are causing both blocking and idle times in the system. Four to six machines were observed in the model to be affected when one single machine was down. At rare occasions,

Table 1: *Bottleneck reduction with DES.*

	Before	After	One year later
Operation 130			
DT per week	22.5 h	15.0 h	
Availability	58.5%	60.2%	
The system			
Overall output increase	-	3%	6%

even more machines were influenced which showed a clear decrease in overall output.

Normally, the machines have one buffer before and another after the same machine. The few extra buffers added in the system are unequally placed. The main extra buffers were six places before and seven buffers after Operation 60, see Figure 2. The buffers help to smooth production flow and it would have been an advantage if the buffers were scattered in different places throughout the system. It can clearly be seen in the system that although the machine time is above average for the first four NC machines there are no bottleneck at this part of the line. The buffers following the first four machines smooth out any production disturbances in the first part of the manufacturing line. If the buffers were more equally distributed throughout the system, the performance of the system would increase even more.

It is a delicate problem to decide the suitable number of buffers in a manufacturing system. Too many buffers will lead to a high cost if something in the manufacturing process goes wrong and the manufactured parts have to be altered or discarded. There is also the question about how much capital should be tied in the products. Moreover, it will hide the real problems from being discovered in due course. Several production improvement techniques such as TPS try to minimize the amount of buffers in order to highlight the actual problems at an early stage.

5.4 Conclusions from the Case Study

There are many advantages with the automatic data collection system. One is the exactness. The time accuracy is not possible to measure to the same extent in a manual or semi-manual system. Another advantage is that the measurement is unaffected by subjective judgments. The experiments showed that an improvement in availability of one single machine can improve the whole system's performance significantly.

The classification of production disturbances chosen by the system is important, as this will be the basis for improvement measures. There are several alternatives to choose from automatic collection systems. If the system is fully automatic and indicates both time and real cause of production disturbances it is important to select the appropriate causes of disturbances. This requires analytical work to be done with the data. In a data collection system intended for disturbance reduction it is important to classify the different background causes in relevant classes. Unclassified data must be less than approximately 10% according to the authors' experience.

The combination of an automatic data collection tool and DES is a suitable way of analyzing production disturbance reduction. The main advantages with the combination seen in the case study are:

- objectiveness of data,
- accuracy of time measurement, and
- the opportunity to classify production disturbances in relevant categories.

6 A Method for Improvement of a Manufacturing System

The connection between DES and the automatic data collection system is illustrated in Figure 3. The automatic data collection system is continuously extracting data from the different machines in the system. Data can be converted with great accuracy to input data for the DES model. Various experiments can then be carried out off-line and do not interact with the actual manufacturing. DES can also be used for prediction of the system. If for example a longer production disturbance occurs, the operator and maintenance team can be given expected downtime to carry out maintenance tasks. The results from the experiments can be used as feedback for different evaluations in the manufacturing system.

A method for improvement in a manufacturing system is presented in Figure 4. The first step is to identify the current bottleneck in the system. The automatic collection system provides adequate data for this issue. The observed bottleneck may be further studied, and although the automatic data collection system gathers various data, even more may be needed. A good way, used in the described case study, is to combine the automatic data with manual logging. A positive aspect is that it includes involvement from the personnel. The operators have valuable expertise that is beneficial to the improvement process. In many projects valuable ideas of improvements are from the operators themselves.

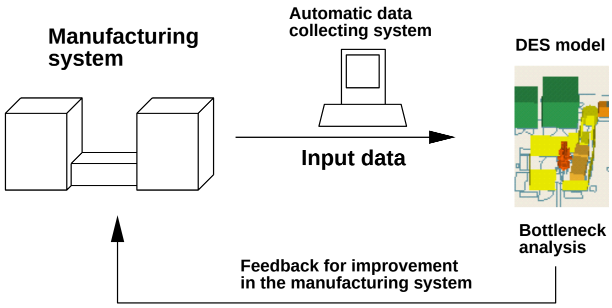

Figure 3: *DES and an automatic data collection system may be used to improve a manufacturing system.*

The next step in the study is the DES model work. A model is designed and input data can be more easily accessible compared to a study made without automatic collection system. If correctly handled, this will also enable the model to be more accurate. Different experiments can be carried out to visualize the real background reasons why a certain machine is a bottleneck in the system. The DES model enables many alternative tests to be carried out to find one of the best possible solutions.

Measurements and actions are then implemented to increase productivity where the bottleneck has been discovered. Changes are done gradually and the results are checked to verify improvements. If everything works according to the plan, the cause of the current bottleneck in the system is eliminated and the production flow has increased.

The process can then be re-started which the arrow to the left in Figure 4 indicates. The improvement process is an everlasting issue. Again, the work has to start all over with a study of the system's new existing bottleneck. A system is seldom so good that it could not be improved a little more. The potential for improvement in terms of equipment efficiency is so sizeable that the process has to be repeated a number of times. In some cases the bottleneck has not changed and more measures have to be taken at the same station until the problem changes to another machine. The work can be repeated until the cost of DES modelling exceeds the savings in performance improvement in the manufacturing system.

6.1 The General Methodology

Improvements of a manufacturing system are needed to stay competitive. Automatic data collection makes it possible to perform bottleneck analysis with the

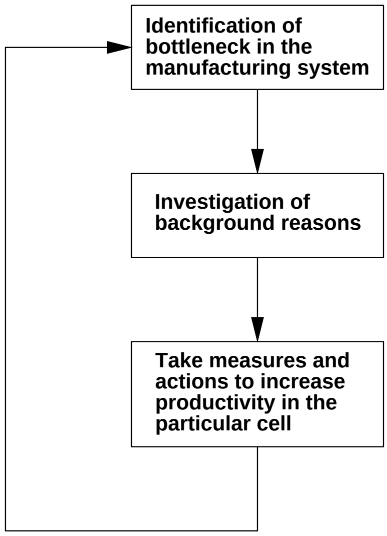

Figure 4: *A method to eliminate bottlenecks in a manufacturing system.*

help of DES, see Figure 5 for the interaction. When all production disturbances are logged down to parts of seconds there are solid input data for the DES model. The DES model will behave accurately compared to the real world and time for validation and verification can be reduced too. A main advantage with the DES model is that bottlenecks are clearly shown. Time can be compressed and the visualization feature is beneficial to decide where the actual bottlenecks are in the system.

A disadvantage of many manufacturing systems of today is that all reasons and causes to production disturbances are not accurately logged. The recommendation is that the case study must be combined with real world review. Thus, involvement of the personnel at the manufacturing system is also beneficial. The operators working with the system have proposals to improve performance of the actual system. The method finds this interaction vital and proof of this was made in the case study.

The main advantage with the methodology is the possibility to test changes in the DES model before it is applied in the real world. When a specific type of production disturbance is identified, it can be removed from the DES model and the new results from output can be observed. If the results are satisfactory, the alteration may be implemented in the real world. There is a risk for the system in every change that anything could go wrong in a manufacturing system. An implementation of an improvement may in worst cases jeopardize the whole system. One of

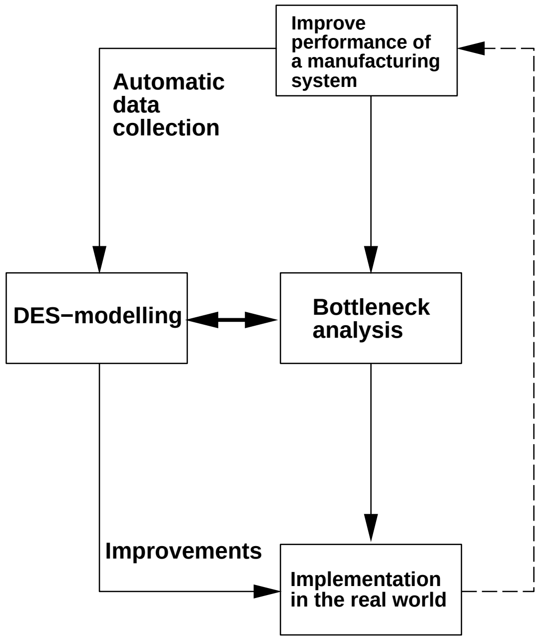

Figure 5: *The DES model can identify bottlenecks in the manufacturing system when automatic data are used. Features such as time compression highlights the bottlenecks over a period of time.*

the strengths is that all tests can be made beforehand in the DES model before the actual implementation. An even better DES model can be achieved in the future when more of the reasons behind the production disturbances are logged in the automatic system. The improvement process can then be repeated according to Figure 5.

7 Discussion

Improvements in a manufacturing system combined with DES modelling have in the case study shown the bottleneck can be identified and analyzed. Proposals to improve the system can then be given. The method indicated that savings could be achieved. Increase in the performance of the manufacturing system was possible by eliminating the current bottleneck and consequently a reduction of the production disturbances.

However, our findings indicated that if an automatic data collection system is in place some matters should be considered for the best results if it is combined with

DES. A relevant table of failure codes and what actual times are logged are necessary for the simulation model. There is a problem of translating the modes of the machines to acceptable codes. It is not acceptable to have a miscellaneous code that cannot be identified as a specific reason of production disturbance. The production disturbances should be split up in different categories clearly distinguished from each other. To emphasize, a real effort should be taken to find an accurate division of disturbances. If this can not be solved by data from the machines, a semi-automatic system may be the solution. In that case the operators have to add the causes (or more exactly what they believe are the causes) to the production disturbances according to a predefined list.

The issue about accurate production disturbance registration is vital. Classification of production disturbances is important as it forms the basis for the efficiency measurements and for the key values that are aimed to promote the improvement work. A clear and logical description of production disturbances is needed and key values should support the chosen description. There is a development in the area and the machine manufacturers are increasingly including the option to obtain data directly from the machines. Other important aspects are how to exchange, utilize and document knowledge and experiences from different participants in the production line and other parts of the company.

Bottleneck reduction may be one way to improve performance in a manufacturing system. Production disturbances in manufacturing lines are a common industrial problem (Smet, Gelders & Pintelon, 1997). This study includes a variety of companies. A more systematic approach is needed to prevent and eliminate production disturbances. Another conclusion is that the same methodological approach can be used independently of products manufactured. TPS (Toyota Production System) main components are quantity control, quality assurance, and respect for humanity (Monden, 1998). Improvement activities are one of the fundamental elements of the TPS and many things can be learnt from here. Shorter tact time, shorter cycle time and increased availability will all lead to increased productivity. This will be beneficial to the company and result in higher income, lower cost, less use of tied-up capital and less work hazards.

The performance of a manufacturing system is to some extent settled when the actual system is built. More effort should be taken before the actual building of the system. Many systems in use today are highly sophisticated. Actually they have been so complex that some are talking about too much automation (Womack & Jones, 1996). A system that functions well will serve as the basis for manufacturing of quality products. System reliability, maintainability and dependability are key factors in influencing customer satisfaction (Madu, 1999). With the suggested method, efficiency improvement can be achieved both before and after the system is designed and built.

8 Conclusions

Working with DES and automatic data collection is a beneficial way of increasing equipment efficiency of a manufacturing system. A case study at a larger manufacturing system has shown the method of bottleneck reduction. An increase of availability from 58.5% to 60.2% in a single machine showed an overall increase in the system of 3% after the improvements were implemented in a system with 21 different operations. One year later the overall output in the system has risen 6% compared to the beginning of the project. The main advantage of the DES model is that all experiments can be carried out off-line and do not disturb the actual manufacturing. The results from the experiments can be used as feedback for evaluations of the manufacturing system. In future manufacturing systems more automatic data will be provided. The data can be used to bottleneck analyses in a manufacturing system with the help of DES according to the described methodology.

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Paper II

Improved efficiency with production disturbance reduction in manufacturing systems based on discrete-event simulation

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Abstract

Discrete-event simulation (DES) and disturbance reduction techniques are a combination for improving efficiency in manufacturing systems. The DES modelling allows different tests to be carried out by step by step alteration. The use of manufacturing improvement techniques should be combined for best results. The changes in disturbances will show us different alternatives in output of the manufacturing system. Two case studies have been accomplished to study the possibilities for disturbance reduction in manufacturing systems by using DES with the proposed method for improved overall manufacturing efficiency. The case studies showed an improvement of output 14% and 18%, respectively.

Keywords

Discrete-Event Simulation, Manufacturing Systems, Production Disturbances, Reliability, Productivity Improvement

1 Introduction

An increased productivity and better overall efficiency of the manufacturing lines are important goals for many companies. Handling of disturbances is of great importance for more reliable and robust manufacturing systems. Disturbances can occur in all system levels in manufacturing and it is important to achieve a more systematic approach to increase overall productivity for a system. The issue of disturbances in manufacturing lines is a common industrial problem (Smet, Gelders

& Pintelon, 1997). There is also potential to increase production when previous research show that of total production time only 50-60% is used for manufacturing and the rest of the time is wasted in different disturbances according to studies (Ericsson, 1997; Drucker, 1990; Viktorsson, 1989). With ever-increasing global competition, the total efficiency of a manufacturing system is of vital importance.

DES is a tool suitable for analysis of the dynamics of discrete processes such as manufacturing systems. Important aspects on applying DES in analysis of manufacturing systems include effect on product changes, changes in the system itself, possibility to compress time so different scenarios can be analysed in a short time (Banks, 1998). There is need for new ideas in the area of disturbance reduction to increase overall efficiency and the combination of DES may be one. More ideas for improvement both regarding machine equipment and human involvement in disturbance handling seem necessary to achieve an increased overall productivity.

The goal of the study is to introduce a methodology based on DES for reducing disturbances in manufacturing systems. Another aspect is to make both the academic and industrial areas more aware of the importance of disturbance reduction. Manufacturing systems tend to become more and more complex and there is a need to take a more scientific approach to the background causes to why production disturbances occur in a system. DES is a powerful tool to analyse disturbances, their effects and propagation in a manufacturing system due to the easiness of alterations in a model and improvement in the system can easily be shown.

2 Production Disturbances in Manufacturing Systems

Disturbances can occur in different parts of a manufacturing system. A production disturbance is an unplanned or undesirable state or function of the system (Kuivanen, 1996). Disturbance elimination consists of all the measures taken to restore the system to a planned or desirable state. In this study all the disturbances are related to the actual manufacturing system of the products. Another approach is to classify mainly "equipment failure" and idling and minor stoppages (Smet et al., 1997). The definition of production disturbances is not yet homogeneous. Many aspects can be included, but the most important is to see the possibilities of disturbance reduction.

To describe the efficiency of a manufacturing line the production disturbances can be classified in downtime, speed and quality losses. Downtime losses can further be divided into planned and unplanned stops, see Figure 1. Different examples are shown to each category in the picture. Downtime losses are seen as the most

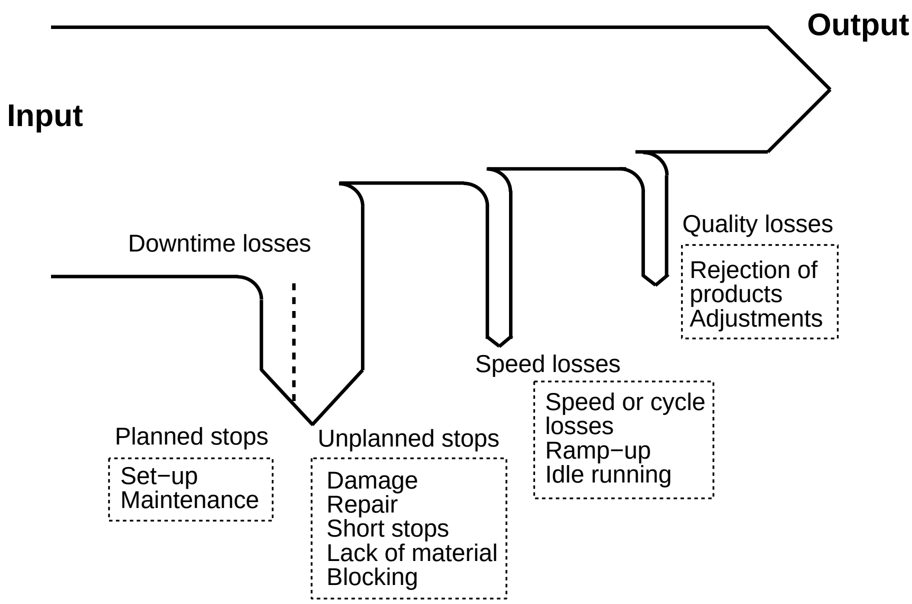

Figure 1: *Different disturbances categorised. To reduce downtime losses are in most cases the best way to increase efficiency of a manufacturing system.*

important to reduce to increase overall efficiency of a system. To describe when the system is down the parameter is DT and TBDT is used when the system is working at normal state.

The disturbances can cause blocking which means that the next machine in the process can no longer deliver their material. The other case is idleness where the machine runs out of new raw material. In linked lines the disturbances often propagate throughout the line. The focus is on the actual manufacturing process but in real life there are also other issues related to the production process depending on supplier, planning etc. The concept of production responsiveness (Matson & McFarlane, 1999) refers to the ability of a production system in terms of its operational goals in the presence of supplier, internal and customer disturbances. Disturbances are those sources of change, which occur independently of the system's intentions. This is an interesting approach but according to the author severe to implement in a simulation model. A first issue is to take care of disturbances within the manufacturing system, as the potential is substantial. In a wider perspective these issues regarding internal and external customers may be included if the simulation model is further expanded.

Different methods to estimate the reliability of manufacturing systems exist. A field survey of the causes and effects in two countries showed that more than one third of the production disturbances were caused by system designed errors (Järvinen, Vannas, Mattila & Karwowski, 1996). Another study suggested a model based on failure due to random shock loads together with a strategy for preventing or minimising such failure at optimum cost (Mathew & Kennedy, 2002).

The human behaviour in a manufacturing system is also important to consider. The time of a manual operation and the behaviour of the operator are important factors to include. The human interaction is almost always necessary to solve production disturbances. It is difficult to put a number on human processing capacity limits for at least three reasons: equipment design, expertise and working methods available (Bainbridge, 1997). As a person becomes more expert they have developed a skill in the subject.

3 Analysing Disturbances with DES

There is a need to apply a more multidisciplinary approach of the design regarding the manufacturing systems. The structure of many manufacturing systems, designed with lack of flexibility and other discrepancies, does not work with the rapid technological change and challenging market demand (Wu, 1994). Often there are little or no differences in the products put on the market by competitors which results in product price and time to market are important variables to achieve success for a company. Thus, manufacturing systems that are able to address these issues put a company in a competitive advantage.

Different manufacturing strategies and improvement techniques have been studied. The best parts of TPS are considered to be adopted for efficiency of a manufacturing system. Lean production has proved to be successful since it points out those who actually are adding value to a product. The interaction between human and machine is also vital for a system (Harlin & Ylipää, 1999). Designer errors of a manufacturing system can be a major source of operating problems. The more advanced a control system is, the more crucial the contribution of the human operator will be. Furthermore, the designer who tries to eliminate the operator leaves the person to do the tasks that the designer cannot think how to automate (Bainbridge, 1983). The organisational part should not by any means be neglected for a high performance manufacturing system. It is important to measure the performance and compare it to other similar systems to achieve an increased overall efficiency. Other improvement techniques that can be mentioned are supply chain management, TPM and SMED (Single-Minute Exchange of Die).

There is always a problem to estimate the accuracy of the model and especially if the model is describing a non-existing equipment or line. The model is an abstraction of reality and perfect representation of it could never be expected (Banks, Carson & Nelson, 1996). There is also a correlation between the accuracy of the model and time spent on it. Therefore, the accuracy of the model must be evaluated in the simulation model to obtain realistic results. There is a limit when improvement on the model is not worth the cost and the limit varies from simulation case to simulation case and it could be useful to evaluate how effective time is spent. A taxonomy that classifies the verification, validation, and testing techniques has been suggested by Balci (1998), many of those performed instinctively when building the model. Incremental development of a simulation model might be an alternative. A smaller model could be expanded or improved in different steps, which also is a way to reduce overall risk in a project (Randell, Holst & Bolmsjö, 1999).

It is necessary to be aware of the connection between the different tools for improvement of production systems and DES to improve a manufacturing system. Unfortunately today simulation is not often integrated in the development process. In a best case scenario the simulation model should be a “virtual copy” of the real manufacturing system (Klingstam, 1999). The production tools are based on improved techniques widely used and successfully implemented all over the world. The system can be showed before and after alterations without expensive modifications in real-world scenarios.

4 Industrial Case Studies

The case studies have been accomplished in order to study the possibilities for disturbance reduction in manufacturing systems by using DES combined with the goal of implementing improved overall manufacturing efficiency. The two case studies described are used to increase efficiency of the manufacturing systems. One of the companies has adopted the DES concept more broadly whereas the other is in a more initial phase. The companies were chosen as they actively work with production disturbance reduction and are judged to benefit from applying DES to increase the efficiency of the manufacturing lines.

4.1 Case Study no. 1

The company in case study no. 1 produces equipment and machines to the window blind industry. The production unit in Sweden employs some 100 people. The company has a wide range of products in the product mix including both ma-

Table 1: *Initial background data to case study no. 1.*

Cause of production disturbance	Number of stops, weekly average per machine	Estimated DT per stop (minutes)	DT per week (minutes)
Full bobbin	1.3	5	6.4
Yarn empty	0.9	30	27.0
Yarn breakage	0.4	2	0.9
Core thread empty	0.3	5	1.5
Miscellaneous	-	-	-
Sum DT			35.8

chines and consumer goods. The studied product, braided cords, is produced in 72 different machines and each of the machines has two units making two cords independently. The machines operate 24 hours a day, 7 days a week and they operate unmanned as long as no disturbance occur, up to some 100 hours. About 60% of the cords manufactured were coloured in a separate colour machine. As a final operation, both coloured and white cords are sales packaged before transportation to storage.

The manning was two operators daytime. Some experiments were carried out to change manning in real life but it was considered by the company as too expensive to have personnel at two shifts or more. Thus, more manning and more shifts may increase the overall capacity of the system. This option is not the most cost effective. However, try-outs were suggested with personnel to be on shorter duty on week-ends. Those simulations are not included in the case studied.

The system in current use for disturbance gathering was a manual log-book. The historical data available were causes of production disturbances logged in different categories. Disturbance data were logged only as reason in five different classes and the actual time involved to take measures to reach normal production was not included, see Table 1 for a weekly average for a measurement period of 26 weeks. The DT was only estimated as the time for action and not including the time for WT. DT was on average only 35.8 minutes per week for each machine. The values were too short and it did not match with current production rate. Additional measurements were necessary.

To receive more relevant disturbance data for the DES model, two vibration indicators with time logging were placed on two different braiding machines. The indicators logged a clock-time table for DT and TBDT for 6 weeks. The operators then manually added the different causes why the machines had stopped. See Table 2 for a summary of the measurements. The weekly average DT increased

Table 2: *Data from measurement of vibration indicators, case study no. 1.*

Cause of production disturbance	Number of measured stops, weekly average per machine	Measured minimum DT per stop (hrs:min)	Measured maximum DT per stop (hrs:min)	Measured DT weekly average per machine (hrs:min)
Full bobbin	1.1	00:05	14:48	08:19
Yarn empty	1.1	00:41	52:38	27:26
Yarn breakage	0.5	00:01	107:35	14:15
Core thread empty	0.3	00:01	01:30	00:10
Miscellaneous	0.7	00:01	45:34	04:27
Sum DT				54:37

from 36 minutes to 54 hours and 37 minutes. The WT changed the values considerable.

The MRP (Manufacturing Resource Planning) system indicated some rough data on annually basis but unfortunately not adequate for simulation input. The data could, however, be used for later validation of relevance of the model. All values were compared to annual production data logged in the MRP-system. The model was simulated in steady-state mode.

A main source for input data was interviews with the personnel. It was possible to recognise their working methods and obtain some solid times for the different activities. Frequent maintenance problems and times for repairs with some parts of the equipment were also raised with the maintenance staff. A simulation model was built of the studied production unit, see Figure 2. Selected bottlenecks, such as the braiding department and the colour machine in the system, were magnified in separate models for further experiments.

Production disturbance reduction

Production disturbances due to very long waiting times before any actions were taken to get the system back to normal state were considered to be most important to reduce. This was found especially around the braiding machines and also in the station where the threads were coloured. In the area of the 72 braiding machines the waiting times were more than 90% of the total DT. Tests were carried out with new working schedules for the personnel to improve the output. To show the status of the machines “Andon” were also suggested. “Andon” is signal signs for easy check of the status of the machines, e.g. working or not working.

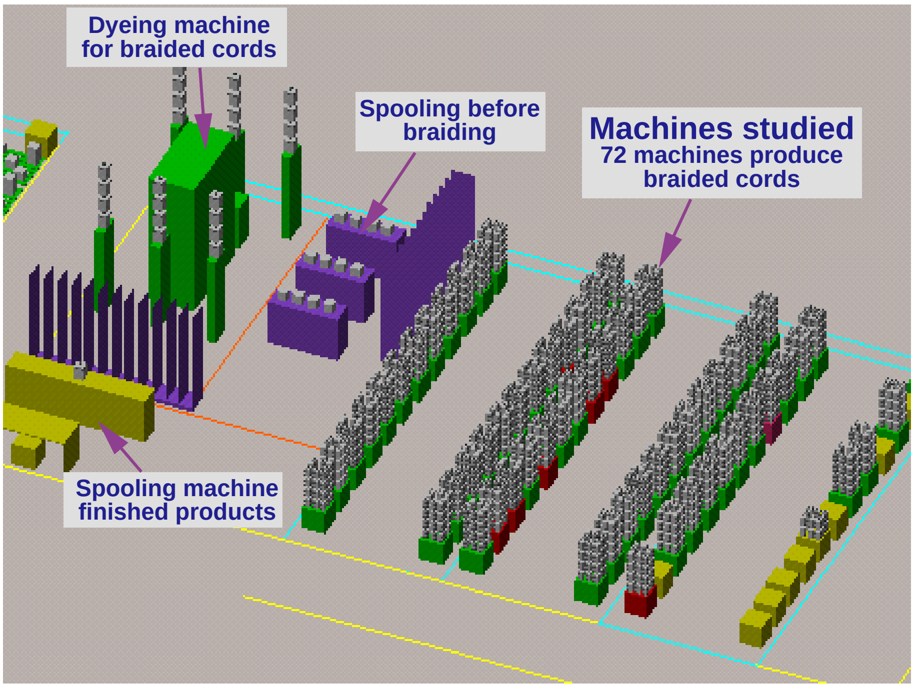

Figure 2: *Layout of case study no. 1. Experiments were carried out with parallel set-up of two machines simultaneously in the section to the right with 72 machines.*

The DES working method made it possible to see what was changed when one disturbance was removed. One cause of disturbance was deleted in the simulation model and the simulation model was then tested again. The results were also confirmed in real-life tests. When parallel changing was introduced it showed an improvement of 18% of the time available for production. The working method showed a good correlation between the model and the real system, the deviation estimated by the author to less than 10%.

The colour machine had a long set-up time, approximately two hours. This combined with the overall demand for the company of reduced lot sizes made it interesting to work with set-up reduction. If the set-up time was reduced by 50% to one hour instead of two hours, the corresponding lot size could be reduced by half with equal total output and comprising much smoother production flow. The company goal to reduce WIP (Work In Progress) also co-operates with the proposal suggested.

Results and conclusions

A conclusion of case study no. 1 was the ability to increase output with non-expensive means. The potential was proven in the DES model before it was implemented in the manufacturing line. A change in work order, parallel changing of two machines at the same time, improved the results. The importance of the operator's knowledge was also a key issue. Interviews with the operators at the manufacturing cell gave valuable information. The current system for collecting production disturbances was suggested to be replaced with a more active system. The vibration indicators enabled real-time measurement. The case study showed that by easy means, e.g. different working routines and preventive maintenance, improvements could be made with cost-effective means. The potential in the case study to increase output was shown to be 18%, which is a considerable advantage on the use of existing machines and equipment. An effect of this study was beside the actual simulation model that issues around the manufacturing line were raised and discussed.

4.2 Case Study no. 2

The company in case study no. 2 manufactures forklift trucks for warehouses. The company has been expanding in volume during a longer period and at the same time with continuous growth in profit. Investments in new production equipment have been extensive to keep pace with increased production output. Production is based on customer orders with flexible manufacturing techniques. The components produced in the studied cell of the case study consisted of two main articles of frames. The fabrication of these frames was divided into some standard lengths and many customised lengths. The system is operating 24 hours a day, 5 days a week and also on two shifts on the weekend. The potential to increase working hours is limited mainly due to the costs with more shifts. Time must also be allocated on the week-ends for example preventive maintenance. This means higher production by increased manning is limited.

The model was partly imported from a larger model previously built at the company. The manufacturing cell was identified as a bottleneck in the overall system studied. The model was updated and modified with alterations included in the station to get it to work like the current existing real-world system. Input data, automatically logged from the PLC system were not adequate for disturbance studies. Only breakdowns and stops more than 15 minutes were logged in this system and all minor stops were missing.

Manual logging was carried out by the author during a week to observe production

Table 3: *Measured data in case study no. 2.*

Cause of production disturbance	Number of measured stops, weekly average	Measured minimum DT per stop (hrs:min)	Measured maximum DT per stop (hrs:min)
On-line programming	4	00:51	02:42
Waiting	21	00:01	00:42
Welding process	16	00:01	00:27
Miscellaneous	6	00:01	00:16

disturbances and to obtain a thorough overall view of the system. The manually logged data combined with interviews were the basis for input data modelling. See Table 3 for an overview of the measured data. The layout of the model is illustrated in Figure 3. The average tact time per frame is 34.3 minutes when the measurement started. To indicate the potential with the case study, in an idealistic state with no disturbances at all the tact time should be as low as 17.0 minutes per frame.

Production disturbance reduction

Different proposals in various areas were suggested to the company to improve the productivity of the station. The model showed that the main production disturbances were concentrated to a combination of long downtime disturbances and also shorter ones related to the welding process. As shown in the previous case study another potential can be achieved by changed organisation and improved preventive maintenance. For example was a new routine established to always have a queue of tacked frames in front of the robot cell. The idle time of robots could by then be reduced. The outcome of increased productivity is so significant that it may delay investments in new production equipment.

The main ideas to be implemented in the studied cell were: off-line programming of the station, all on-line programming moved from planned production time or changed preferably to off-line programming; an increased use of unmanned production; and implementation of TPM in the welding process. The system directly showed an improvement of the time available for production and smoother production flow when on-line programming was removed.

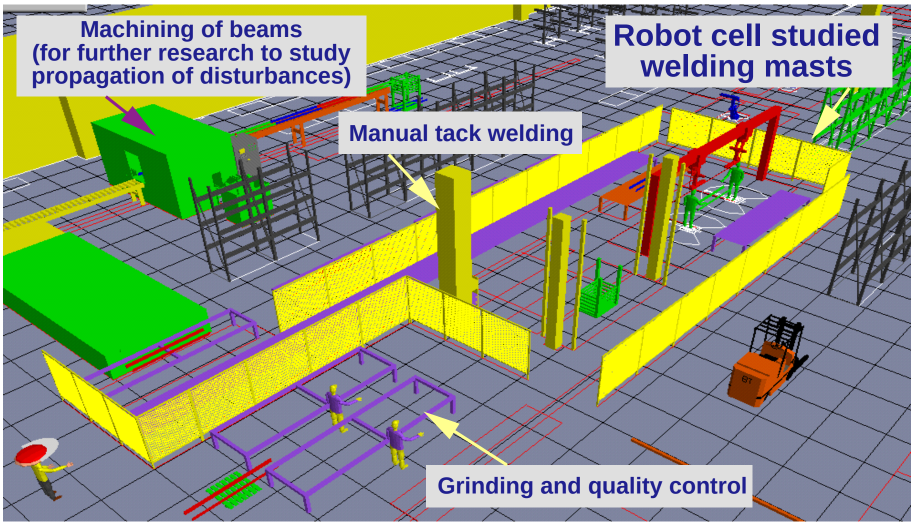

Figure 3: *Layout of case study no. 2. The efficiency of the studied robot cell was improved. Both longer (online programming) and shorter disturbances (due to the welding process) were reduced.*

Results and conclusions

The DES model in case study no. 2 showed that the key issue was to increase the use of the robots in the welding cell. It was the main bottleneck in the station during the step by step alteration phase in the DES model. There should always be a queue of tack welded frames in front of the station. In the most advantageous case there should be a finished tacked frame on each buffer ready for further transportation to the buffer in front of the robots for immediate action. To release the operators working load around the station some additional buffers may be added.

On-line programming is time consuming and disturbs the cell as well as other functions linked in the production chain. The interrupts propagate further down in the manufacturing chain, e.g. painting and assembly. If off-line programming is introduced, a new human resource, off-line programmer has to be allocated to handle the new system. This new resource allocated should be included in the overall cost of the station. However, this should be compared to the savings due to the current on-line programming in a cost-benefit analysis. The cost effectiveness of the new resource will in this case be considerable.

Principal result from case study no. 2 was an improvement of 14% of time available for production which was verified in shop floor tests. The tests showed a correlation between the DES model and the real system, the deviation approximated by the author to less than 10%. The most important conclusions from both case studies are to consider the long waiting times. The waiting times appear before action is taken to remove the actual cause of the disturbance. The best measure is to eliminate the disturbance and the second best is if the disturbance still occurs, to keep waiting times to a minimum. Another problem to consider when a disturbance has occurred is the way back to a normal state. There may be quality problems and also risk for new production disturbances during the ramp up phase especially for the welding process.

5 A Method for Production Disturbance Reduction

5.1 Steps in a Simulation Study

One of the most well-known descriptions of a DES study is introduced by Banks et al. (1996). The comprehended steps are described in this section, see Figure 4.

Identify system suitable for DES. The first step is to identify a system suitable for DES with dynamic variations or complex interactions. If the system is not appropriate to be solved by DES the case should therefore be transferred to be settled by easier means. Another angle is the cost and benefit analysis. If the cost for the study exceeds the expected long-term results a simulation study is not the correct approach.

Input data collection - conceptual model. The conceptual model describes all necessary parameters needed in the simulation model. It will also gain the actual model building. Advantages seen with the working method are that is easy to revert back and check all background data either when the model is built or at a later stage when the model is revised. It is considered to be normal to revise the model in several stages.

DES modelling. When the conceptual model is concluded the modelling phase of the system starts in the DES program. Verification and validation of the model are also important steps to take under consideration for a reliable output. If the input parameters and logical structure of the model are included, verification has been completed.

Result Analysis. Experimental design is carried out for different alterations in the model. A thorough testing period and sufficient number of tests of each scenario is recommended. An output analysis is also suggested. The results and their confidence intervals assure the exactness of the model provided that the input data and the different connections in the model are correct.

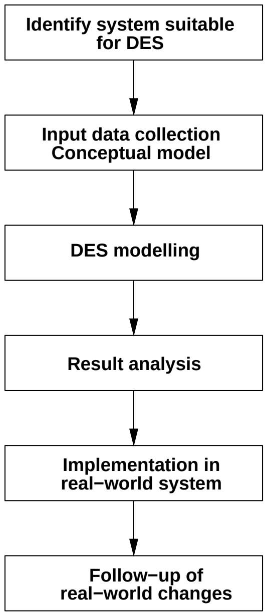

Figure 4: *Process of a DES of a manufacturing system project according to Banks, 1996.*

Implementation in real-world system. When all meaningful output data have been examined, an output result analysis can be concluded for implementation in a real-world system. The success of implementation in the real-world systems depends on how well previous steps have been performed.

Follow-up of real-world changes. As a final step in Figure 4, the implemented changes in the manufacturing system are monitored to see if intended results are fulfilled. This is also feedback to future models built in DES. The length of the monitoring phase can be discussed, but the longer the better. The changes in a steady-state manufacturing system are stabilised in the system after some time depending on which system studied.

5.2 Definition of the Methodology

Disturbance reduction in a system can be comprehended in different steps in a simulation case, see Figure 5. There are three main functions included in the method: First, in the beginning there are the data necessary to study for the causes of disturbances in manufacturing systems. Second, in the modelling and result analysis phases there are the tests of different alternatives to detect the differences

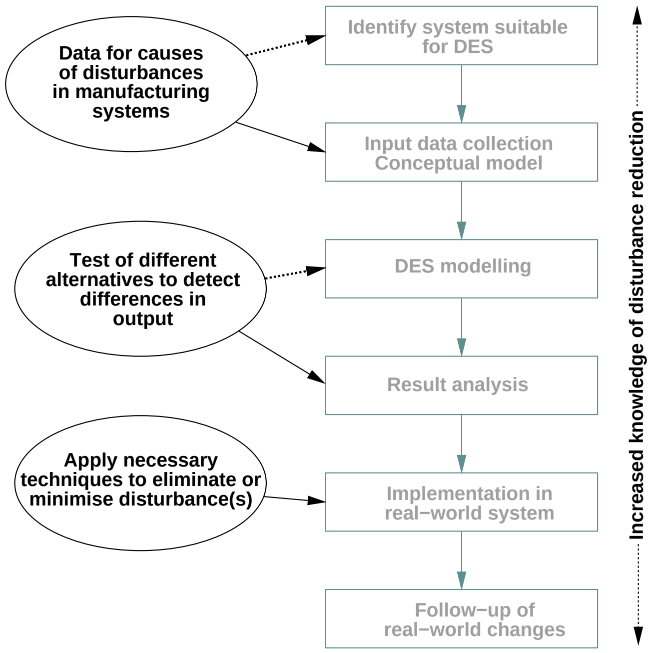

Figure 5: *Method of reduction of disturbances by using DES. Three main functions are combined with the DES process. An overall effect is the increased knowledge of disturbance reduction in the organisation.*

in output. Last, in the implementation in real-world phase of the model it is vital to apply necessary techniques to eliminate or minimise disturbances. This is all combined with continuous loop of improvement to keep the method up-to-date.

Data for causes of disturbances in manufacturing systems

The first important issue, see Figure 5, is the background data. In the input data collection phase different reasons and backgrounds for problems with the manufacturing systems are in many cases brought up for discussion by different groups in the organisation. Experience from field studies by the author shows that awareness of disturbances is not satisfactory in many companies. At the same time as input data are collected there is an educational phase to explain the different causes of disturbances. A discussion in co-operation with all involved parties can, before the simulation is built, show a significant improvement of overall productivity of the system. If the total efficiency of a manufacturing system is to be increased the training of the staff in several steps are to be included. The training may include bottleneck analysis, the value of implementation of TPM, smoother production flow among other things. The increased knowledge of the staff will itself be a valuable element in the overall improvement of the manufacturing system.

An important factor to take under consideration is the error in measurement of input data. If there is a lack of input data there is often a need for additional manual data collection. Collection of manual data has the advantage that one learns a great deal of the actual manufacturing process, the behaviour of disturbances and at the same time obtains many ideas how to improve the system. The disadvantage is that normal working routines can be affected in and around the manufacturing cell by the observer. As shown in the case studies waiting time is a considerable amount of the downtime of a process. Sometimes the operators prioritise the machines differently when a manual study occurs and the waiting times are reduced.

Test of different alternatives to detect differences in output

The second ellipse in Figure 5 is about tests in the DES model. The consequences of different alternatives and the availability to delete one or several disturbances could be easily altered in the model. This makes it advantageous to combine disturbance reduction studies and DES. It is important to simulate different scenarios with alternative variables after validation and verification and document these as a subject for discussion for alterations with related personnel for later changes in the real-world scenario.

Either one or several groups of disturbances can be deleted and the increase in output can be measured. The cost of decreasing disturbances should also be taken into account during the experiments. In many cases, as shown in the presented case studies, non-expensive measures can be taken with good results.

Apply necessary techniques to eliminate or minimise disturbance(s)

The amount of disturbances has to be reduced in the real world too. It is suggested to change one thing at a time. Some alterations could cause unwanted problems. If the changes are implemented slowly there is always a possibility to revert back one step. When changes in the manufacturing system are implemented it is also suggested to increase monitoring to see the actual system's behaviour.

The system with step by step alteration was also used in the industrial case studies presented. It proved to be a good way to follow the changes that affected the output of the manufacturing system. With this method it was also easy to see and understand changes of total output as well as different working conditions for the staff. It was also shown in the case studies that incremental changes of the system were a successful way of knowing what adjustments that were actually made.

Increased knowledge of disturbance reduction

Increased knowledge of disturbance reduction is also included in the process, see Figure 5. Parallel with all other activities there is the teaching and training phase. The new knowledge of the staff related to the manufacturing system could itself provide good results. An important overall effect when working with the method is the increased knowledge of disturbance reduction. The organisation is more aware of the concept of disturbance reduction. Often there is a new awareness of the efficiency of manufacturing systems.

5.3 Continuous Improvement of the Method

The continuous improvement loop of the model is also shown in Figure 6. The implementation of changes according to results in the model will lead to the manufacturing systems to react in a different way and with improved efficiency. Experiences from implemented results need to be fed back into the system both regarding disturbance reduction in real life and simulation building suitable for the working method both of how to implement alterations in a system and in the discrete-event simulation build-up phase. The manufacturing system itself can also be improved, for example when a new system is purchased, if the knowledge of disturbance reduction is increased.

Developing manufacturing systems is a complex task in itself. Therefore it is of importance to keep up with the latest development. Automatic disturbance logging seems in the longer run to be incorporated in the PLC system. This may facilitate the input data collection phase if the disturbance data are classified in relevant categories from the beginning. There are some ongoing projects by the author at Swedish companies that connect PLC system and DES, which will be further evaluated.

5.4 Experiences from Case Studies

The two case studies presented were performed with the actual method in mind and the results from the case studies showed an improvement in output of 14-18% within reasonable significance. This indicates that the combination of DES and disturbance reduction is suitable and will result in improvement of productivity.

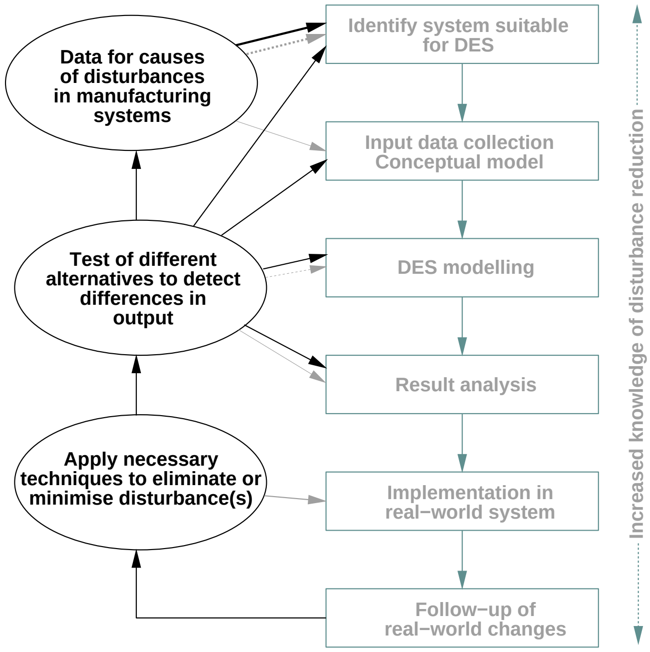

Figure 6: *Experiences from disturbance reduction and DES model building from implemented results need to be fed back into the system for continuous improvement of the suggested method.*

There are always uncertainties and the figures should be used as estimation. The results depend on various issues such as input data collection, model building, model measurement and implementation in the real-world system.

There are different alternatives to evaluate when disturbances are completely removed, reduced or changed to detect differences in output. The results from the model are then implemented in the real manufacturing system. Changes are made in small steps to see the dynamic effects of the alterations in the system. An important issue is the feedback loop that facilitates a continuous improvement of the model. New findings mainly in the real-world manufacturing system are reverted back in the DES modelling environment to achieve best possible results.

The step by step alteration technique presented proved to be useful. Most important are the problems regarding input data. In a case study, companies often have a tendency to think they already have all relevant input data readily available. The fact is that there is often a data collecting system available but seldom the data are adequate enough for direct input in the simulation model. Some data can be used supplemented with manual data gathering. The manual data gathering is time consuming but have advantages as well. It is an opportunity to learn more about the studied system and give input to the analysis as well.

Other issues to take under consideration are the staff's experience to implement the relevant working conditions in the model. Estimated data are in most cases inevitable and the know-how of the personnel is invaluable. Verification and validation and output data analysis have helped to achieve the best possible model and results. The DES projects have been simulated in steady-state simulation environment as the case studies work with the same products over a longer period.

6 Discussion

The objective of the study was to find and use a suitable method for disturbance reduction in a general manufacturing system. The potential of reduced cost is substantial when working with increased overall efficiency due to reduced production disturbances. There is a constant need for a company to improve profitability in a competitive international environment. A combination of a DES scenario and the real-life implementation makes it possible to achieve increased efficiency in a manufacturing system. The idea behind the proposed methodology is to have a useful technique and to apply it in a real-world scenario. The simulation program enables different experiments in production disturbance reduction in an excellent way.

Advantages with this proposed working method of disturbance reduction in a manufacturing system combined with DES could be mentioned as an efficient way of taking control over the system. The issue of documenting and follow-up of relevant data from the manufacturing system now and in the future is also raised. The manufacturing cell will bring up knowledge of the availability of the manufacturing system, documentation of production disturbances and explanation of the background reasons of why different disturbances occur in the system.

The outcomes of the case studies showed the potential for improvement in manufacturing systems. Different work order, without any new major investments, made it possible to increase performance of both case studies significantly. The results of the case studies and their accuracy can be further discussed. For the simulation model the output is dependent on the input data required. The measurement itself of input data on the shop-floor affects the values. Especially in case study no. 2 with manual measurement by the author, it was possible to see a production increase during the measurement period. It is suggested to minimize these errors in case studies with automatic input data collection.

The input data collected were tested in chi-square tests for assessing relevant distributions. Both in-house calculations and commercial software were used. The different distributional assumptions were rejected in both case studies and the method of empirical distribution was chosen for the different categories of production disturbances in the DES models. Practical experience shows the difficulty to transform measured values to distributions. The lengths of simulation runs were one year or longer to achieve best possible precision. The comparison of the DES models to the annual production data shoved a deviation of less than 5% in the DES models.

In the DES models a simulation output analysis was carried out. One of the main points with the performed case studies is the improvements in the models were implemented in real-life. The improvements should by no means be considered as exact values, rather an indication of the potential. The figures mentioned are approximate and the end results according to the authors' estimation may be deviating less than 10% in both case studies. However, the potential is shown to be considerable for production improvement.

Important issues to take under consideration are when working with this method: The time consumed of a simulation project is often underestimated. With parallel activities some time can be saved but if one single piece of input data is missing the model is inadequate to draw any relevant conclusions from. Input data are seldom directly accessible in a simulation study. The last missing data are often the most hard to obtain. In many cases approximations have to be used, e.g. maximum and minimum values. In real-world case studies time and cost are the determinant factors. Measures for improvement of manufacturing systems have to be taken in a short period of time and can in some cases be vital for a company's future existence. Quality of the DES model should, however, not suffer any loss due to lack of time or money.

An important issue to consider is the transformation of events from reality as input to the simulation model and how such events should be represented. Every data record measured must be included and issues such as disturbances are seldom fully considered. It is regarded to be extremely important to cross-check input data. The output data as a result from the simulation is directly linked to the input data. If not enough relevant data is put in the simulation model from the beginning, relevant output data are not obtained from the simulation model either.

Target group for application of the proposed method is production engineers. Today's DES software indicates, however, that it is more or less necessary to work continuously with the program to benefit from the features included. This is easier achieved in larger companies where a specific resource can be allocated.

DES software should benefit if applied with a better user interface.

In the simulation model the system is illustrated in a way that all personnel can understand, without any comprehensive background knowledge of production systems and other techniques, of the actual building and function of the model. The easiness to change different parameters such as the different disturbances is a powerful feature. Within a short notice after the change the results can be shown. A long period of time can be compressed and the dynamic propagation of disturbances can be shown not only in one but several cells or even as far as in a whole company or even further in a longer supply chain.

7 Conclusions

The method described showed an increase of overall output in two industrial case studies of 14% and 18% and is shortly described as follows: When all relevant input data are collected, tests of different alternatives can be implemented to detect changes in output. Based on the experiments and results from the simulation models, necessary measures to minimise or even eliminate disturbances can be carried out and increase overall efficiency. The implementation in the real world is based on the results in the simulation model. Changes in the real world manufacturing system are done in small steps according to the simulation model. Other possible not previous foreseen alterations are at the same time verified in the DES model to prevent any unforeseeable changes in the real-world system. Significant gains can be made by non-expensive measures and increased understanding for the related problems is important for successful improvements. Training of the personnel may be the key to increased overall efficiency for the company. The presented work shows the need of powerful tools such as DES combined with knowledge of disturbance reduction. This combination will enable results in increase of total output if it is applied.

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Paper III

Increasing performance efficiency in manufacturing systems with production improvement techniques and discrete-event simulation

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Abstract

DES (Discrete-Event Simulation) is a tool for better understanding of manufacturing systems. When a simulation model is built, the key values shown in the model enable the user to draw adequate conclusions about the system. To achieve best results, production improvement techniques should be implemented in the analysis. TPS (Toyota Production System), TPM (Total Productive Maintenance), SMED (Single-Minute Exchange of Die) are all production improvement techniques. OEE (Overall Equipment Effectiveness) with its components have shown to be a suitable measurement method of a system. The components of OEE are availability, quality rate and performance. Several case studies have investigated a combination of DES and production improvement techniques of a manufacturing system. When combined with adequate production techniques the potential to improve a system is beneficial. Three case studies improved the performance of the manufacturing system by 6, 14 and 18%, respectively, using the combination.

Keywords

Discrete-Event Simulation (DES), Production Improvement Techniques, Manufacturing Systems, Productivity Improvement

1 Introduction

There is a need to establish a procedure to increase performance in manufacturing systems. A company needs to maintain or preferably increase productivity in a

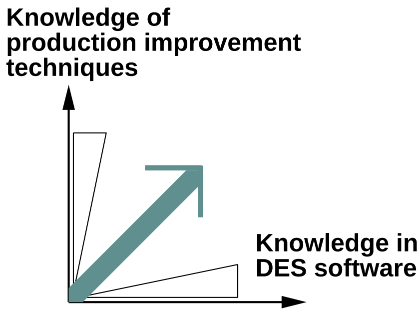

Figure 1: *The combination of production improvement techniques and the DES tool is beneficial.*

system. The continuous improvement process is necessary to stay competitive. Studies from advanced manufacturing systems have shown that the OEE is as low as 50% (Ericsson, 1997; Blanchard, 1997). Production disturbances affect OEE, as well as the overall production efficiency during the life cycle of a manufacturing system. The disturbances may affect product quality as well as work safety, work environment and satisfaction of workers.

It is suggested to combine the two disciplines DES and production improvement techniques, see Figure 1. The figure indicates there is a tendency to be skilled in only one of the disciplines. The manufacturing system will benefit from more integration. When the DES model is used together with adequate production improvement techniques it may yield in improvement of the manufacturing systems.

Flexibility in the systems has also attracted more and more attention. The systems should be designed with production capability and routing alternatives in mind. The inflexible structure of many manufacturing systems does not work with the rapid technological change and challenging market demand (Wu, 1994). A more multidisciplinary approach of the design and performance improvement is desired. Often there are little or no difference in the products put on the market by competitors and therefore product price and time to market are variables to achieve success for a company. Thus, manufacturing systems that are able to address these issues put a company in a better position than those that do not.

2 Design of Manufacturing Systems

From an operator's point of view, automation of a system often means that the most important work tasks disappear (Kidd, 1995; Bainbridge, 1983). The remaining tasks are often characterized as more supportive and could be activities such as filling up material and handling production disturbances. The problems can also be aggravated by a poorly designed HMI (Human-Machine Interface). The introduction of sophisticated computerized systems has in many cases led to tighter connection between human and machine instead of the opposite as was intended. The issue, which needs to be addressed, is why technology is designed in such a way to produce unsatisfactory work conditions. The work task has been given to the robot and the job of the operator has become unskilled, trivial and machine-paced.

The production system is much more than the equipment (Brödner, 1991). The system also includes the work force, its skills, the allocation and the sequences of working tasks. The relations among all these elements determine the performance of the production. The combined resources of technology, work organization, and skill profiles must be well suited to each other. The principle of "organization first, technology second" is also asserted. The development and use of technology is the result of social relations and interests that set the conditions and objectives under which technology develops.

3 Techniques for Improving Manufacturing Systems

There are many production improvement techniques. Some of them are used in the case studies presented. The methods have been established by some of the most profitable companies worldwide.

3.1 Lean production

The trend towards flexible manufacturing, shorter lifetime for the products and a shorter product cycle has shaped new ideas in manufacturing. Lean manufacturing is one of the most significant trends in the last decade that have had a large impact on design of manufacturing systems. Womack, Jones & Roos (1990) have in their study of the automotive industry described the difference between mass and lean production. Mass production consists of interchangeability of parts, simplicity of attaching them to each other, marketing and management techniques. Lean production, on the opposite, focuses on small batches, mistakes to be shown instantly, a continuous and incremental improvement process called "kaizen", five why's, supply chains and JIT system utilizing for example Kanban. In short, the Kanban system is an information system that controls the production quantity in every process. In many cases, the Kanban system handles the JIT production method.

Table 1: *The potential of lean production, figures are indicative (based on Womack and Jones, 1996).*

	Batch-and-queue	Lean
Production time	100%	10%
Inventory	100%	10%
Quality		Superior
Time-to-market		Shorter

The truly lean plant transfers the maximum number of tasks and responsibilities to those workers actually adding value to the product on the line. Furthermore, it has in place a system for detecting defects that quickly traces every problem, once discovered, to its ultimate cause. The automotive industry has been in the front line of lean manufacturing and lean product development. The change of a company in the direction of lean thinking is a long, time-consuming process stretching over many years. It can only be achieved if an overall approach is taken to completely transform the company. However, benchmarking and observations around the world have shown the following astonishing results: converting a classic batch- and queue production system to continuous flow by the customer will double labour productivity throughout the system including all involved personnel, direct and indirect (Womack & Jones, 1996). The production times are typically cut by 90% and reduced inventories are also reduced with 90%. At the same time quality improves and time-to-market for new products shrinks. The potential is summarized in Table 1.

3.2 The issue about highly automated manufacturing systems

Highly automated manufacturing systems are also called monumental ditto (Womack & Jones, 1996). Huge investments in automation and equipment may require production in batch mode. There are various examples when machines have been replaced with more inexpensive and flexible equipment. Because of continuous improvement and change of process requirements require movements or altering of machines, “monumental machining” is another form of waste. Automation of a manufacturing system is often associated with a financial risk. There is a risk especially for smaller companies of financial instability when investing in expensive FMS (Flexible Manufacturing System). It is suggested to develop a manufacturing strategy (Archer, 1984). The shorter life cycles and demand for quicker time-to-market of products may mean that there are other alternatives to new production capacity than investing in highly sophisticated manufacturing systems.

3.3 Supply chain management

Certain trends can be noticed in the area of supply chains and are described as centralization of production units, lead-time reduction, more outsourcing and the content increase in the products. This is normally shown by modularization and augmented functionality. The suppliers' role is widened from only pure manufacturing to other areas, e.g. distribution logistics and design (Mattsson, 1999). There is also an overall change in the market towards shorter and shorter product life cycles. The more different competing companies in the area and the longer backwards from the product market the more difficult for the company to react on the changes and the shorter time is available for any reaction. Production disturbances in manufacturing systems can partly describe the current need for inventories. No facility can fully rely on the production system and products are piled up in advance in different places. Especially in the multinational companies the trend during the last decade has been to produce leaner and leaner with reduced stocks. Combined with globalization and an outsourcing trend has resulted in more semi-finished products to be shipped to different production sites across the globe.

3.4 Toyota Production Systems

Among the most competitive manufacturing systems in the world is the TPS. Many elements in their production systems have been spread around the world as state-of-the-art of manufacturing. The principal consideration is to reduce costs by completely eliminating waste in different dimensions (Monden, 1998). Waste can be found in production operations as excessive production resources, overproduction, excessive inventory and unnecessary capital investments. This has to fit together with the three other sub-goals: quantity control, quality assurance and respect for humanity. All these items together constitute TPS.

Overproduction is a result of continued work when essential operations should be stopped. Excessive inventory allocates resources for more manpower, more equipment and more floor-space both for transport and stock. One of the basic concepts in the Toyota Production Systems is “Kanban”. The main idea is to take control of the material flow and to smooth the production flow by using physical cards. Demand variations of around 10% can be handled by changing only the frequency of Kanban transfers without changing the total number of cards. Kanban should be used to adapt to small fluctuations in demand like fine-tuning of production.

3.5 Total Productive Maintenance

TPM is a concept to get a wider perspective of the maintenance function. The idea is to shift the responsibility for maintenance from a separate department to include all employees. Like TQC, TPM is maintenance of equipment performed on a company-wide basis. The main goals are zero breakdowns and zero defects. Maintenance depends heavily on human input and TPM involves total participation of all staff. If maintenance and design engineers cooperated more to close the gap between maintenance and design technology much waste can be avoided (Nakajima, 1988).

The future of competitive manufacturing is probably more oriented towards human-integrated production. The basic requirements for world-class manufacturing are to be outstanding in applied research, production engineering, improvement capability and detailed shop-floor know-how involving good maintenance and to integrate them in a system.

3.6 Single-Minute Exchange of Die

SMED (Single-Minute Exchange of Die) is a technique for setup time reduction (Shingo, 1985). No setup times are under any circumstances allowed to take more than 10 minutes according to the method. The stages for the method can be summarized as: distinguish different types of setup, separating internal and external setup, and converting internal to external setup. It is a continuous process and improvements can be made under all circumstances. There are various examples when setup time has been reduced extensively and made it possible to reduce lot sizes, WIP and total production times. The potential to cut setup times is substantial in all manufacturing systems.

4 Overall Equipment Effectiveness - Measuring Performance in Manufacturing Systems

How well a manufacturing system performs can be measured in terms of production rate, quality, time, cost and flexibility. Manufacturing systems have up to today been built much on empirical experiences. In today's complex manufacturing systems, there is a need for a more academic and systematic approach. A systematic model could eliminate problems earlier. Increasing production rates have been the industry focus for many years. OEE (Overall Equipment Effectiveness) is a suitable measurement tool for manufacturing systems and is especially suitable for semi- and automated systems as it describes the efficiency of the flow or equipment. The main components of OEE are availability, performance efficiency and rate of quality products.

A primary goal must be to reduce the time of production disturbances and especially downtime losses as it is the main component of reduced performance in a system. Downtime is a component of the availability formula. This is without doubt the easiest way to increase overall performance for manufacturing systems. Quite surprisingly, the figure of OEE has not improved over the years according to the authors' experience. The question to be answered is why an overall improvement has not taken place in spite of all new powerful tools and management techniques. One explanation may be that at the same time the number of variants have often increased in the same manufacturing line. The ability to measure production disturbances has, however, increased especially among larger and some medium-sized companies. All tools to document production disturbances are there and a more systematic approach will help to increase the overall efficiency.

5 The Use of Discrete-Event Simulation in a Manufacturing System

There are several positive reasons for using DES in improving the performance of a manufacturing system. Advantages compared to other tools are: first, the issue of production disturbance reduction as a subject. The effects of production disturbances can be clearly shown in the model as the visualization is an eminent feature. It is also easy to see the results of different changes in the model. An example is the possibility to change and experiment with known production disturbances, for example preventive maintenance. Second, key figures from the model can easily be obtained, more balanced material flows can for instance be designed with the help of DES. Third, a decision has to be taken regarding key figures such as cycle times and connection of logics. Forth, different production improvement techniques can be tested before they are applied. Finally, the model is useful for educational purpose for all kind of personnel. Disadvantages may be the possibility to miss human aspects, as for example information flow and improvement work. It is not always easy to represent the real world in the model and there are different issues regarding input data as well as validation and verification. To achieve best results, knowledge of production improvement techniques is also necessary to apply.

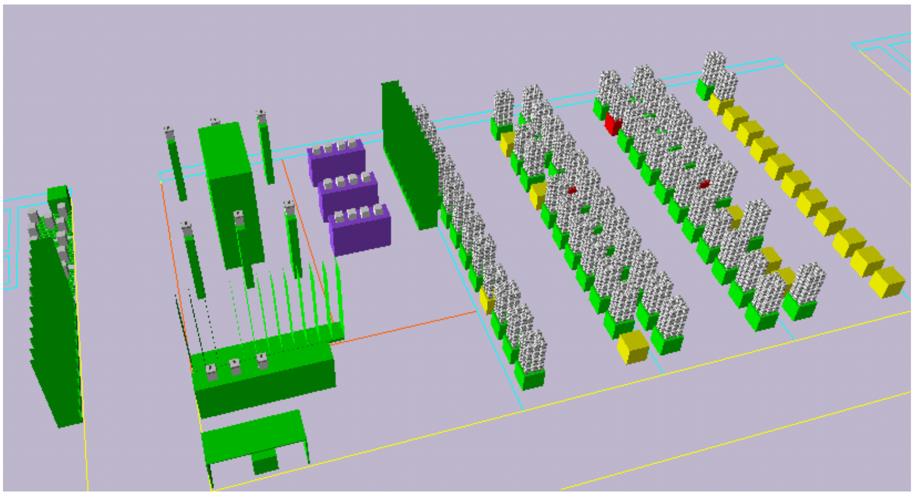

Figure 2: *Case study no 1, setup reduction with parallel changing.*

6 Case Studies

Three case studies are described together with their production improvement techniques. DES was used together with the mentioned methods. This gave the opportunity to evaluate and check the changes before they were implemented in the real world. The manufacturing systems and its logics and measurements were considered. A great effort was made to achieve relevant input data. The new changes in the simulation models were implemented by step by step alteration. Some of the production improvement techniques were used implicitly; lean production, buffers and batch production were avoided whenever possible, TPM, TPS and supply chain management methods were also applied.

6.1 Case study no. 1: Setup reduction with parallel changing

In case study no. 1 the company produces equipment and machines to the window blind industry. A DES model was designed with the objective to increase production and reduce the long waiting times among the 72 braiding machines, see Figure 2. SMED (Single-Minute Exchange of Die) was suggested as working method for production improvement. The method indicated that there where time to save by setup reduction, or more exactly, to reduce the time of changing between the same types of products. However, the SMED method can still be used as the principles are the same.

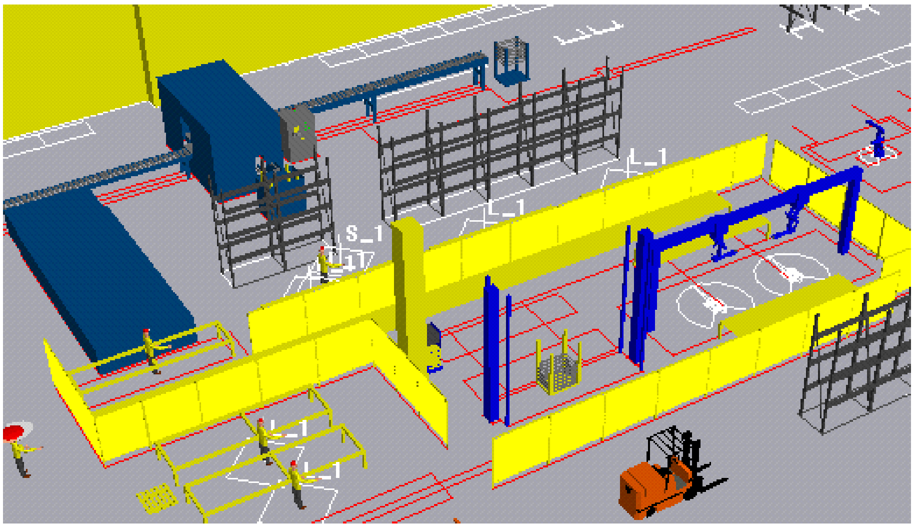

Figure 3: *Case study no 2, improvement of material flow in a DES model.*

It was observed that the machines were often waiting for some action to be taken, especially when the machine was full and new materials have to be loaded. One way of time reduction for setup was to change two or more stations at the same time. Parallel changing of two stations was suggested as an improvement method. The DES model experiments were carried out and the results showed a performance improvement of 18%. The simulation results were then verified by real tests. To go further, experiments were suggested by the authors to investigate the effects if three or more stations were changed at the same time.

6.2 Case study no. 2: Improvement of material flow

The company in case study no. 2 manufactures forklift trucks for warehouses. A manufacturing station that welded frames was studied, see Figure 3. The material flow of products tended to be irregular to some extent. Parts of the ingredients of TPS, (Toyota Production Systems) were implemented. TPS main components are quantity control, quality assurance, and respect for humanity. TPS is also adjusted to lean production which was a method that already was utilized in the company.

Improvement activities were concentrated on achieving better material flow in the robotic welding station. There should always be a queue of frames in front of the robots ready for welding as it was considered the main component of performance improvement. Different proposals for decreasing production disturbances

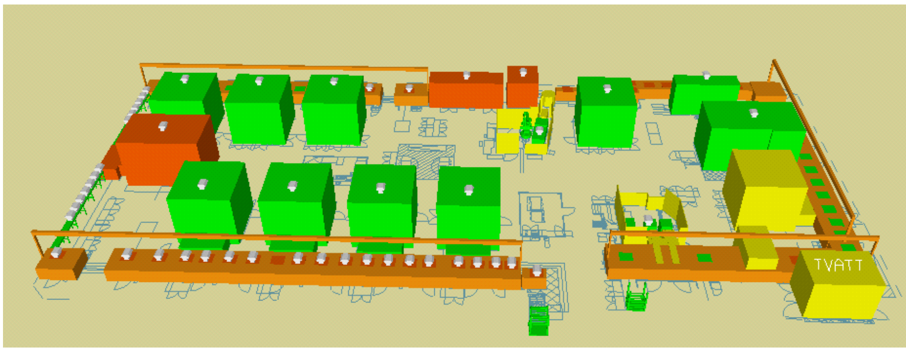

Figure 4: *Case study no 3, bottleneck analysis and DES.*

were also suggested. The implementation of decreased waiting times, eliminated on-line programming and more stable process showed an increase in the model of 14%. Some of the measures were implemented instantly and gave a reliable correspondence with the simulated DES model. New methods of seam track welding were also suggested as way to decrease shorter production disturbances in the welding process.

6.3 Case study no. 3: Bottleneck analysis

The company in case study 3 manufactures engine blocks to the automotive industry. The manufacturing line consists of 11 numerically controlled machines and six other types of stations. Automatic data collection from the machines was used as input data to the simulation model. Bottleneck analysis was utilized as the production improvement method. The DES model helped to identify the bottleneck in the system. A manual study was carried out to further investigate the background reasons to why the bottleneck occurred. Then different proposals were suggested for improvement, for example improved tools.

An example of the potential of possible improvement is described: The DT was reduced by one third from 22.5 to 15 hours a week in one single machine. This was accomplished by reducing the tool exchange time by 50%, which was a feasible task. Availability increased in the same machine from 58.5% to 60.2%. The first initial test of bottleneck analysis resulted in a performance improvement of 3%. The decreased amount of DT will also enable smoother production and better working conditions as well. Two concluded together with one ongoing bottleneck analyses have resulted in an overall performance improvement of 6% one year later. The model is illustrated in Figure 4.

7 Discussion

In a case study it is an idea to combine DES with the adequate production techniques to achieve best possible improvement. The model is needed to be according to all rules with necessary input data and logics. A method of reduction of production disturbances by using DES has been described (Ingemansson & Bolmsjö, 2004). Three different steps are suggested. First, the data for production disturbances have to be collected. Second, tests of different alternatives have to be carried out in the DES model. Third, those improvements have to be applied in the real world. Among other benefits is increased knowledge of production disturbance reduction in the organization.

However, a case study also includes different production improvement techniques. By using appropriate techniques the potential increased significantly to improve performance efficiency in the studied manufacturing system. It can always be a discussed whether the most appropriate production improvement method was chosen in each case study. To the author's knowledge, there are some rules but the more important is that any technique is chosen. The company often has some production philosophy guidelines and it is suggested to apply them accordingly.

The different production improvement techniques are overlapping. The specific method used in each case study is combined with the more general methods. An attempt to relate the used techniques to the more general ones is shown in Table 2. In each case study there are various other methods utilized, some of them more implicitly. For example a technique as TPM is involved in all case studies but to a lesser extent.

Systematic design of manufacturing systems in all parts is rarely seen. Systems are often built in different steps without any extensive strategic planning. In general, only near-time planning is considered for new future products in the same product family and for production capacity increase, e.g. new parallel stations. Many manufacturing systems tend to be considered as "patchworks" built in different sections at different times. There is a need to find more systematic approaches and techniques for overall design of manufacturing systems.

One proven way is to decompose the manufacturing system into subsystems of more manageable sizes. It is of vital importance to dedicate resource requirements for layout design, material handling and production planning subsystems. An overall framework at system level with particular emphasis on system analysis, design and methodology is suggested (Wu & Ellis, 2000). Manufacturing system design specifies physical, human, organizational and finally information and control architecture as principal areas of manufacturing systems design.

Table 2: *The techniques utilized in the case studies are subsets of more comprehensive techniques.*

Case study	Improvement method used in case study	Production philosophy
No. 1	Setup reduction	SMED, TPS, OEE
No. 2	Improvement of material flow	Lean Production, OEE
No. 3	Bottleneck analysis	Lean Production, OEE

In either case study there were any major investments involved. All the studies have shown by non-expensive means that there is a potential to increase overall performance output. However, in all case studies the main cost has been engineering time. This time has been used for data collection, simulation, analysis and implementation of the improvements.

The performance of a manufacturing system is to some extent settled when the actual system is built. More effort should be added before the actual building of the system. Many systems today are highly sophisticated. Actually they have been so complex that some are too automated. A system that functions well will serve as the basis for manufacturing of quality products. System reliability, maintainability and dependability are key factors in influencing customer satisfaction. With the suggested method, efficiency improvement can be achieved both before and after the system is designed and built.

8 Conclusions

The combination of production improvement tools and DES is beneficial. Three case studies have shown the potential for improvement. Improvement in performance has been 6%, 14% and 18% in the studied case studies. The methods of lean production, supply chain management, TPS (Toyota Production Systems), TPM (Total Productive Maintenance) and SMED (Single-Minute Exchange of Die) were used together with methods of measurement like OEE (Overall Equipment Effectiveness). For a company to stay competitive it is suggested that a combination of the described techniques is applied.

Acknowledgments

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Paper IV

A survey of the use of the discrete-event simulation in manufacturing industry

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A survey of the use of the discrete-event simulation in manufacturing industry

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Abstract

Discrete-event simulation improves the possibility to study manufacturing systems. The use is increasing compared to previous studies and 15% of 80 companies investigated are using the tool and of these four companies extensively. The main advantage according to the survey beside the visualization part is that the knowledge about a system is investigated and documented. Other benefits can be basis for new investments and improvements of existing manufacturing lines. Of the companies that have adopted the technology, 79% answered that discrete-event simulation facilitates the decision-making process. Finally, the findings indicate that the potential of the software would be further increased if combined with adequate production improvement techniques to increase overall efficiency of a manufacturing system.

Keywords

Discrete-event simulation, survey, manufacturing industry

1 Introduction

DES is a tool suitable for the study of manufacturing systems and improves overall efficiency. The manufacturing system can be modeled in a simulation environment to study the different options for improving the system both to predict the effect of changes to an existing system as well as a tool to predict performance of new systems (Banks, Carson & Nelson, 1996). In many situations the efficiency of the manufacturing systems has to be improved due to high investment

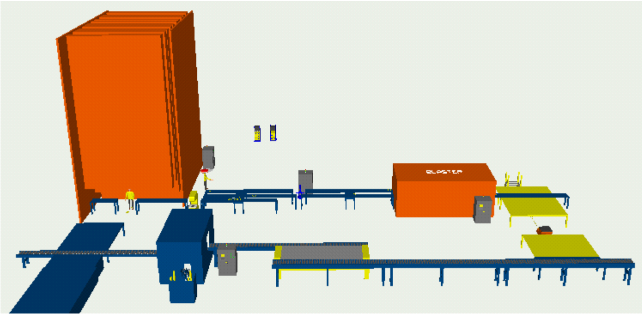

Figure 1: *A DES model.*

costs and expensive development of both products and processes. The increased interest in lean production (Womack & Jones, 1996) has heightened a need for even more efficient manufacturing systems which also contributes to new tools as DES. Manufacturing systems of today tend to be built to facilitate manufacturing in a faster time-to-market pace. A high degree of automation and increased investments in new manufacturing systems highlight the importance of high overall utilization. The move of a productivity frontier can be achieved when a company improves its operational effectiveness (Porter, 1998).

In this work, a survey of companies has been produced from a questionnaire and in-depth interviews. The aim is to give a current view of the use of DES in the industry, see an example in Figure 1. The survey was restricted to Sweden, although the results may be applicable to other countries with similar industrial structure. Some of the companies investigated are also multinational with branches around the world. To illustrate the differences in production systems different sectors have been investigated, e.g. the manufacturing industry and energy sector. Previous surveys of manufacturing efficiency illustrate different aspects. According to one survey, more than one-third (34%) of the disturbances in two countries (the U.S. and Finland) were mainly caused by design-based errors and flaws. The survey also showed the scope of safety problems experienced in the implementation and use of flexible manufacturing systems (Järvinen, Vannas, Mattila & Karwowski, 1996). Another survey in Germany reports a gap between users and non-users of DES. Many companies that are not familiar with simulation are not aware of its benefits. The study suggested integrating simulation into the planning processes as a regular tool. So far, DES is mostly used in system planning, resource planning and scheduling and production planning (Hirschberg & Heitmann, 1997).

A third questionnaire investigated competence in decision making and DES in the engineering industry (Savén, 1994). The study, made in Sweden, indicated that only 4% of the respondents have worked intensively with simulation. The rate was even lower when those who replied said to have extensive knowledge in the area of simulation were considered. Other issues from the study indicated that the lack of knowledge and time intended for new methods as main sparse resources to adopt new technology. The study also concluded that simulation has been used for decision in capacity and in some cases flexibility planning. Finally, Savén (1994) suggested that it could be wise to expand applications of DES to other areas such as activity based management, coordinate commitments between market and production and as a link between design and manufacturing.

2 Methodology

2.1 The disposition of the questionnaire

The inquiry formulated as a questionnaire was divided into five different chapters. Firstly, there was an introductory part describing the respondent's background in the manufacturing sector, products produced, size of company, number of employees, and the company's turnover. In this part questions were raised regarding the equipment of the company, normal batch size, type of manufacturing, number of setups and total output. Finally, in the introductory part, was status regarding the respondent's own background such as education, years of working experience, and age. Classification of events was introduced in the second part of the questionnaire. The purpose was to get a view of how companies define disturbances, OEE and availability. Thirdly, there was a chapter of working methods and supportive tools of disturbances in a manufacturing system. Issues were raised regarding different tools both for preventive and follow-up purpose. The information flow and recording of downtime were also investigated. The section also included questions regarding the need and purpose of improvement work. The fourth part in the questionnaire introduced DES, which is the main subject of the paper. The use of different types of software in the industry was investigated. Questions were raised regarding what kinds of decisions are taken from a simulation project and questions were also asked regarding the tool itself. The fifth and final part of the questionnaire investigated future trends and visions regarding for example modularization and customer satisfaction. Trends regarding design versus manufacturing in a five-year perspective were also looked into.

The disposition of the accomplished questionnaire had been multiple-choice questions in a strict order. The respondents gave their views on what the interviewer considered relevant for the survey. The main advantage with this method is that the results from investigation are measurable and quantitative analyses can be accomplished (Hagström, 1979). The multiple-choice questions in the DES section had four alternatives: (a) to a very large extent, (b) to a large extent, (c) to some extent and (d) not at all. If the issue is not relevant for the respondent there is also an alternative on each question “not applicable” or “do not know”.

2.2 Companies studied

The survey has been mainly directed to large and medium-sized companies in Sweden. The first round of survey was targeted to persons that have all attended a special training program in maintenance for the Swedish part of the European Federation of National Maintenance Society named “UTEK”. The second round has been directed to selected companies in Sweden with at least some 100 employees. The distinction between different functions of personnel in a company is not sharp. For example, the authority differs both between different companies and also in various countries. The following distinctions have been used in this paper: Operators are people who interact with larger systems to produce something easier, simpler, faster, or better. They use machines or systems that designers give them as part of their normal activities (Chapanis, 1996). Maintainers are people who are dedicated to service, maintain and repair machines. Some of the preventive maintenance has been removed from the maintenance personnel to the operators so the boundary is not clear. The designer of the system includes systems engineers, industrial engineers, programmers and human-factors professionals that have a direct role in the design and construction of machines. The production manager is responsible for a section or a part of the manufacturing at the company.

3 Results

3.1 Reply rate

The questionnaire was mailed to 220 persons in May 2001; a second round for unanswered surveys was dispatched in August 2001. Replies came from 114 respondents; thus, the reply rate to all questionnaires sent out was 52%. The replies came in from 80 different companies. To some companies several questionnaires were submitted. When several responses were received from a company the reply included in this study was submitted from the respondent with the highest rank in the company. The rank was chosen in the following order: president (for smaller

Table 1: *Capital turnover for the companies studied.*

Turnover (Million SEK/year)	No. of companies	Percent
< 200	15	19%
201-1000	25	31%
1001-5000	17	21%
> 5001	15	19%
Not responded	8	10%

Table 2: *Number of employees for the companies studied.*

Number of employees	No. of companies	Percent
< 100	13	16%
201-500	28	35%
501-1000	19	24%
> 1001	20	25%

companies), general manager, production manager, head of maintenance department, industrial engineer, and operator. The operators were mainly included in the detailed interviews. The figures in all tables describe how many respondents that have answered each inquiry. The respondent could only chose one alternative to each statement. Due to the current limited use of DES in the manufacturing industry only active answers were included in this investigation as they could contribute to the results and discussion section. The number of active replies can be calculated by adding all numbers shown in each question. The full result of the questionnaire is described in Ingemansson, Ylipää & Harlin (2002).

3.2 Company information

Some general figures as capital turnover, and number of employees, different manufacturing sector, number of set-ups are shown in the first section. The turnover of the companies who responded is shown in Table 1. At the time of measurement 9.5 SEK corresponded to about €1. The size of the companies can also be measured in number of employees as shown in Table 2. The two tables show together that a wide range of companies have been asked in Sweden regarding the DES subject. The different manufacturing sectors participated in the investigation is illustrated in Table 3. Some estimations will be evaluated in the discussion section using the engineering and vehicle industry combined versus the other sectors. Rate of set-ups in production gives an indication if the companies are manufacturing only one product, e.g. electricity or on the other hand produce a lot of

Table 3: *Manufacturing sectors for the companies studied.*

Manufacturing sector	No. of companies	Percent
Engineering industry	28	35%
Vehicle industry	10	12%
Paper mill industry	7	9%
Power industry	12	15%
Food industry	11	14%
Other sectors	12	15%

Table 4: *Number of set-ups in manufacturing lines.*

Rate of set-ups	No. of companies	Percent
Several times a day	36	45%
Several times a week	14	18%
Several times a month/year	11	14%
Not applicable	19	24%

different products that require set-up time. Of the total 80 different companies, 19 replied that question was not applicable (no set-ups at all). 36 answered that changed product a few times a day, 14 a few times a week. As shown in Table 4, the companies are from a wide selection regarding the amount of set-ups in manufacturing.

3.3 Questions related to DES

Some, mainly large and medium-sized companies have adopted the technology and others are in a more initial phase. The results indicate that of total 80 different companies 12 companies use DES in an active way. Of these 12 companies four indicated that they use their software to a very large extent. The survey indicates that there is no particular market leader in Sweden of different DES software. The other questions are related to DES as a suitable working method. There are certain issues often encountered when working with DES and the questions were raised accordingly (Banks et al., 1996). For some questions regarding the usefulness of DES, see Table 5. For other questions, more related to the specific tool of DES, see Table 6. The respondents, who answered the questions in Table 5 and Table 6 are representing the same sectors as for the whole study with an over-representation in the vehicle industry. Furthermore, larger companies are more frequently represented than in the whole study.

Table 5: *The usefulness of DES. The figures show the number of respondents that answered the question.*

Questions in Table 5: Does/Is DES...	To a very large extent	To a large extent	To some extent	Not at all
A: facilitate the decision-making process?	6	24	7	1
B: improve the availability of equipment (system verification)?	4	20	8	1
C: achieve cost reduction in production?	8	23	7	1
D: intended for new investments?	15	16	7	0
E: intended for improvements in current manufacturing system?	10	17	9	0
F: intended for staffing in production?	6	16	14	1

4 Discussion

The use of DES is increasing compared to previous studies and 15% of 80 companies investigated 2001 are using the tool and of those 5% extensively. A common use of DES is to achieve increased efficiency of production lines. Some issues in the results section can be reflected on, though. 45% of the companies are changing products and have set-up time every day, see Table 4. Another 18% of the companies are setting up different products at least a few times a week. The trend is that the lengths of production series are shorter and more varieties are produced in a manufacturing line. By using DES many unforeseeable issues otherwise may be considered without involving huge costs and standstills.

By combining the results it can be seen that larger companies have a higher degree of adaptability to DES than smaller firms have. This can depend on the resources needed, the complexity of the software and the cost. The findings correlate with different in-depth interviews made. A successful project consists not only of knowledge about the simulation software but also of adequate production improvement techniques. The knowledge of different production philosophies can by no means be neglected (Ingemansson, 2001). Not to be forgotten is the avail-

Table 6: *DES as a tool. The figures show the number of respondents that answered the question.*

Questions in Table 6:	To a very large extent	To a large extent	To some extent	Not at all
A: Is it considered easy to prepare a model that corresponds with the real world and perform the actual simulation?	4	10	11	3
B: It is considered effortless to access relevant input data for the model?	2	8	11	5
C: It is considered effortless to use the output data from the simulation and apply it on the real world?	2	11	13	3
D: Can a fast repayment of the software costs with the results from the simulation models that is implemented been seen?	2	8	4	3
E: Is the simulation problem proper visualized?	11	21	3	0
F: Is it reviewed that DES is a faster working method compared to other methods?	4	10	6	1
G: Is it reviewed that DES gives relevant support for the actual decision of a project?	7	20	5	0

ability to use other tools than DES as an alternative. The availability to show the dynamic effects of a manufacturing system is by many seen as the main strength of DES.

There is a threshold to start to use the DES tool but once this is passed a majority finds the tool attractive, see Table 5. In this table, questions are raised regarding what kinds of decisions are taken from a simulation project. The simulation models can be prepared with different purposes and intentions in mind. According to Table 5 question D 82% answered to a very large or a large extent that the most important use is as basis for new investments. Another important purpose is as a basis for improvements in the current manufacturing system where the corresponding figure is 75% (question 5E). On the question (5A) if DES facilitates the decision-making process 79% of totally 38 answered to a very large or a large extent. Regarding the question (5B) if DES is useful for measuring the availability of equipment for example system verification 73% of 33 responded to a very large or a large extent. A majority of the respondents genuinely see an advantage with the use of simulation, which is an important result from the study. The cost reduction aspect of the production (question 5C) is also an advantage of DES. On the question eight answered to a very large extent and 23 to a large extent. The question (5C) demonstrates that the results of a simulation model are indeed used. Finally, in Table 5 the question of DES is used for staffing (5F) indicates that it is not so commonly implemented. The staffing issue requires good knowledge about time measurement of manual labor. The option, however, to include manual a work in a simulation model is in many programs extensive and must be a valuable option to evaluate work intensive part of production line and their improvements. For Table 5 the number of active respondents is between 33 and 39.

The questions raised when working with a tool like DES is indicated in Table 6. Regarding the issue if it was considered to be easy to prepare a model that correspond with the real world (question 6A) to 11% there is no concern at all, to 39% there is concern to some extent, and to 36% there is concern to a large extent and to 14% there is concern to a very large extent for 28 respondents. Quite often in a simulation project, it is harder than expected to prepare a relevant model as also implied in the next question. The interpretation of replies in Table 6 is difficult as some of the replies come from respondents currently not working with DES. Therefore, the replies in Table 6 may be more indicative than in Table 5. The input issue is raised in the next question (question 6B) and similar figures with an even more negative indication. Previous research (Trybula, 1994) and the experience by the authors indicate that the input data issue can allocate up to 40% of the total simulation project time. The operators as well as the maintenance personnel and the production engineers all have valuable experience in the search of relevant input data. It has been indicated in interviews and case studies that one of the main advantages with a simulation case is that the actual problem of a line is discussed and taken care of.

The use of output data from the simulation model is also raised (question 6C). Surprisingly three respondents (10%) answered that the results from the model can not be used at all and 13 answered (45%) that the output data can only be used to some extent. The cost of implementing DES is considered in the next question (question 6D). The question is difficult to answer, as it is a hard task to measure the actual gain of a simulation project versus the cost of hardware, software and training of suitable personnel. The opinion according to the survey indicates that investment is beneficial since 12% of the respondents replied to a very large extent and 47% to a large extent. The visualization part of the simulation model is overwhelming. 32 of 35 (91%) asked have a positive standpoint and find the visual interface attractive (question 6E). One of the main objectives to use DES is the good visualization and it is no surprise that the majority agreed on this point. The issue about DES as a faster working method is asked for in question 6F. Of the 21 replies, 19% answered to a very large and another 48% to a large extent. Finally, the last question in table 6 (question 6G) is regarding the DES availability to give relevant support to the actual decision. Seven answered to a very large extent and 20 to a large extent that gives that 84% of the respondents are agreeing on this standpoint. For Table 6 the number of active respondents is between 17 and 35.

Acknowledgments

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Paper V

Increase the total output when disturbances are reduced in a manufacturing system

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Abstract

Although reduction of disturbances may result in productivity increase, some of the presumed gain may be diverted to other disturbances. There is a need to develop methods that provide a better understanding of the causes and actions of disturbances in manufacturing systems. Discrete-event simulation is used to analyze the effects. Two case studies from manufacturing companies were examined. The investigation shows that the best ways to decrease disturbances are to eliminate those resulting from long waiting times. It is suggested that the new allocation of disturbances be thoroughly investigated before efforts are taken to eliminate disturbances and increase total output.

Keywords

Simulation, Manufacturing systems, Productivity improvement

1 Introduction

Disturbances in manufacturing systems are an issue of considerable importance in the industry of today and have been studied extensively in recent years. Although the definition of a disturbance in a manufacturing system is relatively ambiguous, Kuivanen (1996) defines disturbance as an unplanned or undesirable state or function of the system. In this paper the three main causes of disturbances are classified as downtime, cycle and quality losses. Of particular interest and complexity are downtime losses. They are found in the utmost majority of cases and the main factor holding back increased production. Downtime losses are observed when downtime starts and ends during the ramp-up phase to normal operation.

With ever-increasing global competition, minimizing disturbances can be an important means of gaining a competitive advantage. Empirical studies have shown that only some 50-60% of total production time is used for manufacturing (Drucker, 1990; Ericsson, 1997; Viktorsson, 1989). The rest of the time is wasted in different disturbances. In addition, manufacturing systems tend to be more and more complex as machine cells include greater number of various types of integrated functions.

The various properties and effects of disturbances are still not completely understood. Investigations on the influence of disturbances demonstrate that there is greater risk of work hazards during disturbances than during normal operations (Nakajima, 1988). Other studies examine the issue of shorter life cycle of products and disturbances during the ramp-up phase of FMS, Flexible Manufacturing Systems (Harlin & Ylipää, 1999). In many manufacturing systems losses have been related to inefficiency of equipment and human related losses (Nord, Pettersson & Johansson, 1998). Depending on the type of losses an efficiency rate can be calculated.

Bainbridge (1983) discusses the designer errors in manufacturing systems as major source of operating problems. The designer leaves the operator to do the tasks which the designer cannot think how to automate. As a result the operator can be left with different collection of tasks and little thought have been given to support them.

Another issue to be taken under consideration is that manufacturing needs to develop a proactive rather than reactive role in the formulation of corporate strategy, (Cox & Martin, 1994). Manufacturing often merely responds to demands placed on them by sales and design.

2 Materials and Methods

2.1 Definition of disturbances

Different types of losses can be illustrated using different time utilization (Nord et al., 1998) and categorized, for example, as relating to efficiency of equipment or to more human related work efficiency. Losses of equipment relating to available time in different classes are indicated in Figure 1. Such losses can be classified as downtime, cycle and quality losses. Downtime losses can further be divided into planned and unplanned stops. The figure illustrates the different ideas of time

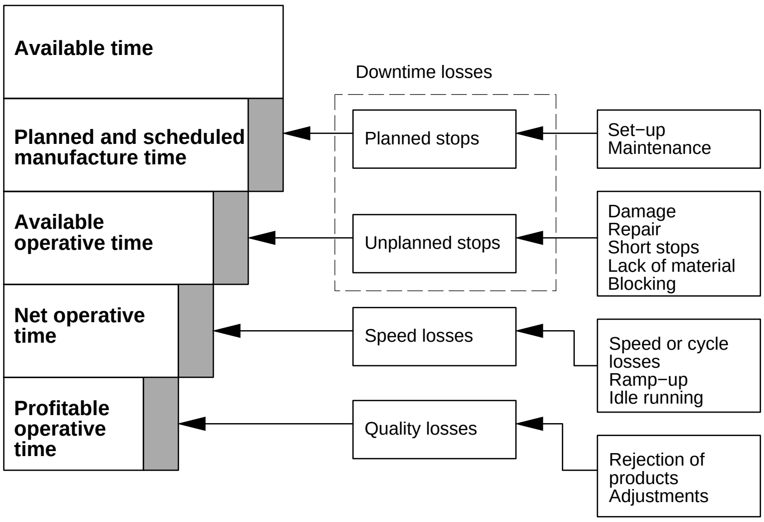

Figure 1: *Efficiency of equipment, based on Nord et al.*

allocation for equipment in a manufacturing system.

Downtime due to human aspects can also affect the allocation of man-hours, as illustrated in Figure 2. When manual work is involved in the manufacturing systems, it is important to study the human factor and organizational type of losses. Examples of losses in this area are management, method, balance, automation and control losses.

The main parameters used to describe disturbances are (see Table 1) Downtime (DT), Waiting Time (WT) and Time to Repair (TTR). Downtime refers to the moment when the disturbance occurs, i.e. when the normal manufacturing state is interrupted. Waiting Time designates the time when the manufacturing system is down and waiting for attention, either from operator or repairman or both. Time To Repair is the time devoted to fault-detecting, exchange of spare parts, adjustment, assembly and testing. “Measure” describes TTR or other action to bring up the manufacturing system to normal state. Finally, Time Between Downtime (TBDT) is the time in the normal manufacturing state.

Downtime losses are given as the relation between total available time and available operative time. The ratio describes the time-share for different activities but not if the stops are divided into many short stops or a few longer. There is also another issue, for example a low share of set-up losses are not necessarily the same as short set-up times or big batch sizes. The share could also be related to a totally different cause, such as long repairs. In conclusion, all disturbances are in

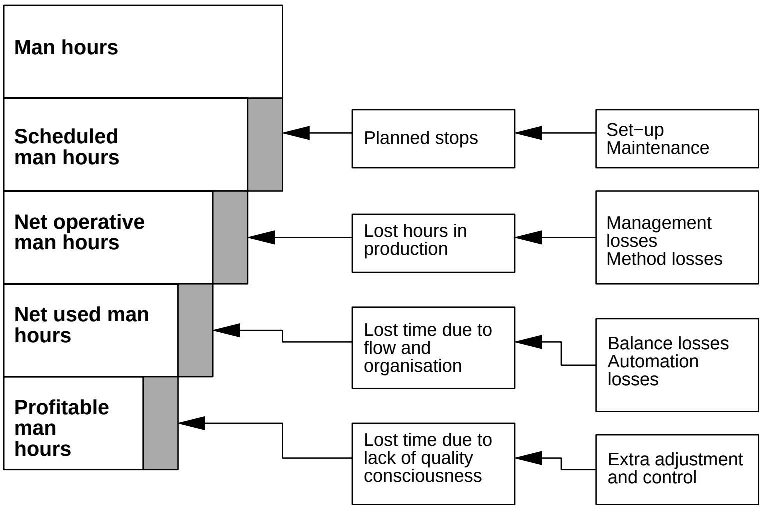

Figure 2: *Efficiency of manual work, based on Nord et al.*

one way or another related to each other. Losses connected to reduced speed are normally calculated as the relation between received and calculated time. Speed losses are calculated as the ratio between available and net operative time. Finally, losses in quality are measured as approved units compared to manufactured units.

2.2 Methodology

Two manufacturing companies in Sweden in different areas were investigated using case studies. The companies were chosen because their manufacturing systems represent typical situations in manufacturing industry. Identified machine cells at both companies are bottlenecks in their production. Finally, both companies are working progressively to increase overall efficiency and reduce disturbances and were also interested in implementing the results of the study.

Several types of data, such as automatic and manual data, were gathered. The data were analyzed together with supplementary site studies. Interviews were also carried out with operators, managers and other personnel. Manual data were also recorded for a thorough investigation. The simulation models were designed in Quest, discrete-event simulation software from Delmia. The disturbance data were statistically checked for relevance applying mathematical models.

Disturbance data gathered in log books show fewer disturbances than the stops revealed by actual observation. Our study thus agrees with previous investigations

Table 1: *Definition of abbreviations.*

Abbreviation	
DT	DownTime
WT	Waiting Time
TTR	Time To Repair
TBDT	Time Between DownTime
Measure	TTR or other action to bring up manufacturing in normal state

(Kuivanen, 1996) which describe the real number of disturbances as about five to ten times higher than recorded stops. Manual data gathering has shown to be a complicated issue. The presence of an observer has been shown to effect the results and increase productivity. In case studies there is normally a significant increase in total output due to the presence of the observer (Yin, 1994). Automatic data gathering from the PLC system are to some extent used in case studies to compare the relevance of manually collected data.

2.3 Case study no. 1

The first company studied was a manufacturer of machines and equipment for the window blind industry. Braided cords are produced in 72 machines, each of the machines making two cords independently. The machines operate 24 hours a day, 7 days a week and they operate unmanned as long as no disturbances occur, up to some 100 hours without interruption.

Disturbance data were collected in the form of manual logging and also using indicators placed on the machines. The personnel logged all stops manually in five different categories. During six months period data were gathered. A schematic layout is shown in Figure 3. A vibration indicator was installed on two different machines to measure duration of TBDT and DT. The survey showed that DT varies considerably due to different WT. WT varied from 1 minute to 107 hours. Time for measures was between 1 minute and 1 hour.

2.4 Case study no. 2

In the second study a welding cell was studied consisting of two robots manufacturing components for different types of forklifts. The components are divided into two main articles and the fabrications of these are divided into some standard

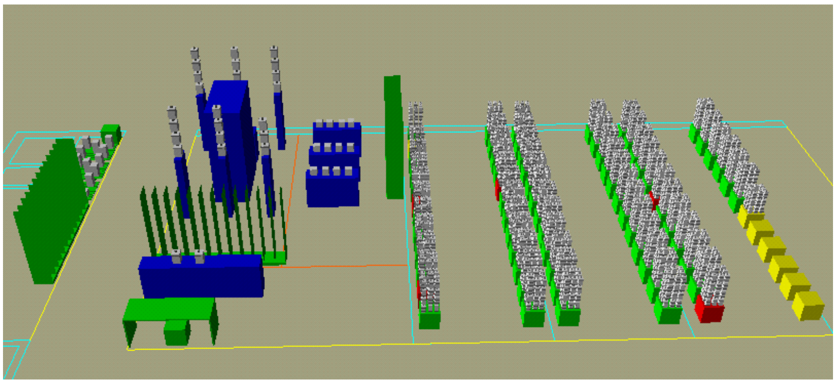

Figure 3: *Layout of case no. 1.*

lengths and many customized lengths. The manufacturing system is operating 24 hours a day, 5 days a week and two shifts on the weekends. Four operators are working adjacent to the cell, two with tack welding preparing for the robots and two with grinding and quality control when the components are fully welded.

The PLC (Programmable Logic Controller) system of the manufacturing cell is recording the different movements in the cell. Longer disturbances could be detected in the log-files of the PLC-system. Data were also recorded manually to observe shorter disturbances. For each new unique length the software of the robots has to be adjusted in time consuming on-line programming.

Welding is a complicated issue to automate due to tight tolerances. This means that there are a lot of short stops in the robot cells caused by stop in the welding process. The operators are also closely linked to the station and if they leave the station a stop is likely to occur some 15 minutes later as a result of the frequent disturbances. The study indicates two different main groups of disturbances, short disturbances related to the welding process and longer related to programming of new software.

2.5 Relevance of gathered disturbance data

Manual data gathering is a complicated issue. The presence of an observer effects the results and normally increases the output. In case study no. 2 there was a significant increase in total output due to the presence of the observer. Automatic data gathering from the PLC system are to some extent used in this case study to compare the relevance of manually collected data.

Table 2: *Disturbances in case study no. 1 in relation to planned and scheduled manufacture time.*

Cause of disturbance	Proportion
Yarn empty	16%
Yarn breakage	8%
Miscellaneous	3%
Full bobbin	2%
Core thread empty	>0%
Sum downtime disturbances	30%

3 Results

The results of the investigation are summarized in Table 2 and 3. The availability of the manufacturing cells are 70% and 49%, respectively, and downtime losses are illustrated according to the simulation models for the two case studies before any methodical disturbance reduction. In case study no. 1 disturbances accounted for 30% of total production time. However, the production rate during the measurements was higher compared to the annual production rate and about 50% higher due to the fact that machines measured were given more priority than the rest of the machines at the department.

The study shows the most important issue affecting efficiency is the decrease of WT before measure, Figure 4. Each of the 72 machines consists of two separate units and the machine stops when either unit stops. The large number of machines being served by only a few operators makes it difficult to carry out measures for each unit independently. Waiting time for the operator in all the types of disturbances is critical and constituted in our study well above 90% of downtime losses due to activities in many machines and there being only two to three operators to attend the machines on a day-time schedule.

Experimental work carried out to work with more parallel tasks for the personnel at several machines at the same time showed a significant increase of total output of 18%. The results of reduced disturbances are also noticed later in the manufacturing chain as another new bottleneck. Long disturbances with long waiting time are generally a major source of decreased productivity in the first study.

Of great interest was the reduction in a major disturbance, in case study no. 2, where total availability was 49%. The online programming was selected as the most important issue to reduce, as it would eliminate longer disturbances. The increase of total simulated output was in this case study 14%. Waiting time was

Table 3: *Disturbances in case study no. 2 in relation to planned and scheduled manufacture time.*

Cause of disturbance	Proportion
Online programming	19%
Waiting	19%
Welding process	2%
Miscellaneous	1%
Sum downtime disturbances	41%

separated from disturbances and sorted out as one single disturbance related to the organizational area. Analysis of the increased output showed that the short stops generally did not affect total output if waiting time was kept at minimum. These stops could be decreased with preventive maintenance and newer supportive tools such as seam tracking. However, the production rate during the measurement was significantly higher compared to the annual production rate. The main reason for this was a reduction of waiting times, most likely due to presence of an observer.

Interviews made clear that reduced disturbances generally lead to more smooth production and better working environment both in, before and after the machine cell. The reduced number of disturbances resulted in that the remaining disturbances being more noticeable. Thus, the reduction in disturbances can in general not fully be utilized in a corresponding higher productivity.

In both case studies experimental work was done to investigate the human effects when one cause of disturbance was reduced. According to the operators and production supervisor at both case studies the production ran much more efficiently after disturbances had been reduced. Less amount of disturbances also reduced problems before and after in the manufacturing chain. Longer disturbances, e.g. more than two hours, have in most cases multiplying effects in production lines.

The simulation models showed the dynamic effects of the disturbances and the results indicate the importance of altering the organization with respect to number of disturbances in order to minimize waiting times. The models were simulated for a year under stable conditions and statistical data were recorded. One class of disturbances in each case study was deleted from the repair and failure schedules. New simulation runs were carried out and compared with those run previously. The simulated data were compared with field tests in the case studies to show the relevance of the simulated results. The simulation showed a good correlation with the real case studies when a disturbance was reduced.

4 Discussion

The extensive potential in productivity improvement of disturbance reduction was illustrated. Two case studies show an improvement of 18% and 14% respectively when one of the major disturbances in each case was reduced. However, of a total gain, up to 5% is redistributed to other disturbances. The importance of the redistributed disturbance and the problems related to this should not by any means be neglected.

The study focused on downtime disturbances, since our preliminary research had shown it to be the main cause of disturbance in production. In addition, many other studies, for example Ericsson (1997), show that of mean downtime in a stable production 80% of all losses related to manufacture time are related to downtime losses. The manufacturing costs are connected to capital turnover and reduced disturbances will result in lower costs for direct labor, such as operators, and indirect labor, such as maintenance personnel. Furthermore, disturbances in the long term will lead to reduction in working capital, safety stocks and machine investments.

The two other types of losses, cycle and quality, were shown to constitute a smaller fraction of the total losses. The quality of the manufactured products is, of course, vital as it generates income and good-will for the company. For many years focus has been on zero fault production to improve overall quality. Tact losses are related to the speed of the manufacturing cycle process. The potential of improvement also exists here with a less potential than for downtime disturbances.

Experimental errors in the study are connected to measurement of input data rather than the simulation itself. Data were compared to annual production data together with interviews. Discussions with personnel at the different companies were evaluated. Unfortunately automated data gathering systems are not designed to focus on disturbance analysis and manual data gathering is necessary to obtain relevant input data.

Advantages other than profitability were shown to result from reduced disturbances; these included a better working environment and smoother manufacturing in the production lines. Our study indicates that if only a few percent of the overall downtime disturbances could be reduced, the productivity would increase significantly and for example investments in increased production capacity in many cases could be postponed or would not be necessary at all. The results of the case studies in this paper correlate with manufacturing industries as a whole.

This research study has focused on disturbances in one machine cell. A future

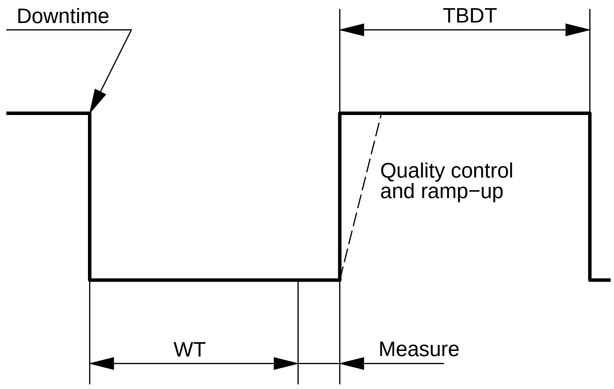

Figure 4: *WT is much longer than time for measure*

study will be expanded to several machine cells where materials and personnel depend on each other. A disturbance created in a machine cell could easily cause disturbances in other adjacent machine cells. The study should take all buffers and other supplier material into consideration. Further research could also study the effects on human aspects when disturbances occur. Each disturbance normally does not take so long to take care of but waiting time is in many cases very long, more than 90% in the first case study. If working conditions are changed, there is a great opportunity to improve total output without using expensive means. Two ways to achieve this might be “andon”, signal signs implemented according to Toyota Production System (Monden, 1998), and a more efficient work organization focusing on disturbance handling.

Flexible manufacturing such as unmanned production is an area also related to disturbance elimination. If there are many disturbances, production will not run without interruption and the idea behind unmanned production is at risk. Finally, further research could also study the connection between design and manufacture. Products should be designed to cause as little disturbance as possible when manufactured.

5 Conclusions

To conclude, disturbance reduction offers great potential for improved productivity in manufacturing systems. Based on two case studies improvement of 18% and 14% respectively was shown directly in the simulation model and of total gain up to 5% is redistributed to other disturbances.

Although our study indicates that significant improvements can be achieved through disturbance reduction, in light of wide variability in background conditions, it is our view that each case study has to be carefully studied to derive reliable results in a disturbance reduction case.

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