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2012

Citation for published version (APA):
Jönsson, M. (2012). *Cost-conscious manufacturing – Models and methods for analyzing present and future performance from a cost perspective*. [Doctoral Thesis (compilation), Production and Materials Engineering].

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Cost-conscious manufacturing

– Models and methods for analyzing present and future performance from a cost perspective

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ISBN 978-91-7473-277-1
LUTMDN(TMMV-1063)/1-85(2012)

Printed by Media-Tryck, Lund, Sweden, 2012

Abstract

Manufacturing is an industry in which the effects of globalization are obvious. Manufacturing costs are a key factor in this respect and affect, for example, decisions about offshoring, i.e., moving production abroad. If Sweden and other Western countries are to maintain large manufacturing sectors, they must be competitive, making cost one of the most critical parameters.

The work presented here seeks to develop tools for cost-conscious manufacturing. These tools should provide insight into how well a manufacturing system is performing and support the analysis and prioritization of manufacturing development activities. To achieve this objective, two research questions were formulated.

The first research question (RQ1) concerns how a general cost model should be designed to take into consideration the most important process-near parameters influencing manufacturing system performance. A cost model developed in accordance with this research question includes critical parameters affecting performance, such as cycle time, setup time, and performance loss parameters. The model is centered on the processing steps involved in processing a part. The losses occurring in the processing steps are important in the model, so the links between structured, detailed monitoring of the loss causes and their impacts on costs are emphasized. Modified versions of the model to analyze volume flexibility and downtime variability are also presented.

The second research question (RQ2) concerns how such a cost model can be used in practice, i.e., the requirements and conditions for industrial use. Implementation in an automotive company indicated that the model was applicable in this context and that interesting insights into manufacturing costs could be gained from using the model. A study of the industrial conditions for applying the cost model identified software products for collecting manufacturing loss data that support the level of detail needed for model input, but found that manufacturing companies do not necessarily collect such detailed data. A demonstration program developed based on the databases available in a collaborating company indicated how the cost model could be used practically in a company. The somewhat deficient detail in the collected loss data, found in the above study, led to an inquiry in another company into the pros and cons of collecting highly detailed performance loss data. The results identified more advantages than disadvantages with collecting more detailed data: the operators responsible for data collection did not perceive any particular difficulties with the increased detail and the production manager believed that the increased detail led to better knowledge of performance losses.

Keywords: manufacturing cost, cost models, performance analysis

Sammanfattning

Tillverkningsindustrin är en bransch där globaliseringen är högst påtaglig. Konkurrensen är global, vilket medför att exempelvis produktionsanläggningar i Sverige konkurrerar med anläggningar i länder med betydligt lägre lönenivå. Om Sverige även i fortsättningen ska ha en konkurrenskraftig tillverkningsindustri krävs att produktionen bedrivs med en hög kostnadsmedvetenhet. Med det åsyftas att produktionspersonalen har kunskap om hur olika parametrar i ett tillverkningssystem påverkar kostnaden för de produkter som produceras samt hur tillverkningskostnaden är fördelad mellan olika kostnadsposter. Med den kunskapen kan produktionsutvecklingsarbete bedrivas med en högre medvetenhet om hur olika utvecklingsinsatser påverkar tillverkningskostnaden och därmed med bättre precision kunna prioritera vilka utvecklingsinsatser som bör genomföras för att bli mer kostnadseffektiv.

Syftet med forskningen som presenteras här är att utveckla ett koncept bestående av modeller och metoder för att skapa kostnadsmedveten produktion. Konceptet ska ge insikter om hur väl ett tillverkningssystem fungerar och utgöra ett stöd vid analyser och prioriteringar gällande utvecklingsinsatser av tillverkningssystemet. För att nå syftet har två forskningsfrågor formulerats.

Den första forskningsfrågan behandlar hur en generell kostnadsmodell bör utformas som beaktar de viktigaste parametrarna som beskriver ett tillverkningssystems prestanda. En kostnadsmodell som beskriver kostnaden per tillverkad detalj har utvecklats i enlighet med den frågeställningen. I modellen ingår kritiska parametrar som påverkar tillverkningssystemets prestanda, såsom cykeltid, ställtid, kassationer och stillestånd. De förluster som uppkommer vid varje förädlingssteg är centrala för modellen. En annan viktig aspekt är att uppföljningen av orsakerna till förlusterna bör vara både strukturerad och detaljerad för att därmed kunna beräkna varje orsaks inverkan på tillverkningskostnaden. Kostnadsmodellen kan anses utgöra en länk mellan tekniska och ekonomiska parametrar i ett tillverkningssystem och kan därmed användas för att analysera kopplingen mellan dessa.

Den andra forskningsfrågan behandlar förutsättningarna för att en sådan kostnadsmodell ska kunna användas i praktiken, det vill säga dess industriella tillämpbarhet. För att besvara den frågan gjordes först en implementering av modellen på ett företag inom fordonsindustrin, som visade att modellen var tillämpbar i detta fall och att detaljerade analyser av tillverkningskostnaderna kunde göras med hjälp av modellen. En annan studie visade att det finns programvaror på marknaden för produktionsuppföljning som stödjer insamling av all den indata som behövs till kostnadsmodellen gällande produktionsstörningar och dess orsaker, men att tillverkande företag nödvändigtvis inte samlar in data av en sådan detaljeringsnivå. För att undersöka hur kostnadsmodellen kan användas praktiskt i industrin utvecklades en demonstrator i samarbete med ett företag inom verkstadsindustrin. I programmet, vars indata hämtas från företagets produktionsplaneringssystem och affärssystem, kan olika typer av analyser göras av tillverkningskostnaden baserat på kostnadsmodellen. Företaget som programmet gjordes tillsammans med hade inte fullt ut den önskade detaljeringsnivån för all den data som ingår i kostnadsmodellen. Detta föranledde en ny studie på ett företag för att studera för- och nackdelar med insamling av förlustdata av hög detaljeringsnivå. Studien, som enbart fokuserade på insamling av stilleståndsdata, visade att det finns fler fördelar än nackdelar med mer detaljerad uppföljning.

Acknowledgements

Now that this thesis has been written, I would like to thank several people for their support.

This work is based on ideas originally formulated by my co-supervisor, Professor Jan-Eric Ståhl. This thesis could not have been completed without him. His enthusiasm and valuable input to the research have been much appreciated. Another person who provided crucial support for this work is my supervisor, Associate Professor Carin Andersson, with whom I have had many rewarding discussions over the years. Being a doctoral student is not always a pleasure: sometimes it can be frustrating and confusing, and in such situations Carin was always a great support.

The work presented here was financially supported by VINNOVA (the Swedish Governmental Agency for Innovation Systems) through the TESSPA and Lean Wood Engineering projects. I would also like to thank the companies collaborating in these projects: AB Karl Hedin, Leax Mekaniska, Sandvik Mining and Construction, Seco Tools, Swepart Transmission, Svenska Tanso AB, and Trelleborg AB. Outside of these projects, I also collaborated with Alfa Laval AB.

I would also like to thank my colleagues at the divisions of Production and Materials Engineering and of Machine Elements for creating a happy and inspiring working environment.

Lund, February 2012

Mathias Jönsson

Appended publications

Paper 1	M. Jönsson, C. Andersson, and J.-E. Ståhl, “A general economic model for manufacturing cost simulation,” *Proceedings of the 41st CIRP Conference on Manufacturing Systems*, pp. 33-38, 2008. Jönsson wrote the paper with the assistance of Andersson and Ståhl. The model was earlier formulated by Ståhl.
Paper 2	M. Jönsson, C. Andersson, and J.-E. Ståhl, “Relations between volume flexibility and part cost in assembly lines,” *Robotics and Computer-Integrated Manufacturing*, vol. 27 no. 4, pp. 669–673, 2011. Jönsson developed the concept together with Andersson and Ståhl and wrote the paper with the assistance of Andersson and Ståhl. Jönsson also presented the paper at the 2010 FAIM conference.
Paper 3	M. Jönsson, P. Gabrielson, C. Andersson, and J.-E. Ståhl, “Dynamic manufacturing costs - describing the dynamic behavior of downtimes from a cost perspective,” *Proceedings of the 44th CIRP Conference on Manufacturing Systems*, 2011. Jönsson developed the concept together with Ståhl and Andersson and wrote the paper with the assistance of Gabrielson and Ståhl. Jönsson also presented the paper at the 2011 CIRP conference.
Paper 4	M. Jönsson, C. Andersson, and J.-E. Ståhl, “Implementation of an economic model to simulate manufacturing costs,” *Proceedings of the 41st CIRP Conference on Manufacturing Systems*, pp. 39–44, 2008. Jönsson initiated the paper and supervised the study. Jönsson wrote the paper with the assistance of Andersson and Ståhl. Jönsson also presented the paper at the 2008 CIRP conference.
Paper 5	M. Jönsson, C. Andersson, and J.-E. Ståhl, “Conditions for and development of an IT-support tool for manufacturing costs calculations and analyses,” Under 2nd review at *International Journal of Computer Integrated Manufacturing*. Jönsson initiated the paper, designed the software application, and supervised the pre-studies. Jönsson wrote the paper with the assistance of Andersson and Ståhl.
Paper 6	M. Jönsson, C. Andersson, and M. Svensson, “Availability improvement by structured data collection: a study at a sawmill,” Submitted to *International Journal of Production Research*. Jönsson initiated the paper and collected the data. He also designed the new downtime-cause structure together with Svensson. Jönsson wrote the paper with the assistance of Svensson and Andersson.

Contents

List of acronyms

ABC	Activity-based costing
ABM	Activity-based management
APP	Aggregate production planning
CIMS	Computer-integrated manufacturing systems
COC	Cost of conformance
CONC	Cost of non-conformance
COQ	Cost of quality
DES	Discrete-event simulation
DT	Downtime
EVA	Economic value added
FMS	Flexible manufacturing system
GE	Generalized exponential
JIT	Just in time
LCA	Life cycle assessment
LCC	Life cycle costing
MIP	Mixed-integer programming
MRP	Material requirement planning
MTBF	Mean time between failures
MTTR	Mean time to repair
NNVA	Necessary but non-value-adding
NVA	Non-value-adding
OAE	Overall asset effectiveness
OEE	Overall equipment effectiveness
OPE	Overall plant effectiveness
OTE	Overall throughput effectiveness
PAF	Prevention–appraisal–failure
PEE	Production equipment effectiveness
PMS	Performance measurement system
POC	Price of conformance
PONC	Price of non-conformance
RCA	Resource consumption accounting
TA	Throughput accounting
TBF	Time between failures
TDABC	Time-driven activity-based costing
TOC	Theory of constraints
TPM	Total productive maintenance
TQM	Total quality management
TTR	Time to repair
VA	Value-adding
VCA	Value chain analysis
VSM	Value stream mapping

List of symbols

The table below presents the parameters used in the developed cost equations. The economic parameters are described in US dollars (USD).

a	Annuity [USD/year]	N_Q	Number of scrapped parts in a batch of N_{i-1} parts [unit]
F	Floor space occupied by the machine [m^2]	n_t	Number of cutting edges [-]
i	Processing step index [-]	q_B	Material waste factor [-]
I_0	Initial investment expense [USD]	q_P	Production-rate loss [-]
j	Failure cycle index [-]	q_Q	Scrap rate [-]
k	Part cost [USD/unit]	q_S	Downtime rate [-]
k_A	Tool cost per hour [USD/h]	q_{S1}	Total planned downtime rate [-]
k_{add}	Cost of additives [USD/h]	q_{S1EP}	Preventive maintenance rate [-]
k_B	Material cost per part [USD/unit]	q_{S1O}	Other planned downtime rate [-]
k_{B0}	Material cost of manufactured part without material waste [USD/unit]	q_{S1UL}	Utilization loss rate [-]
k_{CF}	Floor space cost per square meter [USD/m^2]	q_{S2}	Total unplanned downtime rate [-]
k_{CP}	Hourly cost of machines during production [USD/h]	q_{S2EC}	Corrective maintenance rate [-]
k_{CS}	Hourly cost of machines during down time and set up [USD/h]	q_{S2O}	Rate for non-maintenance-related unplanned downtime [-]
k_D	Wage cost [USD/h]	r	Interest rate [-]
K_E	Total cost of the maintenance department [USD]	t_0	Nominal cycle time per part [min]
k_{ec}	Corrective maintenance cost per part [USD/unit]	t_{0v}	Cycle time including production-rate losses [min]
k_{EC}	Corrective maintenance cost per hour [USD/h]	T_b	Production time for a batch [min]
k_{ep}	Cost of electricity during production [USD/h]	T_{Eavail}	Practical capacity per maintenance employee [min]
k_{EP}	Preventive maintenance cost per hour [USD/h]	t_h	Handling time [min]
k_{es}	Cost of electricity during downtime [USD/h]	t_m	Machine time [min]
k_{NVA}	Cost of non value-added activities [USD/unit]	T_P	Production-rate loss time [min]
k_P	Costs connected to the production-rate loss [USD/unit]	t_p	Production time per part [min]
K_P	Production-rate loss per hour [USD/h]	T_{pb}	Production time of a batch [min]
k_Q	Costs related to the scrap rate [USD/unit]	T_{plan}	Planned production time [min]
K_Q	Scrap cost per hour [USD/h]	T_{prod}	Actual production time [min]
k_S	Costs related to the downtime rate [USD/unit]	T_Q	Nominal production time for scrapped parts [min]
K_S	Downtime cost per hour [USD/h]	t_S	Average down time per part [min]
K_{sum}	Miscellaneous costs not described separately in the model [USD]	T_{S1}	Total planned downtime [min]

k_t	Cost per tool [USD]	T_{S1b}	Planned downtime allocated to a batch [min]
k_{th}	Tool holder cost [USD]	T_{S1EP}	Preventive maintenance time [min]
k_{tOH}	Tool-related overhead cost [USD]	T_{S1O}	Other planned downtime [min]
k_{Tsu}	Setup cost per part [USD/unit]	T_{S1UL}	Utilization-loss time [min]
K_{Tsu}	Setup cost per hour [USD/h]	T_{S2}	Total unplanned downtime [min]
K_U	Utilization cost per hour [USD/h]	T_{S2EC}	Corrective maintenance time [min]
k_V	Variable machine cost during operation [USD/h]	T_{S2O}	Non-maintenance-related unplanned downtime [min]
k_{VA}	Value-added cost per part [USD/unit]	T_{su}	Setup time of a batch [min]
K_{VA}	Value-added cost per hour [USD/h]	T_t	Tool life [min]
m_{part}	Remaining material in the machined part [weight]	T_{th}	Tool holder life [min]
m_{tot}	Total consumption of material per part [weight]	T_{theo}	Theoretically available production time [min]
n	Useful life of a machine [years]	$T_{tOHavail}$	Available time for tool-related overhead activities [min]
N	Total number of parts required to produce N_0 parts [unit]	$T_{tOHused}$	Total time spent on tool-related overhead activities [min]
N_0	Nominal batch size [unit]	t_{vb}	Tool switch time [min]
N_c	Number of parts manufactured during a TBF period [unit]	U_{RP}	Machine utilization [-]
n_{Eavail}	Number of employees in the maintenance department [unit]	x_p	Process development factor for the cycle time [-]
n_{Eused}	Average number of workers performing a preventive maintenance task [unit]	x_{su}	Process development factor for setup time [-]
N_{i-1}	Number of correct parts out of processing step $i - 1$ [unit]	Δz	Change in arbitrary variable
n_{op}	Number of operators [unit]		

1 Introduction

The chapter starts by providing background to the research presented in this thesis; thereafter, the purpose, research questions, and limitations are described.

1.1 Background

Although it is popular today to say that we in Sweden and other Western countries have left the industrial age and now live in the information age, manufacturing is still an important industrial sector. In Sweden, manufacturing accounts for 45% of GDP; 10% of the total workforce is *directly* employed in manufacturing, and, if services connected to manufacturing are considered, then about 25% of the total workforce is employed in the manufacturing industry [1]. However, if Sweden is to maintain or increase the wealth generated by this sector, it must keep up with the global competition that is the reality today.

Considering the relatively high wages in Sweden and other Western countries, certain types of manufacturing, for example, non-complex production demanding a high share of manual work, cannot or are very unlikely to be profitable there. However, there is a risk that manufacturing that could be profitable with appropriate development activities might move to low-wage countries too. Figure 1.1 illustrates this reasoning: the x-axis describes the importance of low costs and the y-axis the importance of customer service capability. Some companies may regard short lead times and high customization as more important than low costs; for these companies, offshoring (i.e., relocating production abroad) to low-wage countries is not a competitive advantage. The opposite may be true for other companies, whose competitiveness is based primarily on the ability to produce at low cost—offshoring may be the best solution for them.

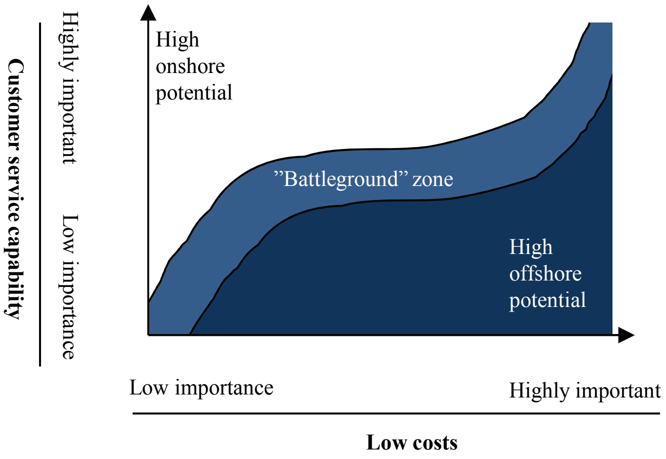


Figure 1.1: Factors influencing the potential for onshore versus offshore manufacturing, adapted from the Bay Area Economic Forum [2]. Customer service capability includes lead time, demand volatility, obsolescence, labor experience, and sensitivity to supply interruption.

There is a borderland—a "battleground" zone as it is called in Figure 1.1—between the more obvious situations in which companies can remain competitive without offshoring either by moving to the left in the figure and improving their manufacturing performance, or by moving upward and competing on the basis of more than just low costs. Companies could, of course, both reduce costs and improve customer service.

This thesis deals primarily with the first alternative, how to move to the left in the figure. Cost reduction can of course benefit even a company competing on the basis of high-quality customer service. Studies from 2004 identified considerable potential for improved efficiency in Swedish production facilities, and realizing this potential does not have to be overly costly [3]. If a company wants to move to the left in Figure 1.1 by lowering its manufacturing costs, it is advantageous to understand the link between the manufacturing system and its costs. What types of costs exert the greatest influence on the products produced, and what parameters are most critical in reducing these costs? Answering such questions could facilitate the shift toward better performance and lower costs.

Manufacturing companies use various measures to monitor the performance of their manufacturing systems and serve as a basis for improvement work decisions. Many of these are non-cost measures, such as overall equipment effectiveness (OEE), lead time, and delivery conformance. The OEE measure originates from the maintenance philosophy total productive maintenance (TPM) and is defined by the product of three performance rates: availability, performance efficiency, and quality [4].

Cost-related performance measures and cost analyses have historically been under the authority of a company's financial department. The financial department traditionally uses manufacturing-related costs for management accounting activities, such as pricing decisions and cost control, by comparing standard costs with actual costs, supported by data from the manufacturing department. Management accounting has been widely discussed in the research community since the introduction in the 1980s of new accounting methods, such as activity-based costing (ABC), target costing, kaizen costing, throughput accounting, and later the balanced scorecard measurement system. The best known of these methods is probably ABC, developed in response to the deficiencies of traditional cost accounting. In traditional cost accounting overhead costs are distributed down to the product level in a simplified way, in many cases based on direct labor, meaning that there is no clear causal relationship between individual costs and cost drivers. ABC assumes that various company activities consume resources and that the products produced by the company consume activities. An advantage of ABC is its more precise allocation of overhead costs, but it is a general concept applying to the whole company, not just to the manufacturing processes. In addition, it provides only a framework for how costs should be calculated, and consequently does not specify particular cost relationships, for example, the cost relationships in a manufacturing system. Kaizen costing is an interesting concept in relation to the present topic, because of its focus on cost reduction. Kaizen costing is closely related to target costing, both of which originated in Japan. While target costing is a management tool for reducing costs in the product development phase, kaizen costing takes over after the product launch as a tool for ongoing cost reduction [5]. In kaizen costing, annual cost reduction targets are determined for plants, which are then distributed to individual targets for various processes in the plant. A weakness of the concept is that it does not describe how costs should be calculated and consequently does not describe the relationship between performance and costs.

Specific manufacturing cost models can be found in the literature. Many of them are for cost-estimation purposes before product launch, but some are for describing costs during the manufacturing phase. None of the models found has a clear relationship to performance rates such as the ones included in OEE.

This thesis presents a cost model for use by manufacturing personnel as support in analyzing and improving manufacturing system performance. The model focuses solely on parameters related to manufacturing systems, and connects manufacturing performance parameters to cost parameters for the purpose of calculating actual costs specifically connected to manufacturing systems. These models are not intended for use in product pricing decisions or cost control; instead, they are solely designed for use as support in decisions concerning development activities for manufacturing systems.

1.2 Objective

Though cost is an essential manufacturing parameter, as stated earlier, there is a lack of models that consider all relevant parameters (including performance parameters) in a manufacturing system that affect the cost of the parts produced in the system. Having such a model would raise the cost consciousness in the manufacturing plant, supporting improvement work to reduce costs, for example, in companies located in the "battleground zone" depicted in Figure 1.1.

The present work seeks to address this lack by developing a model that can raise the cost consciousness in a manufacturing company. The model should provide insight into the link between the design of a manufacturing system, its performance, and the cost per part of the products produced in the system, thereby supporting the analysis and prioritization of manufacturing development activities.

1.3 Research questions

To achieve the objective, two research questions were formulated, the first concerning model development and the second implementation issues.

RQ1: How should a general cost model be designed to take into consideration the most important process-near parameters influencing the performance of a manufacturing system?

RQ2: How can such a cost model be used in practice, i.e., which are the requirements and conditions for its industrial application?

1.4 Delimitations

The work presented here focuses on costs directly connected to the manufacturing process; accordingly, overhead costs for manufacturing management, support functions (e.g., the quality-control department), and other overhead functions not directly linked to the manufacturing process are not considered. This limitation was imposed because the focus is on describing the costs affected by the performance of the manufacturing system and thus can be changed by activities to improve the manufacturing system.

The models were developed assuming that discrete parts are processed or assembled and that an ideal cycle time per unit can be identified, which means that the model is intended for use primarily in discrete manufacturing. The model is also designed primarily for batch manufacturing, and the implementation examples described here are batch manufacturing cases. It is possible, however, to apply the model in continuous manufacturing by neglecting the setup time and in one-piece manufacturing by setting the batch size to 1, but these scenarios are not empirically evaluated here.

1.5 Outline of the thesis

The thesis has the following structure:

Chapter 1: Introduction
This chapter introduces the topic and presents the research objective and questions.

Chapter 2: Research methods
This chapter describes the research approach and methods used in the work presented here.

Chapter 3: Frame of reference
The chapter reviews the literature relevant to the research questions. The literature comprises mainly research on performance measurement and various aspects of manufacturing costs.

Chapter 4: Results
This chapter summarizes the results of the appended papers and describes how each paper addresses the research questions. The chapter also includes a section presenting improvements to the cost model not found in any of the appended papers.

Chapter 5: Discussion
Here the literature reviewed in chapter 3 is discussed in relation to the research results, emphasizing cost accounting methods and manufacturing cost models.

Chapter 6: Conclusions
This chapter summarizes the answers to the research questions.

Chapter 7: Future research
The thesis ends with proposals for future research.

2 Research methods

This chapter describes the research methodology used in the present work. First, the research is positioned among various methodological philosophies and approaches. The methods used in each appended paper are then described in detail, after which the validity and reliability of the work is discussed.

2.1 Research approach

There are several ways to characterize research traditions, paradigms, or philosophies. One distinguishes between positivist and interpretivist traditions [6]. The positivist tradition follows natural science traditions, claiming that the social and natural sciences should be investigated in the same manner. This tradition is connected mainly to quantitative methods, such as experimental and survey research, in which the research outcome is often numerical. Hypotheses are used and the research focuses on the link between cause and effect, so the research employs deductive reasoning. The interpretivist tradition is in many ways the opposite of the positivist tradition. The interpretivist researcher is interested in meaning and believes that the social world is not objective; instead, it is interpreted and constructed by individuals and thereby differs in character from the natural world. Qualitative methods are often used in the interpretivist tradition. The research presented here cannot be categorized as solely positivistic or interpretive, as it was carried out using diverse methods and is not easily placed along the positivistic–interpretative continuum. Papers 1–4 are positivistic due to their mathematical focus, whereas papers 5 and 6 lean towards the interpretative side of the scale.

The present research falls into the category of applied, practical research, as opposed to basic or pure research in which knowledge is sought for its own sake [7], [8]. The work in some of the appended papers can be characterized as theory or concept building, together with the testing of these theories or concepts in a natural setting, i.e., in industry. The research group to which the present author belongs has a long tradition of a kind of applied research that can be described as engineering based, for example, the development of new manufacturing technologies. This tradition has influenced the approach in some parts of the present research, where the work can be better described as method and concept development than as inquiry-based research.

The present research aims to contribute to both to the scientific community and industry. This balance can be difficult to achieve, and there has been considerable debate regarding this issue in the scientific community, especially after Gibbons et al. [9] presented the idea of modes 1 and 2 research. Mode 1 represents traditional research conducted primarily for the scientific community, to fill gaps in existing theories. Mode 2 is more problem-solving oriented and multi-disciplinary, and the practical usefulness of the results are considered important. The pros and cons of research according to mode 2 have been debated, for example, in the management research community [10], where some argue that scientific rigor and practical relevance cannot and should not be combined [11], whereas others are of the opposite opinion, claiming that research conducted jointly with practitioners can have both scientific rigor and practical relevance [12]. The latter opinion is shared by the advocates of interactive research, a Scandinavian initiative that supports mode 2 ideas. This approach is largely similar to action research, but with higher ambitions to contribute to theory development [13]. Interactive research aims to support development-oriented research closely connected to practice [13]. It emphasizes the joint learning process between researcher and practitioner [14] and can be characterized as research conducted *with* practitioners as opposed to traditional research, which is normally conducted *on*. In a similar vein, action research can be described as research conducted *for* [13]. Another way to address similar issues regarding lack of practical relevance is the industry-as-laboratory concept developed by Potts [15]. The concept originates from software engineering research, and its main idea is that the research process entails constant interaction between researcher and practitioner in which the solutions developed by the researcher are constantly evaluated in the "real world". The work presented here has not been carried out strictly according to any of these approaches, but the ideas in these interactive approaches about the importance of practical relevance are considered crucial throughout the thesis. The author believes that, in the field of manufacturing systems, there is a need for research with a clear focus on practical relevance, because of the highly applied nature of the field. Manufacturing systems research is also often practice oriented, aiming, for example, to improve design, analysis, and improvement methods in order to increase industry competitiveness. The research presented here was conducted mainly within the VINNOVA-financed TESSPA and Lean Wood Engineering research projects, and based on the results from the SSF-financed Shortcut project. All these are projects in which university–industry collaboration was a precondition for financing. This collaborative aspect has made practical relevance a natural part of the research process. A risk of research conducted in close collaboration with practitioners is that it may move in a direction resembling consultancy work rather than scientific research, but as stated earlier, this thesis aims to combine scientific and practical relevance. Scientific relevance has been considered, for example, by reviewing the literature to ensure the uniqueness of the work.

The research process for this thesis entailed developing models and concepts, and testing them in real-world settings in various ways. The procedure is largely similar to a framework developed for applied research in the systems development field [16]. This framework includes several research activities that can be both positivistic and interpretive. A model of the framework is shown in Figure 2.1, in which theory building, observation, and experimentation represent different methods used to develop a prototype that constitutes both a proof of concept and a basis for continuing research. This procedure is somewhat similar to the industry-as-laboratory approach, as both seek to ensure the practical relevance of research by iteratively testing their concepts in industry. Though the present work is not systems development, it comprises similar activities, encompassing both model development and the industrial conditions for the models, including prototype development. The various methods used relate to the two research questions. Some of the work presented here constitutes theory building as presented in Figure 2.1, some observation and experimentation, and some prototyping. Section 2.2 will present the research methodology in greater detail, describing and categorizing each paper with reference to the model presented in Figure 2.1.

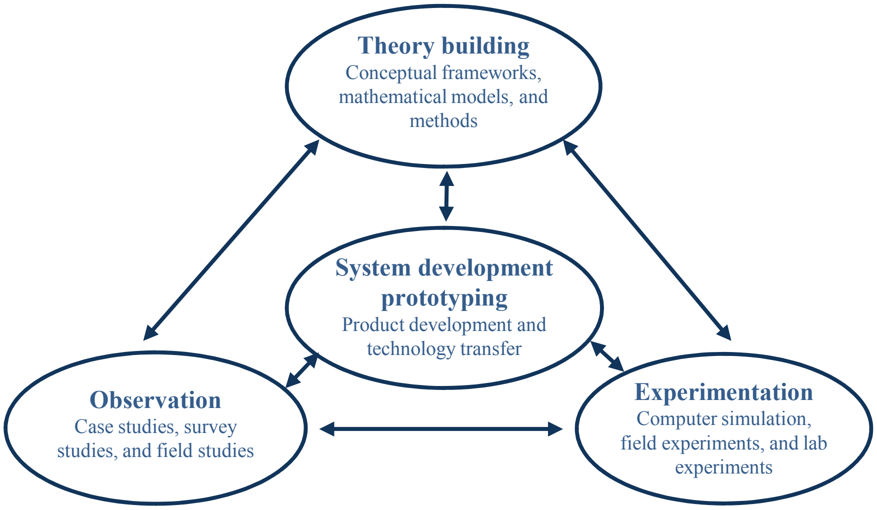


Figure 2.1: Methodological approach to information systems research, adapted from Nunamaker et al. [16].

2.2 Methodological description of the appended papers

The first three papers are model oriented, are clearly related to the first research question (RQ1), and lean primarily toward theory-building as shown in Figure 2.1. The three subsequent papers are primarily linked to the second research question (RQ2).

Paper 1: A general economic model for manufacturing cost simulation

This paper presents a mathematical model for making manufacturing cost calculations. The origin of the model was a belief that the manufacturing industry lacked appropriate methods for analyzing its manufacturing systems from a cost perspective, not least when it came to outsourcing decisions. The problem formulation that led to the formulation of RQ1 originated from industry experience, but the model was developed simultaneously with the literature study in order to investigate the scientific relevance of the problem. The literature study reviewed the literature on manufacturing costs, manufacturing cost models, and cost accounting. The main purpose of the developed model was to link production performance parameters to cost parameters. This would produce a tool for analyzing current manufacturing systems and simulating future scenarios, consequently raising cost consciousness in the manufacturing department. The solution to the problem formulation partly originates from a method developed by Ståhl [17] for collecting and analyzing losses in downtime, quality, and production rate in manufacturing systems. Using this method, data regarding the quantity and the causes of the losses are systematically collected. Results from implementing that model in various companies indicated that these performance losses were often large. Because these losses directly affect production time and the quantity of scrapped parts, they also affect costs, and were therefore considered necessary parameters of the cost model. The cost model presented here can be viewed as building on the method developed by Ståhl [17], in which the results of data collected by the use of the method become part of the input data for the cost model, allowing the costs of specific loss causes to be calculated. These ideas for a production analysis method including a cost perspective, in combination with the results of a literature study of existing cost models, resulted in the model described in Paper 1. The three previously mentioned losses constitute central parameters of the cost model, and the resulting connection between these losses and their costs is what makes the model original.

The cost model is in the paper exemplified by hypothetical data, i.e., no specific empirical data were used when working on this paper. Besides the mathematical model, the paper also suggests how the model can be used in practice. The paper fits well into the theory building category shown in Figure 2.1.

Paper 2: Relations between volume flexibility and part cost in assembly lines

This paper describes how the cost model presented in Paper 1 can be used to analyze volume flexibility in an assembly line from a cost perspective. The idea for the paper originated from a case study of the development of a flexible assembly line, in which the number of operators could be varied to meet varying demands in production volume. In studying the line, the idea emerged of using the cost model presented in Paper 1 to analyze how such flexibility affects the assembly cost. A literature review on volume flexibility and its relationship to costs was conducted to ensure that the problem was also of interest from a scientific perspective.

The data collected during the case study and the configuration of the studied assembly line were used in developing the concept presented in Paper 2. The empirical data come from observations of the assembly line and from interviews, and were gathered to gain an understanding of the assembly line characteristics. The paper includes a modified version of the model presented in Paper 1, based on the collected empirical data regarding the characteristics of the studied line. As in Paper 1, the work presented in this paper originated from problems found in practice. Using the framework presented in Figure 2.1, the paper can be categorized as a combination of theory building and observation, with an emphasis on theory building.

Paper 3: Dynamic manufacturing costs - describing the dynamic behavior of downtimes from a cost perspective

Paper 3 is somewhat similar to Paper 2, as it also describes a new application area for the cost model presented in Paper 1. The concept for the work presented in the paper was not based on any specific empirical findings, but is presented here using data from a company. The data consist mainly of downtime data extracted from the company's downtime collection system, and of cycle time data and cost data regarding material, wages, and equipment. Real data were used to ensure that the results would be representative of real-world conditions. A literature review on downtime variability and downtime costs was conducted to relate the proposed approach to existing research in the field. Using the framework presented in Figure 2.1, the paper can be categorized as theory building, with some elements of observation due to the use of real data.

Paper 4: Implementation of an economic model to simulate manufacturing costs

This paper applies the cost model developed in Paper 1 in an industrial setting. The study tests the applicability of the model in a real-world case, thereby investigating how it could be applied in practice. A manufacturing cell in an automotive company was selected for the study. The company was regarded as an intended typical user of the model in terms of production configuration (i.e., batch production divided into several processing steps) and products (i.e., products entailing significant manufacturing costs). The study started by defining and characterizing the cell in relation to the model parameters by means of observations and interviews. Input data for the model were then collected by means of observations and from databases (in the case of cost-related data). The observations were made using the production performance matrix (PPM) concept (see section 3.1.2.1) to gather data on manufacturing performance parameters, comprising downtimes, scrapped parts, along with the registration of the causes of those losses, and setup time. This paper constitutes observations as presented in Figure 2.1.

Paper 5: Conditions for and development of an IT-support tool for manufacturing costs calculations and analyses

Paper 5 investigates the conditions for the industrial use of the cost model and describes a prototype software application of the model. The conditions were investigated in two studies. The first study investigated the functionality of various commercial manufacturing performance data collection systems in terms of their support of the collection of the data required for the cost model. The second study investigated whether manufacturing companies were indeed collecting the required data. The first study investigated four data collection systems by interviewing the relevant software suppliers. The interviews were semi-structured and aimed at mapping the performance of the systems. The second study was conducted by visiting five manufacturing companies to evaluate their performance data collection systems by means of semi-structured interviews. The purpose of these studies was not to obtain generalizable results, but rather to gain an idea of the prevailing conditions. The software products chosen for the first study were based mainly on the software products used by the companies collaborating in the TESSPA project. Companies participating in that project, with one exception, also constituted the participating companies in the second study. The software prototype was developed in collaboration with an intended user of the software. The collaboration ensured that the prototype would be developed based on real-world conditions in terms of, for example, data storage and parameter definitions. The purpose of developing the software application was to explore the requirements for a user-friendly software application of the cost model, what functions it should include, and how the results could be presented and visualized. Using the framework presented in Figure 2.1, the paper can be categorized as a combination of observation and system development prototyping.

Paper 6: Availability improvement by structured data collection: a study at a sawmill

Paper 6 investigates how the detail level of the downtime data companies collect for follow-up and analysis of availability affects data usability and examines how the operators responsible for data collection perceive changes in the level of data detail. This study used an interactive approach and was conducted at a sawmill company. It was interactive in the sense that the researcher and company personnel jointly developed a new structure for grouping the various downtime causes available in the downtime data collection system used by the company. In addition, new downtime causes were added to the new structure to increase the detail level of the collected data. The new structure was based on a structure found in the PPM concept, developed by Ståhl [17] and described in section 3.1.2.1. This structure was presented to the production manager and the most experienced maintenance worker in the company. The original structure was then modified and new downtime causes were formulated, based on the experience of these two company representatives and the present author. The new structure was immediately put into use in one section of the sawmill. After it had been used a few months, operators and the production manager were interviewed. The operator interviews concerned their experience of registering downtimes based on the new structure and the increased number of downtime causes. The interview with the production manager concerned whether the higher level of detail in downtime causes affected the knowledge gained from the collected data. This paper fits into the observation category presented in Figure 2.1.

Additional model development not included in the appended papers

Section 4.2 describes developments of the cost model presented in Paper 1, including enhanced equations for calculating downtime and equipment costs. There is a major difference between planned and unplanned downtimes regarding their link to manufacturing performance and when they occur. This knowledge evolved during the course of the PhD project and was therefore not considered sufficiently in Paper 1. When implementing the model in industry, it was realized that equipment costs were the most difficult to determine with desired accuracy. Every company has its own opinion as to how these costs should be calculated, for example, concerning what costs to include and the time frame on which to base depreciation calculations. Hence, it was considered necessary to define the two equipment cost parameters of the cost model in greater detail, suitable for the type of analysis for which the cost model is intended. The proposed hourly equipment cost expressions were developed based on literature studies of the subject. The section largely constitutes theory building and fits into the theory building category presented in Figure 2.1.

2.3 Validity and reliability

Two common parameters used to describe the quality of research work are validity and reliability.

Validity

Validity relates to accuracy, i.e., whether the research instrument measures what it is designed to measure [6]. This is a fairly complex term for which several definitions can be found in the literature. Yin [18] lists three types of validity: construct validity, internal validity, and external validity. Construct validity is about constructing correct operative measures of the phenomenon being studied and avoiding subjective judgments in the data collection phase. Internal validity concerns the establishment of causal relationships in which one demonstrates that certain conditions lead to other conditions (this applies only to explanatory and causal studies). External validity is equivalent to generalizability and describes the extent to which a study can be generalized.

The construct validity of papers 1–3, characterized by method and model development, is strengthened by literature studies, in which the proposed methods and models are compared with similar findings in the literature. The thesis also describes implementations of these methods and models in an industrial context to strengthen the construct validity. For the work presented in Paper 6, the construct validity was considered by interviewing several people in the company and by holding ongoing discussions of the research with company representatives. The construct validity of this thesis is also strengthened by the fact that results were presented in international conferences that included review procedures and in peer-reviewed scientific journals.

Internal validity is mainly applicable in the work presented in Paper 6, which includes a pre-experiment that can be described as a one-shot case study. This is generally viewed as the weakest form of experiment because the parameters included are not controlled. This study design was used because the interviews conducted after the change focused on comparisons between the old and the new downtime collection structures, concerning how the respondents experienced the change, so no causal relationships were established.

Yin [18] claims there are two types of generalizations, statistical and analytical. Statistical generalization is perhaps the most obvious type, and describes how generalizations can be extended to a population from a sample. Analytical generalization refers to the generalization of results into a theory and not to a population. The generalizations made in this thesis are based on analytical generalization. The proposed mathematical models and methods are designed to be applicable in the area of discrete manufacturing. The aim has been to develop general models and methods in this area, though, as various implementations have demonstrated, minor adjustments of the mathematical models have to be made in every case.

Reliability

Reliability describes the repeatability of the research, i.e., the degree to which one obtains the same results when repeating the research. Appended papers on model and method development cannot be described in terms of reliability as they are not based primarily on empirical findings. However, reliability is considered when implementing these concepts in industry, as described in papers 4–6. The data used in the implementations are stored in databases or written documents. The interviews conducted for the work described in Paper 6 are also stored in databases.

3 Frame of reference

This chapter describes the frame of reference of the thesis. Because this thesis concerns the links between a manufacturing system's technology, performance, and cost, the frame of reference focuses on these issues. It starts with work on performance and performance measurement in manufacturing systems; thereafter, various methods and models concerning manufacturing costs are described.

Since all of the work presented in this thesis concerns manufacturing system performance, in some respects, section 3.1 can be considered to be related to the entire work, except for section 3.1.2.3 on downtime registration, which is clearly linked to Paper 6. Section 3.2 on cost accounting, section 3.3 on manufacturing cost models, and section 3.4.1 on quality cost relate primarily to Paper 1, but also to papers 4 and 5. Section 3.4.2 on downtime variability and its costs relates to Paper 3 and section 3.4.3 on volume flexibility and its costs relates to Paper 2. Section 3.4.4 on equipment cost relates to the additional results presented in section 4.2.

3.1 Manufacturing system performance

Manufacturing system performance is a broad topic including modeling techniques, methods for analyzing and improving the performance, and measurement system design. The performance literature reviewed below is clearly linked to the parameters included in the proposed cost model and covers theories of performance improvement and its relationships with costs, and performance measurement.

3.1.1 Theories of the relationship between performance improvement and cost

In 1990, Ferdows and De Meyer presented a model of manufacturing development called the sand cone model [19] (see Figure 3.1). The idea underlying the model is based on the assumption of Skinner [20] and many subsequent researchers that there are tradeoffs between various manufacturing capabilities, an increase in one leading to a decrease in another, meaning that a manufacturer cannot excel in all. The manufacturing capabilities in question are, above all, cost efficiency, quality, dependability, and flexibility. Ferdows and De Meyer found that not all companies encountered such tradeoffs, and the authors believe that this is due to the sequence in which the capabilities are improved. The sand cone model illustrates the appropriate sequence, according to Ferdows and De Meyer. In this model, quality is the basis: for lasting improvements in any other capability, quality must be considered first. Only when quality is acceptable can one also start to improve manufacturing dependability; thereafter, work on improving manufacturing speed (or flexibility) can begin. When effort has gone into increasing manufacturing speed, then cost efficiency programs can be started, although Ferdows and De Meyer claim that cost efficiency may be reduced due to improvements in other capabilities.

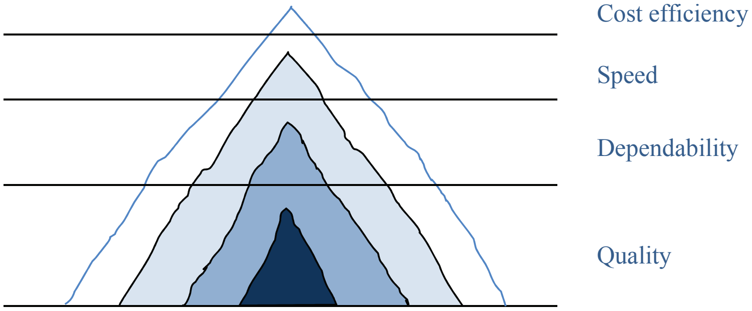


Figure 3.1: The sand cone model, adapted from Ferdows and De Meyer [19].

Whether this model is true, that is, whether the sequence suggested in the sand cone model is better than another, has been investigated extensively with mixed results [21]. According to Schroeder et al. [21], many previous evaluations of the model have been inadequate, as they have not really examined the suggested sequence but only established positive relationships between the capabilities. Schroeder et al. therefore conducted a new evaluation based on two types of tests considering the sequence, and found no consistent support for the sand cone model. Schroeder et al. believe that there might be a consistency effect, i.e., the best sequence could vary based on, for example, country and industry.

Besides the tradeoff and sand cone theories, other theories treat the same theme. Schmenner and Swink [22] have developed a theory of performance frontiers. The theory includes both the tradeoff and sand cone theories, concluding that both are valid, but in different situations. A performance frontier is defined as "the maximum performance that can be achieved by a manufacturing unit given a set of operating choices" [22]. The model includes two frontiers: the asset frontier and operating frontier. The asset frontier is altered by investments in manufacturing equipment, while the operating frontier is altered by changes in the operation procedures and policies of the manufacturing system given its existing asset frontier. Figure 3.2 depicts the theory. Figure 3.2 (a) shows the performance frontiers of two hypothetical plants, A and B. Both plants share the same asset frontier, i.e., the same equipment, but have different operating frontiers. The different operating frontiers suggest that the plants may have different management policies, plant B's being more successful. Schmenner and Swink distinguish two types of movements within the operating space (i.e., within the operating frontier): improvement and betterment. *Improvement* is defined as improved performance in one or more dimensions without degradation in any other dimension, for example, by increasing efficiency or utilization; Figure 3.2 (b) illustrates this, A representing the condition before improvement. After improvement, the company has moved to the operating frontier, meaning that, from now on, further improvements will cause higher unit costs. *Betterment* is defined as any change in operation policies leading to a rightward movement of the operating frontier or to a new shape of the frontier. This is depicted in Figure 3.2 (b), which shows that betterments lead to a new operating frontier as the company moves from A_1 to A_2. Schmenner and Swink are saying that when a company is far away from its operating frontier, it can make improvements in one performance dimension without risk of degrading other dimensions, in accordance with the cumulative effect argued for in the sand cone theory. However, when the company has reached its operating frontier, then improvements in one performance dimension will likely cause degradation in other dimensions, i.e., tradeoff theory will then apply.

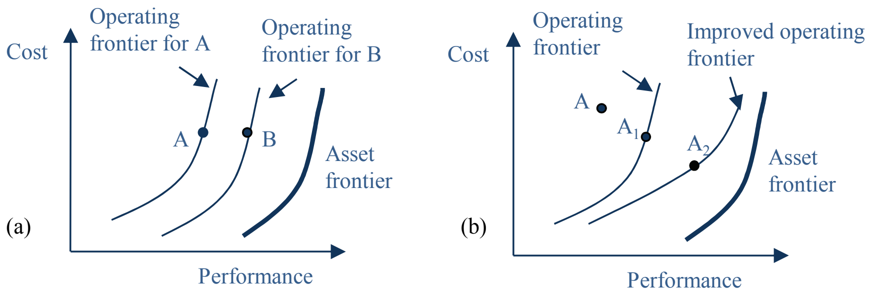


Figure 3.2: (a) Performance of two companies with identical asset frontiers but different operating frontiers. (b) Improvement leading to a shift from A to A_1 and a betterment leading to a shift from A_1 to A_2.

3.1.2 Performance measurement

A performance measurement system (PMS) is defined by Neely et al. [23] as a "set of metrics used to quantify both the efficiency and effectiveness of actions." Despite an extensive, decades-long PMS literature related to manufacturing, there has been a marked increase in publications in this field over the last 20 years [24]. According to Ghalayini and Noble [25], the PMS literature can be divided into two main phases, the first extending from the 1880s to the early 1990s and the second, or current phase, covering the period since then. In the first phase, financial measures were emphasized. In the current phase, considerable emphasis is placed on the shortcomings of traditional financial measures; the use of non-financial measures is advocated, although there is no clear consensus among authors as to what non-financial measures companies should select.

Neely et al. [23], in reviewing the PMS literature, distinguish four dimensions of performance measures, namely, quality, time, flexibility, and cost. These four dimensions describe what these authors found that the literature regarded as the most important dimensions in defining manufacturing performance. White [26], in his survey of performance measures, proposes a similar division, but as well as the four dimensions mentioned above, his also includes delivery reliability as a major dimension. White says that these five dimensions jointly constitute competitive capability, and adds four additional dimensions that describe various aspects of the measures, such as data source and type, as shown in Table 3.1.

Table 3.1: White's five dimensions of a PMS.

Competitive capability	**Data type**	**Reference**	**Orientation**	**Data source**
Cost Quality Flexibility Delivery reliability Speed	Subjective Objective	Benchmark Self-referenced	Process input Process outcome	Internal External

White concludes that most measures used by companies are internal, objective, and self-referenced, and have a process–outcome orientation. At the same time, he argues for the importance of companies' also obtaining externally based, subjective, benchmark, and process input-oriented measures and not simply focusing on cost capabilities, as many companies have traditionally done.

Arguing as White does for multidimensional measures is common in the second phase of PMS research. Gomes et al. [27], in their review of the PMS literature, constructed a five-phase framework for the evolution of PMS. The framework they advocate suggests that development is headed toward multidimensional, balanced, and integrated measures, as well as toward acceptance of the importance of non-financial measures and of the connection between these measures and company strategy.

3.1.2.1 The production performance matrix (PPM)

The production performance matrix (PPM) model for collecting and analyzing process-near losses has been developed by Ståhl [17] and is shown in Figure 3.3. This model was originally developed to analyze tool breakdowns in metal cutting, but has since also been used to analyze whole manufacturing systems. The performance parameters Q, S, and P represent the OEE parameters quality, availability, and performance efficiency, respectively. The groups A to H in the figure represent the causes of the disturbances involved. A benefit of this model is its structure, i.e., the division of the causes into different groups, which can facilitate both downtime registration and result analysis.

		Performance parameters			
Groups of causes	Description	$Q_1,..,Q_n$ (units)	$S_1,...,S_n$ (min)	$P_1,...,P_n$ (min)	Σ
$A_1,...,A_n$	Tool-related failures				
$B_1,...,B_n$	Material-related failures				
$C_1,...,C_n$	Machine-related failures				
$D_1,...,D_n$	Failures related to personnel and organization				
$E_1,...,E_n$	Maintenance-related factors				
$F_1,...,F_n$	Specific process-related factors				
$G_1,...,G_n$	Factors related to peripherals such as material handling equipment				
H	Unknown factors				
Σ					

Figure 3.3: Structure for systematic analysis of manufacturing processes.

3.1.2.2 Overall equipment effectiveness (OEE)

One measurement manufacturing companies often employ is overall equipment effectiveness (OEE). Nevertheless, the PMS literature seldom treats this measure, possibly because of the previously described emphasis on multidimensional measures in the PMS literature. OEE focuses on what Nakajima [4] calls the “six big losses” due to equipment failure, required setup time, idling and minor stoppages, reduced speed, quality defects, and reduced yield. As can be seen, OEE measures the performance of equipment on the shop floor. OEE is calculated by multiplying availability rate, A, by performance efficiency, P, and quality rate, Q. The rates are defined in equations 3.1 to 3.4.

$$Q = \frac{\text{processed amount} - \text{defect amount}}{\text{processed amount}} \tag{3.1}$$

$$A = \frac{\text{operating time}}{\text{loading time}} \tag{3.2}$$

The operating time is defined in Equation 3.3, in which loading time is total production time minus planned downtimes, such as planned maintenance and scheduled meetings. Unplanned downtimes result from, for example, failures, setup times, and time for die exchange.

$$\text{operating time} = \text{loading time} - \text{unplanned downtime} \tag{3.3}$$

$$P = \frac{\text{processed amount} \cdot \text{ideal cycle time}}{\text{operating time}} \tag{3.4}$$

Using White's categorization as shown in Table 3.1, OEE then measures various aspects of quality, flexibility, and speed. OEE is also internal, objective, and self-referenced and measures process outcome. It fails, however, to use all the proposed dimensions of a measurement system and needs to be complemented by additional measures, as has also been noted by Jonsson and Lesshammar [28]. Another shortcoming of OEE is that it measures only the performance of individual pieces of equipment, failing to take account of the links between various machines and the flow of materials in the manufacturing system. This shortcoming of OEE has been identified by Jonsson and Lesshammar [28], Muchiri and Pintelon [29], and Muthia and Huang [30]. Muthia and Huang [30] propose a solution to the insufficiency of individually measuring pieces of equipment, introducing the term overall throughput effectiveness (OTE). OTE is based on OEE and can be described as a factory-level version of OEE that takes equipment dependability into account. OTE is expressed in four ways, depending on the characteristics of the layout of machines, such as whether they function in series or parallel.

In their review of the OEE literature, Muchiri and Pintelon [29] consider various suggested modifications of OEE, all of which attempt to overcome its various insufficiencies. The modified measures include production equipment effectiveness (PEE), overall asset effectiveness (OAE), overall plant effectiveness (OPE), and OTE. Muchiri and Pintelon [29] believe that the absence of a cost dimension is a serious shortcoming of OEE and that future research should explore the translation of equipment effectiveness into costs. They also believe that future research should investigate the benefits of investing in automated data collection systems to gather the data needed for OEE calculations.

3.1.2.3 Documenting downtime losses

After Nakajima presented the OEE measure, several papers examined the subject, some proposing improvements to the original OEE definition. For example, Jeong and Phillips [31] extended Nakajima's six losses to 10 losses, a schema they believe is more suitable in capital-intensive companies. The losses defined by Jeong and Phillips are: nonscheduled time, scheduled maintenance, unscheduled maintenance, R&D time, engineering usage time, setup and adjustment, WIP starvation time, idle time without operator, speed loss, and quality loss. Jeong and Phillips claim that a deficiency of the original OEE definition is that planned downtime, such as planned maintenance, is not considered a downtime loss. They believe that as planned downtimes are crucial to capital-intensive companies, these must be included in OEE. They acknowledge that the accuracy of the OEE measure depends on the quality of the collected input data. The available downtime causes to choose from in a computerized collection system must be well defined, which calls for careful collection system design.

Bamber et al. [32] advocate the use of cross-functional teams to improve OEE figures, because they believe that several competences, for example, maintenance, production, and quality, are needed for successful improvement work. In their case study, the OEE monitoring apparently consisted solely of time data without any data describing the downtimes or their causes. This means that the OEE figures were used only to measure the performance; the causes underlying the losses had to be found when developing the cause–effect diagram. Dal et al. [33] describe OEE implementation by an airbag manufacturer. Operators documented the downtime losses by recording the durations and descriptions of the downtimes on a record sheet. They also discuss the importance of accurate data: data must be convincing to production management, otherwise they will not be used effectively. Ljungberg [34] also discusses the importance of data collection, claiming that data collection problems have been insufficiently treated in the literature. Such problems include poor data collection systems—which must be fast but still accurate—and resistance on the parts of operators and foremen to collecting the data. This resistance can be decreased, according to Ljungberg, by designing the data collection system together with the users, an approach also mentioned by Gibbons and Burgess [35]. Resistance can also be decreased if users are helped to understand how the data are actually compiled and used, according to Ljungberg. Ljungberg [34] also discusses the pros and cons of registering the losses using pen-and-paper versus computerized systems. Pen-and-paper solutions are simpler than computerized systems, but the recorded downtime durations will not be completely accurate. A computerized system can register correct downtime durations, and some systems even force the operator to register a downtime cause before the equipment can be restarted, meaning that all losses will be registered. However, such software systems can be expensive and difficult to use. A computerized system in which the operator registers failure number and type while the computer keeps track of the downtime and the actual cycle time is recommended. Ljungberg's OEE measurements used five independent variables to categorize the cause of every recorded loss; these variables were production process, process knowledge, maintenance activities, external factors, and production conditions.

Wang and Pan [36] recommend computerized data collection in which the operator chooses a specific downtime cause to describe the failure. They present an example from the semiconductor industry in which seven downtime causes are available. They also demonstrate how a cause–effect diagram can be used to determine more detailed downtime causes. How the collected data are or should be used is not considered. Andersson and Bellgran [37] have compared manual and automatic downtime registration in a company having both systems. They too declare the advantages of an automatic system, its only disadvantages being investment and licensing costs and setup time.

Some non-OEE-related literature also considers downtime registration. For example, De Smet et al. [38] describe various case studies of disturbance registration. In one case, the downtime causes from which the operator could choose when registering a failure were too general and vague. Operators could also supply additional explanation in a comment line, but did not use this feature satisfactorily. Consequently, a more relevant and detailed list of causes was developed for each machine, and feedback was given to the people who registered the failures to motivate them to better describe the failures.

3.2 Cost accounting methods

In Swedish industry, the principles of cost accounting stem from a model presented in 1936 called “Enhetliga principer för självkostnadskalkylering” [39]. The model is often called EP and is used for absorption costing, i.e., a method for distributing all costs generated in the company down to every produced product. In this model, the cost items are as follows:

- Direct material cost
- Indirect material cost
- Direct labor cost
- Manufacturing overhead costs
- Special direct costs
- Cost of sales
- Administration costs

In EP, manufacturing overhead costs are divided into costs closely connected to manufacturing and costs that are not. The first group includes costs such as those of maintenance, additives, energy, equipment, building, and employees in the manufacturing department. The second group includes costs such as design department, patent, and laboratory costs. According to EP, manufacturing overhead costs are allocated based on direct material, direct labor, labor hours, or machine hours.

3.2.1 Activity-based costing (ABC)

According to Kaplan and Anderson [40], activity-based costing (ABC) corrected some of the problems found in traditional cost accounting. The traditional cost accounting model was developed at a time when direct labor constituted a larger part of the total cost than it does today, meaning that direct labor has become an increasingly worse allocation key for overhead costs. Furthermore, companies have shifted from mass production strategies to more flexible, customer-focused strategies, resulting in increased overhead costs. According to Plowman [41], when traditional cost accounting was developed, overhead costs constituted such a small proportion of the total cost that it was not seen as worthwhile to have a system that more accurately captured the proportion of the overhead costs associated with each product. Distributing the overhead costs based on, for example, direct labor was in this context seen as simple and sufficiently correct.

ABC is a method aiming to allocate overhead costs more correctly by tracing these costs to activities and then connecting the activity costs to the order, product, or customer levels. Instead of grouping several activities into an overhead cost pool, such as manufacturing overhead, the cost item is segregated into several activities [42]. ABC can be divided into two stages. The first entails allocating costs based on the main activities occurring in various departments to form activity cost pools, called resource cost drivers. The second stage entails allocating these costs to cost objects (e.g., products, customers, or any chosen unit of analysis) by identifying activity cost drivers. See Figure 3.4 for a generic model of the process.

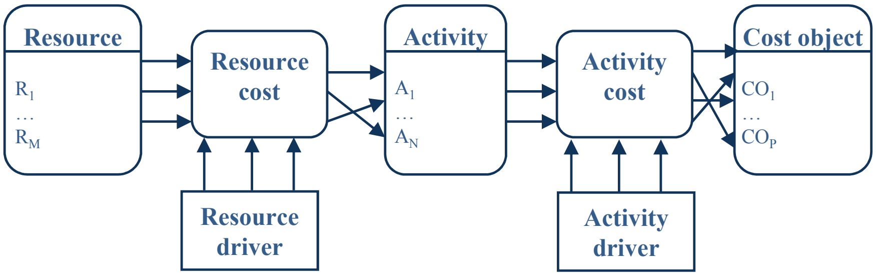


Figure 3.4: Generic ABC model, adapted from Bart et al. [43].

The accuracy of the activity cost drivers can be divided into three levels: transaction, duration, and intensity/direct charge [44]. Thyssen et al. [45] illustrate these accuracy levels by citing the setup activity in a manufacturing system. In this case, a transaction cost driver can be the number of setups, assuming all setups consume equal costs, while a duration cost driver can be setup time, assuming the setup cost per hour is the same in every case. Finally, an intensity cost driver is identified by measuring the resource consumption of each setup. In ABC, the aim is not necessarily to allocate all costs down to individual units; Cooper and Kaplan [42] present a hierarchical principle in which activities are grouped as unit-level, batch-level, product-sustaining, and facility-sustaining activities (see Figure 3.5). According to this principle, only unit-level activities should be allocated to individual units. Unit-level activities are activities conducted on every unit, such as a specific machining operation. Setup activities, on the other hand, are batch-level activities and should not be allocated to units. This division is made because, for example, dividing batch-level activities by the quantity of products produced in the batch gives the false impression that the batch-level costs vary with the number of products.

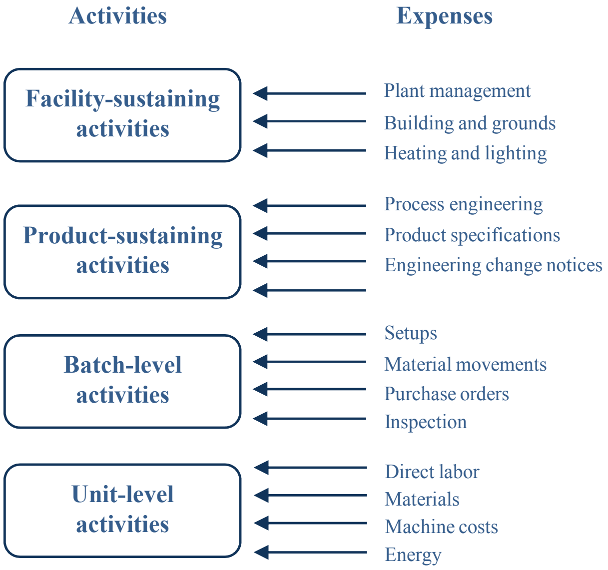


Figure 3.5: The hierarchy of activities and expenses, adapted from Cooper and Kaplan [42].

In ABC, unused capacity does not influence the cost of an activity [46]. The activity cost per cost driver, for example, cost per purchasing order in a purchasing department, is based on the available resources, i.e., the practical number of purchase orders the department can handle based on the resources available to purchasing staff. The cost of supplied resources of an activity can consequently be described as:

Cost of activity supplied = Cost of activity used + cost of unused capacity

This does not mean that the cost of unused capacity is neglected in ABC. Unused capacity cost indicates a mismatch between supplied and used resources, which the company should reduce by either reducing the quantity of supplied resources or exploiting the unused capacity, for example, by producing a new product.

Some years after the first papers on ABC were published, a variant of ABC evolved called activity-based management (ABM). ABM focuses on processes instead of products, using ABC data for performance measurements [47]. Figure 3.6 depicts the difference between ABC and ABM.

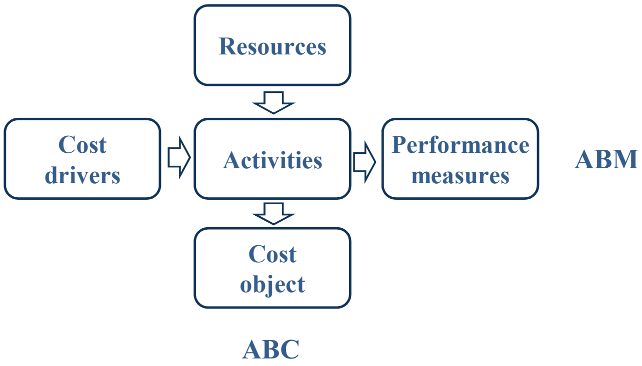


Figure 3.6: The difference in perspective between ABC and ABM.

In 2007, Kaplan and Anderson released a book in which they presented the concept of time-driven activity-based costing (TDABC) [40]. TDABC was developed because many users found traditional ABC too time-consuming to implement, sustain, and modify. Many users also doubted the accuracy of the resulting cost calculations. The principle of TDABC can be divided into two steps. The first entails calculating the cost of a specific resource, for example, a purchasing department. This cost is then divided by the available capacity in terms of time, giving the capacity cost rate. The next step is to estimate the time required for specific activities, for example, the time required to process a particular order. The cost of processing this order is then calculated by multiplying the capacity cost rate by the processing time. The cost of a process comprising several activities, for example, the manufacturing cost of a product produced using several machines, is calculated by building a time equation including the capacity cost rates and processing times of every machine used. The numerator of the capacity cost rate should include the costs of all resources required for the employee or equipment to perform the work. In many examples cited by Kaplan and Anderson [40], the capacity cost constitutes the cost of a department in the company—this is considered the simplest way to calculate the capacity cost. However, the authors also acknowledge that department cost can sometime be insufficient, for example, if some of a department's resources are used by only one product. In such cases, the department cost can be divided into several process costs.

The denominator of the capacity cost rate, i.e., the capacity, should be the practical capacity, meaning the theoretical capacity minus breaks, training, education, repairs, and maintenance. Although this concept is called time-driven ABC, Kaplan and Anderson [40] acknowledge that not all capacity cost rates should be based on time; sometimes, for example, square meters may be a better choice of dominator.

TDABC is considered to reduce the time spent collecting data, because changes only need to be made when resource cost or processing time changes. The accuracy is also considered to increase because staff no longer need to estimate the proportion of their time spent on specific activities.

3.2.2 Throughput accounting

Another cost accounting method sometimes mentioned alongside ABC as an example of a new cost accounting concept is throughput accounting (TA), a method based on the theory of constraints (TOC). TOC was developed by Goldratt, among others, in the 1980s; the first ideas that would form the concept were introduced in *The Goal* [48] and have since been developed further in several papers. According to Rahman [49], TOC can be summarized by the following statements: "every system must have at least one constraint" and "the existence of constraints represents opportunities for improvement." Constraints determine the performance limits of an organization: without any constraints, a profit-generating organization would have unlimited profits. According to Dugdale and Jones [50], there is no consistent TA theory, as the approach has been developed in parallel by various authors. Some regard TA as based on Goldratt's theoretical work, while others associate TA with the work of Galloway and Waldron.

Goldratt's theory includes three operational measures: throughput (T), inventory (I), and operating expense (OE) [51]. T is the sales revenue less the total variable cost, I is the total money invested in the products in inventory, and OE is the non-variable costs spent turning inventory into throughput. Based on these measures, net profit (NP) and return on investment (ROI) can be calculated. NP is defined as T – I and ROI as NP/I.

According to Dugdale and Jones [50], Galloway and Waldron are the key figures in developing TA. Central to TA is the rate at which businesses earn money, and the focus is on maximizing the return per bottleneck hour. In Galloway and Waldron's version of TA, all costs, except material cost, are viewed as fixed costs in the short term, referred to in TA as total factory cost (TFC). The rate at which a product generates money is central to TA, and this rate determines a product's profitability in relation to other products. A product's absolute profitability is the relationship between its profitability rate and cost rate. TA ranks products according to the TA ratio, which is defined by equations 3.5 to 3.7. The return per factory hour is defined as:

$$\text{Return per factory hour} = \frac{\text{Salesprice} - \text{Material cost}}{\text{Time on key resource}} \qquad 3.5$$

The cost per factory hour is defined as:

$$\text{Cost per factory hour} = \frac{\text{Total factory cost}}{\text{Total time available on key resource}} \qquad 3.6$$

Based on equations 3.5 and 3.6, the TA ratio is:

$$\text{TA ratio} = \frac{\text{Return per factory hour}}{\text{Cost per factory hour}} \qquad 3.7$$

Galloway and Waldron developed their view of TA over several years, and in that time they abandoned some of their previous ideas and added others. A later contribution was T/TFC, an overall process measure defined as:

$$\text{T/TFC} = \frac{\text{Throughput}}{\text{Total factory cost}} \tag{3.8}$$

In T/TFC, throughput is defined as the contribution margin after material cost, and total factory cost as all the costs occurring except for material cost.

3.2.3 Life cycle costing

Woodward [52] describes life cycle costing (LCC) as a method that “seeks to optimize the cost of acquiring, owning, and operating physical assets over their useful lives by attempting to identify and quantify all the significant costs involved in that life by the use of the present value technique.” The method was originally used by the US Department of Defense in the 1960s, but has since been applied in many other contexts, such as consumer products, equipment acquisition in manufacturing companies, and building acquisition [52], [53]. Woodward presents [52] an overview of the LCC concept, primarily in the equipment acquisition context, identifying the following elements:

- Initial capital costs, including purchase costs, acquisition/finance costs, and installation/training costs
- Life of asset
- Discount rate
- Operating and maintenance costs: the former include direct and indirect costs of labor and materials, direct expenses, and establishment costs; the latter include direct labor, materials, fuel, equipment, and purchased services
- Disposal cost
- Information and feedback
- Uncertainty and sensitivity analysis

The German VDMA 34160 standard, “Forecasting model for lifecycle costs of machines and plants” [54], includes a comprehensive list of items influencing the cost of a machine throughout its life cycle. The various cost items are grouped into three phases, the preparatory, operating, and further utilization phases, each including different cost pools containing various constituent parameters. The phases and their cost pools are listed below:

Preparatory phase

- Acquisition
- Infrastructure costs
- Other preparatory costs

Operating phase

- Maintenance and inspection
- Repairs
- Unscheduled repairs
- Occupancy costs
- Material costs
- Energy costs
- Production and process materials
- Disposal costs

- Personnel costs
- Tool costs
- Setup costs
- Warehousing costs
- Other operating costs

Further utilization phase

- Dismantling
- Residual value
- Other further utilization costs

The standard also includes formulas for calculating the values of the cost pools based on the cost items and parameters listed for each cost pool.

An example of LCC implementation is described by Folgado et al. [55]. In this case study, LCC is used to compare two mould manufacturing alternatives. The total cost is divided into three categories: process cost (i.e., machine and labor), material cost (i.e., raw materials, standard components, disposable tools, and other consumables), and energy costs (i.e., energy consumed by the equipment). Other input parameters are times (e.g., setup and operation), equipment availability, production volume, and batch size. Any equations for the cost calculations are not presented.

3.2.4 Kaizen costing

Kaizen costing is a cost management concept that originated in Japan. In Japan, it is often used together with target costing, a Japanese cost management concept used to reduce costs in product development. After this phase, the focus shifts to reducing the current manufacturing costs of a product, and it is in this phase that kaizen costing is employed. The main purpose of kaizen costing is to achieve ongoing cost reduction by periodically setting cost reduction goals for manufacturing processes. Lee and Monden [5] have described the use of kaizen costing in a Japanese company. The studied company set annual cost reduction targets for its plants as part of the budget process. These targets are broken down into cost reduction targets for specific processes in the plant. The cost reduction targets for the processes are then translated into improvement actions. Monden and Hamada [56] take a cost reduction target for a manufacturing department as an example. In this case, cost reduction can be realized in two ways: reducing labor cost by increasing capacity availability or reducing workforce size. The availability increase is then further divided into goals for specific processes, for example, goals for setup time reduction and machine breakdown reduction. According to Lee and Monden [5], fairly simple cost accounting methods can be used for the cost calculations.

3.2.5 Resource consumption accounting

Resource consumption accounting (RCA) is a new accounting method, conceived circa 2000 [57]. It is promoted as a method combining the best of the German accounting tradition and ABC. According to Clinton and Webber [58], cost management in the USA and German-speaking countries belongs to different traditions. In the USA, cost management is highly influenced by financial accounting and external accounting, which has led to simpler accounting systems than those in many other developed countries. According to White [59], RCA is an accounting system that focuses on the manager and not the external financial statement. RCA represents an attempt to integrate the best ideas from the German tradition, internationally often called GPK, with existing ideas from the USA, for example, ABC.

Resource flows and pools are central concepts in RCA. The resources flow between resource pools and to products. A resource pool (i.e., cost pool) needs specific inputs to produce an output, which can in turn support another cost pool or a product or service for a customer. It is important that the flows be modeled correctly, because one objective of RCA is to provide managers with cause-and-effect information so they can make the right decisions. Another central principle is responsiveness. This principle acknowledges that the relationship between resource pools can include both fixed and proportional costs and that the nature of the costs can change between pools. An example of this is electricity: it comes to the company as a proportional cost, but in some resource pools it becomes a fixed cost, for example, the cost of heating and lighting a manufacturing plant. The opposite of responsiveness is variability, i.e., that there is a clear relationship between total cost and total volume [59].

In RCA, only the costs of resources used should be allocated to products; the costs of idle capacity should be acknowledged but not affect the product cost. Costs of idle capacity should be attributed to the person or department responsible for them. Causality between resources and resource drivers are considered important. If causality cannot be determined, for example, regarding idle capacity, the costs should not be allocated to products [58]. Causality entails a cause–effect relationship between cost pools. If costs in one cost pool do not influence those in another cost pool or product, no such relationship should be included in the cost model, i.e., no arbitrary allocation should be made. The causality between resources and between resources and products should be based on non-cost quantitative relationships, i.e., not on percentages or other arbitrary principles [59].

RCA recommends that depreciation costs should be calculated based on replacement cost. If the same product is made using two different machines, one older than the other, the product cost should be the same [58].

3.3 Manufacturing cost models

Besides the general cost accounting methods mentioned above, several papers describe more detailed cost models that capture the costs related solely to the manufacturing system, not attempting to be full cost models. These models can be classified in various ways depending on their characteristics; according to Tipnis et al. [60], these models can be divided into microeconomic and macroeconomic models. The microeconomic models describe specific process parameters influencing the part cost. Microeconomic models dealing with machining have been described, for example, by Colding [61], [62] and Alberti et al. [63], while Knight et al. [64] have developed a corresponding model for forging. In the machining field, a microeconomic model can describe how, for example, the cutting rate or feed influences the part cost. Macroeconomic models tend to aggregate parameters, for example, when cost calculations are based on the cycle time and not on the individual factors influencing the cycle time.

Another distinction that can be made is between product cost-estimation models and models describing the historic cost of products already in production. The product cost-estimation models attempt to estimate primarily the manufacturing costs of products before they are put into production. A widely cited paper in this area is one by Shehab and Abdalla [65], which describes a knowledge-based system that can propose manufacturing methods and estimate product manufacturing costs based on a set of design and production parameters. For a review of various product cost-estimation techniques, see Niazi et al.

[66]. Eleven manufacturing cost models will be described below; the first three are based on ABC while the others are not based on any specific accounting method.

Koltai et al. [67] have developed a cost model based on ABC for calculating costs in flexible manufacturing systems (FMSs). One argument for developing the model was that the increasing overhead costs relating to the use of FMS cells render traditional accounting systems unsuitable. Another argument was that the cost model should consider the flexibility of FMSs, for example, the cost impacts of various production routes and setup times. In their ABC model, Koltai et al. [67] have focused on overhead costs, dividing these into five activity centers: tooling, loading/unloading, material handling, inventory, and other overheads. The tooling cost is allocated to products based on the number of tools used. The loading/unloading cost is allocated based on the order size. The material handling cost is allocated based on the use of material handling equipment, determined based on the distance travelled by the orders. The inventory cost is allocated to products based on order completion time. The overhead cost center consists of costs of maintenance, quality control, depreciation, etc., and is allocated based on order processing time. It can be concluded that, though the allocation principles used are fairly detailed, the model includes too few cost items to function as a complete manufacturing cost model; notably, no performance parameters are included.

Özbayrak et al. [68] have also developed an ABC model for an FMS cell. The model is used to determine the manufacturing and product costs for a manufacturing system that employs either the material requirement planning (MRP) strategy or the just-in-time (JIT) strategy. The FMS cell cited as an example in the paper is a simulation model and not a real system. The FMS cell is divided into six activity centers: workstations, inspection station, assembly line, setup activities, and robot and AGV systems. The resource costs distributed to the activity centers are: machines and cutting tool holders, computer system, robot and AGV system, automated storage and retrieval (AS/RS) system, fixed assets, externally provided resources (e.g., fuel for heating and electricity for lighting and ventilation), direct and indirect labor, insurance and indirect material, cutting tools and fixtures, direct energy consumption, direct material, and other services (i.e., costs of non-manufacturing services). These costs are divided into direct and indirect costs when they are distributed to the activity centers. The direct costs are directly distributed to the activity centers while the indirect costs are distributed based on utilization levels obtained from system simulation results. The investment cost of workstations is assumed to be a direct cost while the investment costs of the other equipment are assumed to be indirect costs. The investment costs are calculated as hourly costs by dividing the investment cost by the estimated economic life of the investment in hours. The calculations to convert the activity centers to unit costs are made using a unit cost equation. The equation calculates the cost per part by taking specific part characteristics, such as processing time, into consideration. Table 3.2 and the following equations describe the model.

Table 3.2: Cost parameters of the Özbayrak et al. model.

j	Part level index	$DMCR[a(i_j,o)]$	Direct machining cost rate
i_j	Part i at level j	$ACR[a(i_j,o)]$	Assembly cost rate
$R(i_j)$	Part route	$DACR[a(i_j,o)]$	Direct assembly cost rate
o	Operation index	$HC(i_j)$	Handling cost
$S(i_j,o)$	Standard setup time	$d_{R(ij)}$	Distance route
$B(i_j)$	Batch size of i_j	sp_{AVG}	Speed of AGV vehicle
a	Activity index	$StC(i_j)$	Storage cost
$OSCR[a(i_j,o)]$	Overall setup cost rate	$w(i_j)$	Average waiting time
$DSCR[a(i_j,o)]$	Direct setup cost rate	$M(i_j)$	Unit material cost
$t(i_j,o)$	Processing time	$W(i_j)$	Weight of material
$MCR[a(i_j,o)]$	Machine tool cost rate		

The setup cost includes both an hourly rate and a direct cost and is defined as:

$$\text{Setup cost} = \sum_{o=1}^{R_{ij}} \left\{ \frac{S(i_j,o)}{B(i_j)} \cdot OSCR[a(i_j,o)] + DSCR[a(i_j,o)] \right\} \tag{3.9}$$

Even the machining cost includes both an hourly rate and a direct cost and is defined as:

$$\text{Machining cost} = t(i_j,o) \cdot MCR[a(i_j,o)] + DMCR[a(i_j,o)] \tag{3.10}$$

The equation for the assembly cost is similar to that for the machining cost and is defined as:

$$\text{Assembly cost} = A(i_j,o) \cdot ACR[a(i_j,o)] + DACR[a(i_j,o)] \tag{3.11}$$

The handling and storage cost is defined as:

$$\text{Handling and storage cost} = HC(i_j) \cdot \frac{d_{R(i_j)}}{sp_{AVG}} + DACStC(i_j) \cdot w(i_j) \tag{3.12}$$

The material cost is defined as:

$$\text{Material cost} = M(i_j) \cdot W(i_j) \tag{3.13}$$

In the paper [68], Özbayrak et al. say that they also consider losses such as scrapping, reworking, and downtime, but do not describe exactly how these losses are treated.

Aderoba [69] has developed an ABC estimation model for job shops. The activities in a job shop are classified as machine-based production, labor-intensive production, technical services, and administrative services. The model includes two model alternatives, depending on whether the production is mainly machine or labor based, the difference being that the former has more machine-related parameters. In the machine-based version, the machine cost is calculated based on the initial investment cost and the installation cost. These costs are divided by the total number of expected operation hours. This rate is then multiplied by a factor greater than one, which takes account of maintenance, repair, and other costs related to the machine. Other production-related costs included in the model are floor space cost and utility cost. The model can be said to include several essential cost parameters, but no performance-related parameters.

Dhavale [70] has developed a cost model primarily for computer-integrated manufacturing systems (CIMSs). Dhavale argues that traditional cost accounting methods are inadequate in CIMS environments and describes three of their main shortcomings. One shortcoming is that direct labor has become a manufacturing overhead cost because operators cannot be easily identified with specific products: operators now operate several machines at the same time, each machine producing a different product. Another shortcoming is that since direct labor is a relatively small cost in CIMS-equipped versus conventional job shops, it has become inappropriate as an allocation basis for manufacturing overhead. Due to the small amount of direct labor in a CIMS environment, an error in assigning direct labor to a product has a greater impact on the overhead cost allocation than in a case with proportionally higher direct labor costs. The last shortcoming is that plant-wide manufacturing overhead pools are frequently used in traditional cost accounting systems. This means that all manufacturing overhead costs are put into just one cost pool, thereby ignoring the machines with which specific products are manufactured. Since machines usually differ in their share of the total overhead cost, the results can be fairly inaccurate.

The parameters included in the Dhavale cost model are presented in Table 3.3, after which the cost equations are presented.

Table 3.3: Parameters of the Dhavale model.

j	Product index	hl_i	Expected production hours on machine i over its economic life
MC_j	Manufacturing cost of product j	C_{2i}	Operating cost
DM_j	Direct material cost	UBD	Annual operating cost
i	Machine index	a_i	Fraction of total plant area occupied by machine i
h_{ij}	Processing time in machine i	hy_i	Expected production hours on machine i this year
AR_i	Application rate per machine hour	C_{3i}	Personnel cost
C_1	Cost of capital expenditure	PO	Total annual personnel cost
M_i	Investment cost of machine i	C_{4i}	Cost related to various service departments
ACC	Total cost of accessories	S_i	Annual service department costs allocated to machine i
m_i	Fraction of the total investment in machine i		

The manufacturing cost of a product is calculated using Equation 3.14.

$$MC_j = DM_j + \sum_i (h_{ij} \cdot AR_i) \tag{3.14}$$

The application rate, AR_i, consists of four cost groups: capital expenditure, costs related to the factory building, personnel costs, and costs related to various service departments. The cost equations for every cost group are presented in the paper [70]. The cost of capital expenditure, C_{1i}, is calculated using Equation 3.15. The accessory cost parameter, ACC, includes the costs of central computing, automatic material handling, tools, fixtures, pallets, inspection, and assembly equipment.

$$C_{1i} = \frac{M_i + ACC \cdot m_i}{hl_i} \tag{3.15}$$

The operating cost, C_{2i}, is formulated in Equation 3.16. UBD includes the costs of heating, electricity, water, custodial services, and building depreciation.

$$C_{2i} = \frac{UBD \cdot a_i}{hy_i} \tag{3.16}$$

The personnel cost, C_{3i}, includes the costs of process analysts, maintenance, operators, systems manager, etc., and is formulated according to Equation 3.17.

$$C_{3i} = \frac{PO \cdot m_i}{hy_i} \tag{3.17}$$

The costs related to various service departments, C_{4i}, for example, costs of personnel, design, and production engineering, are calculated using Equation 3.18.

$$C_{4i} = \frac{S_i}{hy_i} \tag{3.18}$$

Because the model does not include performance-related parameters, it is unsuitable for analyzing the performance of manufacturing systems.

Cauchick-Miguel and Coppini [71] developed a model for calculating the cost per piece in a manufacturing process, because they did not consider traditional accounting methods accurate enough for the current manufacturing environment. Cauchick-Miguel and Coppini acknowledge that new accounting methods have emerged, such as ABC, but at the time of writing the paper, they believed that research into the advantages and disadvantages of ABC was inadequate, so they instead based their cost model on traditional costing systems. Their model is based on the cost center approach, but with the novel inclusion of two "contribution factors" intended to distinguish the costs related to each machine in situations in which the cost center comprises several machines. One contribution factor considers cost, productivity, and the number of machines in the cost center; the other considers technical parameters such as flexibility, automation level, and accuracy. Their approach is somewhat similar to the model proposed by Dhavale [70], as both models are based on cost centers and both propose using the relative cost of a specific machine as a way to allocate overhead costs to each machine. The Dhavale model, however, is slightly more detailed and includes two cost drivers, whereas the Cauchick-Miguel and Coppini model is based on only one cost driver. The paper also includes a more detailed cost model in which every machine constitutes a cost center. This model includes direct and indirect material, labor, machine, tool, inspection, overhead, and variable costs. Except for a fairly detailed expression for the tool cost, their work does not describe how the other costs should be calculated. The model includes only some aspects of performance-related costs, namely, inspection, reworking, and setup costs. The authors seem to believe that this detailed model would be too difficult to implement, so they instead propose a model based on contribution factors.

Noto La Diega et al. [72] have developed a cost model for FMSs based on a cost model presented by Alberti et al. [73]. What Nota La Diega et al. address is that in FMSs one cannot simply add the manufacturing costs of every operation to obtain the total cost. This is because the high variety of products and small batch sizes in FMSs result in varying utilization rates. Moreover, because of the high equipment cost in FMS, the utilization rate and general efficiency of the system become critical parameters in cost calculations. The part cost is based on five cost items: technological, logistics and control, tooling, specific, and opportunity costs. Opportunity costs are the costs of system utilization losses and are viewed as a consequence of choosing an FMS. The cost is formulated such that the part cost is lower if the part is produced in a mix constituting a well-balanced workload between workstations. By including the opportunity cost equation, a lower and upper bound can be formulated for the manufacturing cost, the lower bound describing a system with perfect balance between workstations. Besides the inclusion of an equation describing the costs related to balancing losses, the model lacks performance-related parameters.

Needy et al. [74] have developed a cost model for evaluating configuration alternatives for manufacturing cells. The cost model consists of only three factors: setup, material handling, and investment costs. The authors agree that more cost factors can be included, for example, labor costs and energy costs, but they believe that the more factors a cost model includes, the more prohibitively complicated and expensive it becomes to collect data and use the model. The cost is expressed as the cost for a specific planning period. This cost model permits the calculation of how the cost of introducing manufacturing cells into a job shop influences the total cost, which is the sum of the three mentioned cost factors. This model clearly contains too few parameters for the type of analyses addressed in this thesis.

Yamashina and Kubo have proposed a concept for cost-conscious manufacturing development called manufacturing cost deployment [75]. The concept includes a cost model in which the costs are divided into fixed and variable costs. The fixed costs consist only of depreciation costs; the variable costs include the costs of direct material, indirect material, direct labor, indirect labor, tool, die and jig, energy, and maintenance. The authors then connect these costs to production losses. The identified losses are the following: breakdown, setup, tool change, startup, short stoppage, speed down, defects, management, operation motion, logistics, line organization, measurement, yield, indirect material, die and jig, and energy-related losses. For each type of loss, cost formulas are presented expressed in cost per part. The authors distinguish between time-related and physical losses, the former being measurable in terms of time and the latter in quantity. They also distinguish between the scenarios when the production capacity is smaller than the planned output quantity and when it is larger, depreciation only being included in the cost of time-related losses in the first case and energy and direct labor costs only being included in the second. This cost concept only describes the costs of losses, not the total manufacturing cost. For example, how the cost of defects in processing steps after the first should be calculated is not formulated; it is only mentioned that the costs for the previous steps should be considered. Manufacturing cost deployment is more than just cost formulas; it is a whole concept of how to implement improvement activities in a structured way. The concept is based largely on five matrixes, each having a specific function. The first one is used for identifying losses, the second for clarifying the cause–effect relationships of the losses, the third for describing the costs connected to processes and losses, the fourth for clarifying what improvement techniques to use for specific losses, and the fifth for establishing a cost-reduction program. It can be concluded that this is a comprehensive model, developed to solve issues similar to the one considered here. However, the Yamashina and Kubo model focuses only on losses and does not consider the impact of improvements resulting in shorter cycle times. In addition, the model neglects the cumulative material cost, i.e., that the value of the material increases after every processing step.

Another example of a manufacturing cost model is the one developed by Son [76]. This cost model is intended to be used to support decision-making for factory automation and is also used in a performance measure called IMPM. Son divides the costs into three groups, i.e., productivity, quality, and flexibility costs: the productivity cost group includes the costs of labor, material, depreciation, machine, tool, floor space, and computer software; the quality cost group includes the costs of prevention and failure; and the flexibility cost group includes the costs of setup, waiting, idle, and inventory. The cost equations presented in the paper yield the total cost of a specific period. The labor cost, C_L, is formulated as follows:

$$C_L = \text{direct labor cost} + \text{indirect labor cost} \tag{3.19}$$

The material cost, C_R, is described as:

$$C_R = \text{direct material cost} + \text{indirect material cost} + \text{ordering cost} \tag{3.20}$$

The machine cost, C_M, is formulated as:

$$C_M = \text{utility cost} + \text{maintenance cost} + \text{repair cost} + \text{insurance cost} + \text{property tax} \tag{3.21}$$

The tool cost, C_T, is formulated as:

$$C_T = \text{unit cost per tool} \cdot \text{total number of tools changed} \tag{3.22}$$

The floor space cost, C_S, is formulated as:

$$C_S = \text{space cost per square foot} \cdot \text{manufacturing floor space} \tag{3.23}$$

The computer software cost, C_C, is the sum of the licensing costs of all software products:

C_C = licensing cost · number of licenses 3.24

The depreciation cost is not defined by Son [76], who only says that the cost is available from accounting records. The prevention cost, C_P, for preventing defects in product j in machine k is:

C_P = prevention cost per hour · planning horizon 3.25

The prevention cost per hour consists of the costs of sampling, assignable cause, and process capability. The failure cost, C_F, of part j is formulated as:

C_F = failure cost of part · quantity of parts produced 3.26

The failure cost includes the costs of reworking and scrapping, and the cost of dissatisfying a customer by selling a defective part. The setup cost, A, for machine k is defined as:

A = setup cost per unit time · total setup time 3.27

The waiting cost, C_W, is defined as:

C_W = waiting cost per unit time · total waiting time for parts produced 3.28

The idle cost, C_I, due to underutilized equipment is defined as:

C_I = idle cost per unit time · total idle time of equipment 3.29

The inventory cost, C_H, is formulated as:

C_H = warehouse space cost + holding cost + shortage cost 3.30

Like the Yamashina and Kubo [75] model, the Son [76] model is a comprehensive model that includes several performance-related costs. The purpose of both of these models is to calculate the total of each type of cost for a specific period. The model has the same deficiencies as does the Yamashina and Kubo model, i.e., it does not include a cycle time parameter and the cumulative effect of the material cost is neglected.

A model with similarities to that of Son [76] is the one developed by Chiadamrong [77]. The focus of the model is quality-related cost and it includes theoretical considerations relating to cost of quality (see section 3.4.1). The material cost, C_{mat}, is formulated as:

C_{mat} = direct material cost + indirect material cost + extra cost due to defective units – scrap resold cost 3.31

The machine cost, $C_{m/c}$, consists only of the operating cost of the machine and is formulated as:

$C_{m/c}$ = machine operating cost for normal parts + machine operating cost for reworks 3.32

The labor cost, C_{labor}, is formulated as:

C_{labor} = direct labor cost incurring from operating normal units + direct labor incurring from operating rework units + indirect labor cost 3.33

The setup cost, C_{setup}, is defined as:

C_{setup} = setup cost caused by normal parts + setup cost caused by reworked parts 3.34

The material handling cost, C_{mh}, is driven by the actual transportation time and is formulated as:

$$C_{mh} = \text{transportation cost for delivering normal parts} + \text{transportation cost required to carry back rework parts} \quad 3.35$$

The failure repairing cost, C_{rp}, is defined as:

$$C_{rp} = \text{failure repairing cost caused by normal parts} + \text{failure cost caused by defective units} \quad 3.36$$

The ordering, receiving, and delivery cost, C_{rd}, is defined as:

$$C_{rd} = \text{ordering, receiving, and delivery costs for normal parts} + \text{ordering, receiving, and delivery costs for replacement parts} \quad 3.37$$

The preventive maintenance cost, C_{pm}, is defined as:

$$C_{pm} = \text{preventive maintenance cost per unit time} \cdot \text{total preventive maintenance time} \quad 3.38$$

The process control cost, C_{pc}, includes the costs of control chart sampling, inspection, and adjusting the process back to normal after variations above the specification limits:

$$C_{pc} = \text{control chart sampling cost} + \text{subgroup inspection cost} + \text{chart alarm cost} \quad 3.39$$

The costs of product sampling, inspection, and testing, C_{ap}, include the cost of checking the product conformance:

$$C_{ap} = \text{sampling cost} + \text{samples subgroup inspection cost} + \text{100\% inspection cost} \quad 3.40$$

The idle cost, C_{idle}, is the cost of underutilizing the manufacturing equipment. The idle opportunity cost can be based on the company's profit rate when there is demand, and on the cost of capital or the company's rate of return when there is no demand:

$$C_{idle} = \text{idle opportunity cost per unit time} \cdot \text{total idle time of the equipment} \quad 3.41$$

The cost of waiting is the cost of the work in process inventory and consists of the cost of waiting in front of the machine, C_{proc}, and of the batch waiting cost, C_{batch}, a cost occurring when a part is finished in a machine but is waiting for the completion of its batch:

$$C_{proc} = \text{waiting opportunity cost per unit time} \cdot (\text{total process waiting time of normal parts} + \text{total process waiting time of rework parts}) \quad 3.42$$

$$C_{batch} = \text{waiting opportunity cost per unit time} \cdot \text{total batch waiting time of parts produced} \quad 3.43$$

The external failure opportunity cost, C_{efo}, is the opportunity cost of products not performing satisfactory after being supplied to the customer:

$$C_{efo} = \text{number of defective units sold to the customer} \cdot \text{cost of dissatisfying a customer by selling a defective part} \quad 3.44$$

As stated earlier, the Chiadamrong [77] model is very similar to the Son [76] model to which it refers. The main difference is that the Chiadamrong model has a clearer focus on performance losses. A deficiency of the model, which it shares with the Son model, is that it does not state how all of the included cost rates should be calculated, i.e., what costs they include. In addition, the model shares the mentioned deficiencies of the Yamashina and Kubo [75] and Son [76] models, i.e., it does not consider the cycle time or the cumulative material cost.

Branker et al. [78] propose a manufacturing cost model based on life cycle assessment (LCA) that also includes environmental parameters. It is a cost per part model and, besides including environmental parameters, it also includes parameters similar to those of the Özbayrak et al. [68] model and the detailed model proposed by Cauchick-Miguel and Coppini [71]. However, the model is inappropriate for use in analyzing manufacturing system performance, because of its lack of performance-related parameters.

3.3.1 Summary of presented cost models

Table 3.4 summarizes the cost models presented above with respect to the parameters included. The models differ in their main purposes, some having been developed to analyze specific problems or contexts, while others were developed to be more general models. They also differ in their unit of analysis, some being period cost models, others being part cost models. The various aims of the models partially account for the varying level of cost parameter detail between the models.

The parameters chosen for inclusion in the summary are taken from the examined models. Parameters were selected if they were: a) found in more than one model and b) closely related to manufacturing. Exceptions were made to allow the inclusion of the costs of environmental considerations, prevention of poor quality, and speed losses. The inclusion of environmental costs is justified by the current general interest in this area. Quality prevention was included because several models included appraisal and failure costs but not the prevention cost, which is one of the three quality cost groups in the PAF model (see section 3.4.1). Some of the authors claim that their models include prevention costs, but according to the definition in section 3.4.1, what is included more closely resembles appraisal costs. The speed loss parameter was included because it is one of the three rates in OEE and also one of the parameters of the proposed model presented in Chapter 4.

Table 3.4: Summary of the presented models.

	Koltai et al. [67]	Özbayrak et al. [68]	Aderoba [69]	Dhavale [70]	Yamashina and Kubo [75]	Son [76]	Chiadamrong [77]	Cauchick-Miguel and Coppini [71]	Branker et al. [78]	Noto La Diega et al. [72]	Needy et al. [74]
Material		x		x	x	x	x	x	x		
Labor		x	x	x[1]	x	x	x	x	x		x
Machine depreciation	x[1]	x[1]	x	x	x	x		x	x[1]	x[1]	x[3]
Floor space		x[1]	x	x		x		x			
Utilities (e.g., energy)		x[1]	x	x[1]	x	x	x	x[1]	x		
Tools	x	x	x[1]	x[1]	x	x		x	x	x	
Maintenance	x[1]	x[1]	x[1]	x[1]	x	x	x	x[1]	x[1]		
Repairs			x[1]			x	x[1]				
Material handling	x	x		x[1]			x		x	x[1]	x
Computer		x[1]		x[1]		x			x[1]	x[1]	
Inventory	x	x		x[1]		x					
Quality: prevention							x[2]				
Quality: appraisal	x[1]				x	x	x	x			
Quality: failure (scrap)		x[2]			x	x	x				
Reworking		x[2]				x	x	x[1]			
Downtime		x[2]			x		x[1]				
Speed loss					x						
Setup	x	x			x	x	x	x	x		x
Waiting		x	x[1]			x	x				
Idling						x	x			x	
Environmental									x		

[1] Included but not as a separate parameter.
[2] Mentioned as considered, but the equation is not presented in the paper.
[3] The cost is expressed as a leasing cost.

3.4 Specific manufacturing cost parameters

Besides the general cost accounting methods and specific models, other cost models and theories focus on specific manufacturing cost parameters that are included in the cost model proposed in this thesis.

3.4.1 Quality cost

According to Schiffauerova and Thomson [79], there is no clear definition of cost of quality (COQ), though it is often understood as the sum of the conformance and non-conformance costs. Conformance cost is the cost of preventing poor quality (e.g., inspections) while non-conformance cost is the cost incurred from poor quality (e.g., rework and returns). In their review of quality cost models, Schiffauerova and Thomson [79] divided the models found into four categories: the prevention–appraisal–failure (PAF) model, opportunity cost models, process cost models, and ABC models. According to Hwang and Aspinwall [80], the PAF model is the oldest quality cost model, developed by Feigenbaum and Masser in the 1950s. This model emphasizes that costs are associated with preventing poor quality from occurring, i.e., prevention costs, comprising the costs of employee quality training and quality engineering for example. Appraisal costs are the costs of the appraisal system used to detect quality deviations in the factory. Appraisal costs comprise the costs of inspection, testing, quality audits, etc. Failure costs comprise the costs of scrapping, reworking, spoilage, etc. [79], and can be divided into internal and external failure costs [81]. According to Schiffauerova and Thomson [79], a basic underlying assumption of the PAF model is that investment in prevention and appraisal will reduce failure costs. A classic theory states that there is an optimal quality level that minimizes the total quality cost; see Figure 3.7 (a). This theory has been challenged; many believe that no such optimal level exists and that the total quality cost does not need to rise above a certain quality level; see Figure 3.7 (b).

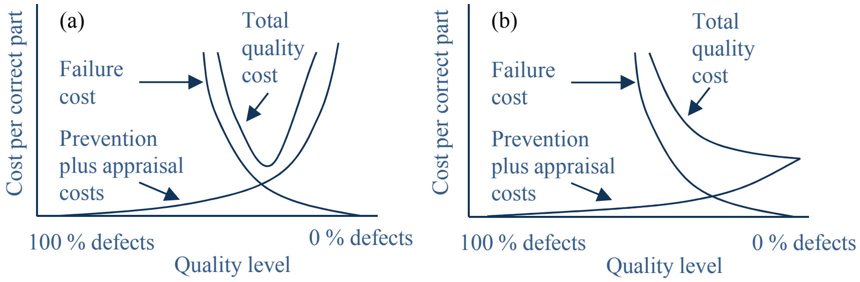


Figure 3.7: (a) Traditional model showing optimal quality level and (b) newer model with no optimal level; adapted from Schiffauerova and Thomson [79].

Models that include opportunity cost emphasize that poor quality can lead to revenue reductions and lost customers. Process cost models emphasize quality costs related to processes and not products. According to Hwang and Aspinwall [80], the first process cost models were developed in the late 1970s and comprise the price (cost) of conformance (POC or COC) and the price (cost) of non-conformance (PONC or CONC). Every cost element in a process is categorized as either a COC or CONC, and then actions can be taken based on whether the process has a high COC or high CONC. The final category, ABC, is the quality cost calculated by activity-based costing.

According to Schiffauerova and Thomson [79], researchers in the area argue that it is meaningless to recommend that specific parameters be included in a COQ model, because the necessary parameters are to some degree company specific. However, one example is the model developed by Omachonu et al. [81], consisting of material, machine, and personnel costs. The material and machine costs are formulated as individual cost parameters, while the personnel cost is considered a cost component of the first two parameters. The model is based on the PAF concept and consequently includes the quality costs of prevention, appraisal, and failure (both internal and external). The material cost includes the costs of raw material inspection, supplier quality evaluation, scrapping, reworking, etc. The machine cost includes the costs of machine calibration, preventive maintenance, repair, operating costs for reworking, etc. No equations for how these costs are to be calculated are presented in the paper.

3.4.2 Downtime variability and its costs

The size and frequency of the failures that occur in a manufacturing system can be described statistically using various distribution functions. Vineyard et al. [82] analyzed failure-rate distributions in an FMS. They collected failure data and classified them in terms of six failure types: human, software, electrical, mechanical, hydraulic, and electronic. For each failure type, they calculated the time between failures (TBF) and the time to repair (TTR) for each failure that occurred. They then investigated what types of distributions best fitted the TBF and TTR values. They found that the TBF values for all types of failure except electrical ones could be described by a Weibull distribution, while the electrical failures were lognormally distributed. Regarding the results for the TTR values, all the failure types except for hydraulic and electronic failures were lognormally distributed. For hydraulic failures, the TTR values were found to be gamma distributed, whereas the TTR values for electronic failures were found to display a Weibull distribution. Yazhou et al. [83] analyzed the failure distributions at 24 machine centers over one year, and found that the failures could be fitted to an exponential distribution. In the literature, exponential distributions are usually assumed to apply in modeling failures [84], [85]. Dallery [85] argued that, although an exponential distribution can be properly employed in modeling the time distribution of failures, it is not equally useful in modeling repair-time distributions; he instead considered that failure times could be described by generalized exponential (GE) distributions. Mohanty [86], in turn, argued that, whereas failure times are often modeled in terms of exponential distributions in electronic components, the Weibull distribution is more suitable for describing fatigue. In modeling repairs, Mohanty considers the lognormal distribution to be the best choice in many cases.

Additional views concerning the handling of failure data are found in discrete-event simulation (DES) research. In this literature, it is often argued that TBF and TTR data are best described using a theoretical distribution to which the chi-square, Kolmogorov-Smirnov, and Anderson-Darkna tests [87], [88] can be applied.

Questions connected with the calculation of performance rates can be raised concerning such matters as sample size and the durations samples should encompass for reliable results to be obtained. Lamberson and Wasserman [89] have developed models of the relationships between the sample size, failure occurrence, and standard deviations obtained for different degrees of availability. Their models are based on the assumption that TBF and TTR values have exponential distributions.

There are models in the literature that link availability losses to costs. Das [84] has developed a multi-objective mixed-integer programming (MIP) model that takes into account both the reliability and costs of a manufacturing cell. One aim of his model is to create the basis for a tradeoff between system availability and system cost when alternative processing routes are available, involving different machines with different availabilities. There are two versions of the model, one for exponentially distributed reliability and the other for Weibull distributed reliability. Several papers have presented models of the relationship between availability and maintenance costs. Murty and Naikan [90] developed an optimization model of the optimal availability level in terms of the costs associated with improving availability, assuming that the costs of improving it increase exponentially with the targeted availability level. In this model, the profit per time unit is maximized. Calabria et al. [91] also modeled an exponential cost function, but treated the mean time between failures (MTBF) and the mean time to repair (MTTR) as separate from each other, assuming that an improvement in one does not affect the other. Their cost model thus contains two cost expressions, one for MTBF and the other for MTTR. Jones et al. [92] discuss similar issues and present a model for calculating optimal inspection intervals, i.e., optimal preventive maintenance intervals in terms of minimizing costs; they assume the failure rate to have an exponential distribution.

Life cycle costing (LCC) usually includes downtime costs based on the use of mean values for TBF and TTR in the cost calculations [53].

3.4.3 Volume flexibility and its costs

Flexibility can be divided into several categories, how they are defined differing slightly between authors. Volume flexibility, sometimes also denoted capacity flexibility in the literature, is defined as follows by two widely cited authors in the area:

- "the ease with which changes in the aggregate amount of production of a manufacturing process can be achieved" (Gerwin [93])
- "the ability to manufacture profitably in spite of changing manufacturing volume" (Browne et al. [94])

In a survey of factors that affect volume flexibility, Oke [95] found three major such factors: demand variability, demand uncertainty, and customer influence on lead time. Volume flexibility can be dealt with in a variety of ways: Jack and Raturi [96] surveyed the main sources of volume flexibility, finding both short- and long-term sources of it. The major short-term sources were overtime, inventory buffers, and capacity buffers. The major long-term sources were plant networks, outsourcing, the ability to increase or decrease plant capacity, and the ability to increase or decrease the current labor force or number of shifts.

Capacity management has received considerable attention recently. Wijngaard and Miltenburg [97] present an approach to the use of resources for promoting sales opportunities when operator capacity is flexible and machine capacity is fixed, using primarily two parameters: r, the reward achievable by accepting additional sales opportunities and c, the capacity required to produce the additional products. Tang [98] presents a dynamic model of planning capacity and flexibility over a finite period, a model that includes parameters for equipment and processing cost, but no performance parameters. In addition, no application of the model is presented.

Alp and Tan [99] refer to capacity flexibility as the ability to adjust the total production capacity during a given period when having the option of utilizing contingent resources in addition to permanent resources. In their study, they consider a tactical-level capacity planning problem in which production and inventory decisions are to be made. They present a model for balancing out variations in backlog, hiring temporary workers, and selecting inventory strategies. The model parameters include fixed production costs and the ordering of contingent capacities. The cost parameters are aggregated at a system level, and not all of the manufacturing costs are included in the fixed costs.

Aggregate production planning (APP) is a technique for determining the minimal cost of handling a specific forecast future demand. Research on APP started in the 1950s, and since then there have been numerous contributions to the field, much of the research being based on the groundbreaking work of Holt et al. [100], [101]. The general idea is to calculate the minimal manufacturing costs of a forecast demand by finding the optimal balance between different sources of volume flexibility, such as hiring and firing, inventory levels, and overtime [102]. Although considerable work has been carried out in the field, it has had only a limited impact on industry [102], [103]. Various reasons are cited for this gap between theory and practice. One reason is that of the underlying preconditions inherent in APP models, for example, that various products can be grouped and be viewed as a single aggregated product and the complexity of the technique.

3.4.4 Equipment cost

To compare the cost of equipment of different ages and the equipment cost with labor cost, it is crucial that the machine cost be described as accurately as possible. However, the machine cost is often treated fairly briefly in cost accounting literature. Cost accounting textbooks often describe how to formulate hour-based overhead rates for cost centers, but seldom contain any specific description of how to formulate an hourly machine cost; the descriptions of manufacturing costs in such books are at a more general level. There are, however, contributions in the field if one looks beyond the cost accounting textbooks and instead searches, for example, the LCC literature. LCC is a strategic technique primarily used in the planning phase before an acquisition is made; it is not specifically a method for determining the machine cost per hour parameter in the field of manufacturing costing, but its essence can be considered when formulating the machine cost. In addition to the LCC literature, some findings concerning the machine cost parameters can be found in the cost models presented in section 3.3. Son [76] divides machine-related costs into the machine, tool, floor space, computer software, and depreciation costs. The machine cost component is further divided into the utility, maintenance, repair, insurance, and property costs. Özbayrak et al. [68] have applied the following cost items to every machine: equipment and building depreciation, electricity, gas, direct and indirect labor, tools, and fixtures. Except for the LCC literature, the cost of capital rate or interest rate is seldom included in descriptions of the manufacturing cost. However, examples can be found recommending the use of a uniform machine cost over the useful life of the machine, which also includes the cost of capital. Groover [104] advocates a uniform machine cost per hour based on the capital recovery factor. In his machine cost model, the capital recovery factor is multiplied by the initial cost of the machine and the total machine cost is obtained by adding an overhead cost to the machine cost the use of an overhead rate.

3.5 Empirical findings regarding cost structure and cost accounting principles used in practice

Many of the papers on manufacturing cost referenced in the above sections criticize traditional costing principles without citing any comprehensive evidence on how manufacturing companies actually calculate their costs. Are companies indeed using traditional cost accounting principles? Brierley et al. [105] have reviewed the literature on product costing practices in Europe between 1990 and 2001 from seven perspectives: the number of accounting systems firms use, corporate cost structure, the use of blanket overhead rates, bases used to calculate overhead rates, the use of product costs in decision making, the use of product costs in pricing decisions, and the application of ABC. The results of the corporate cost center review indicated that material and overhead costs dominated and that labor cost represented a minority of the total cost. The tendency was for material cost to be larger than the overhead cost. A survey conducted by Al-Omiri and Drury [106] on accounting practices in the UK found that the direct material cost constituted 75% of the total cost, direct labor cost 14%, and indirect manufacturing cost 10%. Brierley et al. [105] presented a review on the use of blanket overhead rates, i.e., the use of plant-wide overhead rates. The results indicated that a minority of the companies used blanket overhead rates; instead, they tended to use some type of cost centers, for example, departments or machine groups. The results regarding overhead rate bases indicated that direct labor and other volume bases were dominant. Direct labor cost and direct labor hours were often used, though some results indicated that machine hours were increasingly being used as a basis. Alnestig and Segerstedt [107] examined product costing principles in ten Swedish manufacturing companies, and found that machine hours are used as a basis in some companies. The results on the use of product costs in decision making presented in Brierley et al. [105] are unclear. The results indicate that companies use product costs to some extent in decision making, but Brierley et al. argue that more research is needed on the circumstances in which companies decide whether or not to use product costs in their decision making. As for ABC application, the results of various studies indicate that the use of or intention to use the procedure is limited, ranging from 5% to approximately 25% of the companies examined in the various reviewed studies. Fullerton and McWatters [108] surveyed 121 US manufacturing companies to study the relationship between use of advanced manufacturing techniques, JIT, total quality management (TQM), and six sigma with various accounting principles. The survey indicated that traditional cost accounting principles are still widely used, in both advanced and non-advanced companies, but that companies using advanced manufacturing techniques tended also to use some of the more advanced accounting techniques, such as economic value added (EVA), LCC, and value chain analysis (VCA). The study does not investigate why companies still use traditional cost accounting techniques, but one reason Fullerton and McWatters [108] suggest is that the benefits of more advanced accounting techniques do not seem to outweigh the costs. An older study conducted by Drury and Tayles [109] came up with the same reason, arguing that the relatively small share of total manufacturing cost comprising overhead costs (25% in their study) does not justify the use of more advanced techniques by the companies.

4 Results

This chapter summarizes the appended papers and presents their links to the research questions. In addition, developments of the proposed cost model that are not included in the appended papers are presented.

The appended papers are presented in the order of their alignment with the research questions presented in chapter 1. The first three papers deal with manufacturing cost modeling, addressing RQ1. The three subsequent papers deal with various implementation issues encountered when using the cost model in industrial settings, addressing RQ2. During the course of the research, additional issues concerning manufacturing cost modeling, mainly regarding equipment and maintenance costs, have arisen. These are not treated in any of the appended papers, but are instead considered in section 4.2.

4.1 Summary of appended papers

4.1.1 Paper 1: A general economic model for manufacturing cost simulation

A manufacturing cost model is proposed, the purpose of which is to describe the link between the technical performance and economic parameters of a manufacturing system. Because the model is intended to describe the performance of a manufacturing system, it includes only parameters near the manufacturing process. The model describes the cost added to the manufactured part at every processing step, and is intended to be used to describe and analyze present and future conditions by changing the parameter values. The model is intended to be used to support manufacturing development activities.

Results

First the technical and economic parameters included in the cost model are defined. Central technical parameters of the model are the cycle time and performance loss parameters, while the economic parameters are material, equipment-related, and labor costs.

The nominal processing time (cycle time), t_0, for a part comprises machine time, handling time, and tool change time:

$$t_0 = t_m + t_h + t_{vb} \tag{4.1}$$

The nominal cycle time describes the ideal case. Losses in a manufacturing system can be divided into three main types: scrap, downtime, and production-rate losses. The downtime rate, q_S, is formulated as the downtime, t_s, divided by the total cycle time including downtime:

$$q_S = \frac{t_S}{t_p} = \frac{t_p - t_0}{t_p} \tag{4.2}$$

The scrap rate, q_Q, is formulated as the quantity of scrapped parts divided by the total quantity of parts including scrapped parts:

$$q_Q = \frac{N_Q}{N} = \frac{N - N_0}{N} \tag{4.3}$$

The production-rate loss is defined based on the real cycle time, t_{0v}, and the nominal cycle time, t_0, according to Equation 4.4:

$$q_P = \frac{t_{0v} - t_0}{t_{0v}} \tag{4.4}$$

Machine utilization, U_{RP}, is defined as the ratio of real to planned production time according to Equation 4.5. It is allocated to the manufactured parts based on the batch time as defined in Equation 4.6, where T_{su} is the setup time.

$$U_{RP} = \frac{T_{prod}}{T_{plan}}; \quad T_{plan} = T_{prod} + T_{free} \tag{4.5}$$

$$T_{pb} = T_{su} + N \cdot t_p = T_{su} + \frac{N_0 \cdot t_0}{(1 - q_Q) \cdot (1 - q_S) \cdot (1 - q_P)} \tag{4.6}$$

In situations in which the material wasted in a processing step greatly affects the cost, a material waste factor, q_B, can be introduced according to Equation 4.7. This factor considers the total consumption of material, m_{tot}, per part, including material machined or cut off, for example, chips when turning or milling and retainer surfaces during sheet metal forming, as well as material wasted during test runs or run-in procedures. The remaining material in the machined part is denoted m_{part}. Considering both the waste and scrap, the total material cost can be defined according to Equation 4.8, where k_{B0} is the material cost of the manufactured part and K_B is the material cost of the batch, including scrapped parts and material waste.

$$q_B = \frac{m_{tot} - m_{part}}{m_{tot}} \tag{4.7}$$

$$K_B = \frac{N_0 \cdot k_{B0}}{(1 - q_B) \cdot (1 - q_Q)} \tag{4.8}$$

It may sometimes be necessary to introduce a disturbance factor, q_{Ssu}, to handle deviations in the nominal setup time.

The manufacturing costs per part k, including the previously described parameters and assumptions, can be expressed as:

$$\begin{aligned} k = {} & \frac{K_{sum}}{N_0} + \left(\frac{k_B}{(1-q_Q)\cdot(1-q_B)} \right) + \left(\frac{k_{CP}}{60} \cdot \frac{t_0}{(1-q_Q)\cdot(1-q_P)} \right) + \\ & \frac{k_{CS}}{60} \cdot \left(\frac{t_0}{(1-q_Q)\cdot(1-q_P)} \cdot \frac{q_S}{(1-q_S)} + \frac{T_{su}}{N_0} + \frac{1-U_{RP}}{N_0 \cdot U_{RP}} \cdot T_{pb} \right) + \\ & \frac{k_D}{60} \cdot \left(\frac{t_0}{(1-q_Q)\cdot(1-q_S)\cdot(1-q_P)} + \frac{T_{su}}{N_0} + \frac{1-U_{RP}}{N_0 \cdot U_{RP}} \cdot T_{pb} \right) \end{aligned} \tag{4.9}$$

The cost item, K_{sum}, in Equation 4.9 comprises miscellaneous costs not described separately in the model. A more complete economic model has a higher resolution and includes more separate terms for the costs included in K_{sum}, which can, for example, include tool and maintenance costs.

Considering that many factors, singly or jointly, influence the cost of a specific part, various changes in these factors can lead to the same cost effects. To distinguish the influences of these factors on the part cost, various development factors are introduced into the parameters of Equation 4.9 according to Equation 4.10:

$$\begin{aligned} k = {} & \frac{K_{sum}}{N_0} + \left(\frac{k_B}{(1-q_Q)\cdot(1-q_B)} \right) + \left(\frac{\kappa_C \cdot k_{CP}}{60} \cdot \frac{x_p \cdot t_0}{(1-q_Q)\cdot(1-q_P)} \right) + \\ & \frac{\kappa_C \cdot k_{CS}}{60} \left(\frac{x_p \cdot t_0}{(1-q_Q)} \cdot \frac{q_S}{1-q_S} + \frac{x_{su} \cdot T_{su}}{N_0} + \frac{1-U_{RP}}{N_0 \cdot U_{RP}} \cdot T_{pb} \right) + \\ & \frac{k_D}{60} \left(\frac{x_p \cdot t_0}{(1-q_Q)\cdot(1-q_S)} + \frac{x_{su} \cdot T_{su}}{N_0} + \frac{1-U_{RP}}{N_0 \cdot U_{RP}} \cdot T_{pb} \right) \end{aligned} \tag{4.10}$$

The development factor, x_p, operates on the cycle time and enables the analysis of changes in cycle time. The development factor, x_{su}, operates on the setup time and enables the analysis of changes in setup time. A cost development factor, κ_C, is introduced to describe changes in equipment cost connected to a change in cycle time.

Cost derivatives can be formulated to determine what parameter most affects the part cost. Changes in part cost caused by a limited change in an arbitrary variable, z, are calculated by partial derivative, and are described in linear form as:

$$\Delta k_i = \frac{\partial k_n}{\partial z} \cdot \Delta z \tag{4.11}$$

The changes in part costs can be calculated with respect to different parameters, for example, changes in wage costs and share of downtime, Δq_{Si}.

Connection to research questions

The work presented in this paper addresses RQ1. A general cost model is proposed, taking account of important performance and cost parameters. This is a key paper in this thesis, forming the foundation for the following papers.

4.1.2 Paper 2: Relations between volume flexibility and part cost in assembly lines

This paper endeavors to demonstrate how the proposed cost model can be used to analyze the cost effects of volume flexibility. Volume flexibility is achieved in the described case by altering the number of operators in an assembly line comprising both manual and automatic assembly stations.

The volume flexibility analysis is illustrated by an example based on a real assembly line, but with modified cycle times. The assembly line contains a total of 18 work stations, 10 operated automatically and eight manually. If eight operators staff the studied assembly line, this means that there is one operator for each manual work station. As the number of operators decreases, each operator will eventually perform the tasks of two or more work stations. The assembly line can be operated by one to eight operators, each new staffing setup resulting in a different ideal cycle time for the assembly line as a whole.

Table 4.1 shows the ideal cycle time, t_0, for each number of operators. Depending on the variations in ideal cycle time between the staffing alternatives, the ideal production capacity varies between 85 and 12 parts/h. For the OEE of 75% obtained here, the real production capacity varies between 9 and 64 parts/h. If there are fewer than eight operators, the operators need to walk between different manual work stations; accordingly, an average transfer time of five seconds is included in each ideal cycle time.

Table 4.1: The ideal cycle times, production rates, and balance delays for the presence of different numbers of operators.

No. of operators, n_{op} [unit]	**Ideal cycle time, t_0 [sec]**	**Production capacity, P_C [unit/h]**	**Balance delay, D [%]**
8	42	85	0.29
7	51	70	0.37
6	67	53	0.49
5	80	45	0.57
4	81	44	0.49
3	116	31	0.62
2	155	23	0.69
1	285	12	0.82

Results

Studying how costs are affected by changes in capacity requires an additional set of parameters. In the cost model, the fixed ideal cycle time, t_0, is replaced by a varying ideal cycle time, $t_0(n_{op})$, dependent on the number of operators. If the operators share setup tasks, the setup time is dependent on the number of operators. This is taken into account by introducing the operator-dependent setup time, $T_{su}(n_{op})$. The modified cost model is defined in Equation 4.12:

$$\begin{aligned} k = {} & \frac{K_{sum}}{N_0} + \left(\frac{k_B}{(1-q_Q)\cdot(1-q_B)} \right) + \left(\frac{k_{CP}}{60} \cdot \frac{t_0(n_{op})}{(1-q_Q)\cdot(1-q_P)} \right) + \\ & \frac{k_{CS}}{60} \left(\frac{t_0(n_{op})}{(1-q_Q)\cdot(1-q_P)} \cdot \frac{q_S}{(1-q_S)} \right) + \frac{k_{CS}}{60 \cdot N_0} \left(T_{su}(n_{op}) + \frac{1-U_{RP}}{U_{RP}} T_{pb} \right) + \\ & \frac{k_D \cdot n_{op}}{60} \left(\frac{t_0(n_{op})}{(1-q_Q)\cdot(1-q_S)\cdot(1-q_P)} \right) + \frac{k_D \cdot n_{op}}{60 \cdot N_0} \left(T_{su}(n_{op}) + \frac{1-U_{RP}}{U_{RP}} T_{pb} \right) \end{aligned} \tag{4.12}$$

Applying this part cost model to the previously described case provides an idea of how various staffing alternatives can affect the manufacturing costs per manufactured part. These costs are presented for two cases:

Case 1: The line is staffed by four operators who are regular company employees.

Case 2: The line is staffed by eight operators, four of whom are temporary workers.

As the temporary workers have little or no training for working on the assembly line, their performance will be affected. The performance and cost parameters used in the example are chosen from Table 4.2.

Table 4.2: Cost and production performance parameters used in the assembly line example.

Parameters	**Case 1: $n_{op} = 4$**	**Case 2: $n_{op} = 8$**
k_B [USD/unit]	10	10
k_{CP} [USD/h]	110	110
k_{CS} [USD/h)	100	100
k_D (USD/h]	35	45
$t_0(n_{op})$ [sec]	81	42
$T_{SU}(n_{op})$ [min]	12	8
q_Q	0.02	0.04
q_S	0.25	0.25
q_P	0.15	0.25
U_{RB}	1	1
N_0 [unit]	60	60

The rest of the parameters of Equation 4.12 are set to zero. The part costs calculated using Equation 4.12 are as follows for the two cases presented:

Case 1: k = USD 19.9/part

Case 2: k = USD 21.5/part

If case 2 is compared with that of four trained in-house operators replacing the temporary ones and, if one assumes that this yields the same performance parameters as for the regular operators, then the part cost, k, is USD 18.1/part. If one instead assumes that using the four extra in-house operators results in the same poorer performance as for the temporary workers, then k is USD 19.6/part. The results obtained indicate the importance of taking account of the performance parameters in cost analyses concerning volume flexibility.

Figure 4.1 shows the part cost, k, as a function of the number of operators, n_{op}, using the same parameter values as in case 1. The setup time in this example is considered to be independent of n_{op}. The figure indicates that this line is operated most cost effectively by either four or more than six operators.

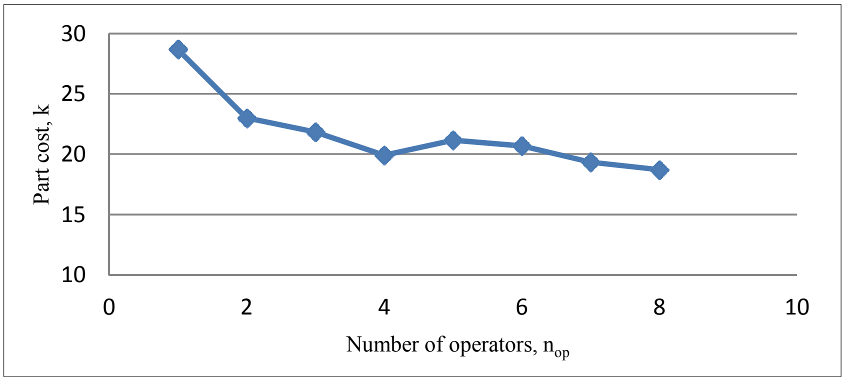


Figure 4.1: The relationship between the part cost, k, and the number of operators, n_{op}.

Connection to research questions
The paper presents a development of the basic model presented in Paper 1, thereby contributing to work related to RQ1. It broadens the applicability of the model by covering an issue, in this case volume flexibility, not considered in the original model.

4.1.3 Paper 3: Dynamic manufacturing costs

This paper proposes a method for describing the dynamic behavior of downtimes in terms of costs. The method includes statistical analyses and provides insight into how downtime variability affects the cost of the parts produced.

If downtime data collected for a processing step are categorized in terms of the types of downtimes or downtime causes involved, a strategy of some type can be used for determining what downtime category has the greatest impact on the total downtime. Manufacturing companies usually adopt strategies of this sort. This paper describes an alternative way of analyzing downtime data by analyzing the dynamic behavior of downtimes in order to develop improvement strategies for reducing the variability.

Results
Most of the data used in the paper are TBF and downtime (DT) data pertaining to a sheet-metal forming and cutting line. The data cover approximately 260 production hours, consisting of 1164 TBF-DT cycles. A TBF-DT cycle is here defined as a TBF and its subsequent DT, according to Figure 4.2. The data were extracted from the company's automatic downtime collection system and pertain to one of the company's products.

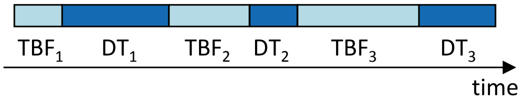


Figure 4.2: Each TBF value referred to here is linked to a subsequent DT value.

For a given series of TBF and DT, the downtime rate for each failure cycle can be calculated using Equation 4.13. The equation is also used to calculate the cost of every downtime cycle.

$$q_{S_j} = \frac{DT_j}{TBF_j + DT_j} \tag{4.13}$$

The cost equation used here is the same as the one presented in Paper 1 and can be formulated in accordance with Equation 4.14. In this study, the downtimes caused by setup were not separated from the other downtime causes, so the setup time parameter, T_{su}, is excluded from Equation 4.14. The batch size, N_0, which affects only the number of parts to which the setup time is allocated, is therefore also excluded from the equation. In the analysis presented here, q_Q, q_P, and q_B are set to 0 and U_{RP} is set to 1.

$$\begin{aligned} k_j = {} & \frac{k_{B0}}{(1-q_Q)\cdot(1-q_B)} + \frac{k_{CP}}{60}\cdot\frac{t_0}{(1-q_Q)\cdot(1-q_P)} + \\ & \frac{k_{CS}}{60}\left(\frac{t_0}{(1-q_Q)\cdot(1-q_P)}\cdot\frac{q_{S_j}}{(1-q_{S_j})} + \frac{1-U_{RP}}{U_{RP}}T_{pb}\right) + \\ & \frac{k_D}{60}\left(\frac{t_0}{(1-q_Q)\cdot(1-q_{S_j})\cdot(1-q_P)} + \frac{1-U_{RP}}{U_{RP}}T_{pb}\right) \end{aligned} \tag{4.14}$$

The number of parts, N_c, manufactured during a TBF period can be calculated as the integer of the ratio between TBF and cycle time, t_0, using Equation 4.15. If a part can be completed after a downtime without speed losses, then N_c can be expressed in decimal form.

$$N_{cj} = trunc\left(\frac{TBF_j}{t_0}\right) \tag{4.15}$$

Figure 4.3 shows the number of parts produced during TBF_j at cost k_j. Several TBF periods can produce the same number of parts, N_c, but at different costs, k_j. In the figure, the minimal part cost, k_{min}, and the mean part cost, k_{mean}, are plotted; k_{min} is the part cost for which $q_S = 0$ and k_{mean} the part cost with a mean value of q_S. From the figure, it is evident how the cost per part is affected by short TBF periods.

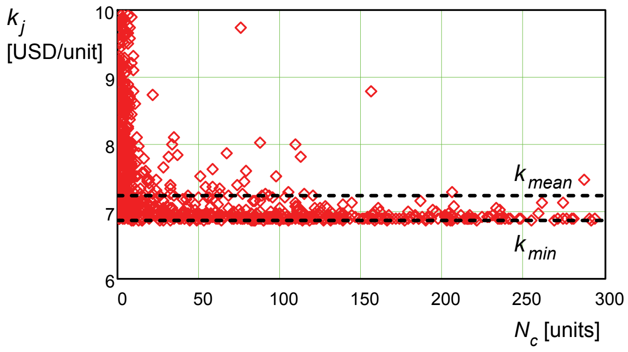


Figure 4.3: Part costs, k_j, shown as a function of the number of parts manufactured during a TBF period, N_c.

Improving the performance of a manufacturing system calls for actions to lower k_{mean}. This can be done in various ways, depending on the strategy employed. For example, k_{mean} can be lowered by reducing k_{min}, thus reducing the part costs by considering parameters other than q_S. It can also be lowered by reducing the highest k_j values. This way of looking at production development can be illustrated by considering the graph in Figure 4.4, in which the empirical distribution function for part costs is plotted. The k_{mean} value can be lowered both by reducing the high part costs shown at the right in the figure or by making changes that affect all the parts, thus shifting k_{min} to the left. No general advice or conclusions can be formulated; instead, each case needs to be studied thoroughly and individually.

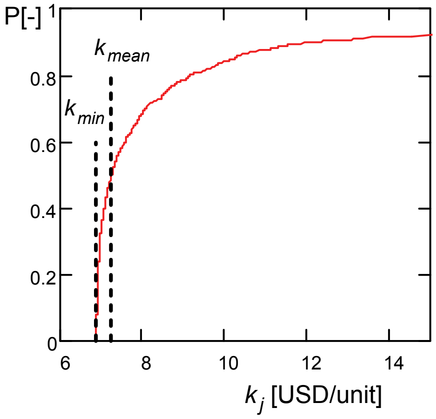


Figure 4.4: The empirical distribution of all part costs.

Connection to research questions

Like Paper 2, this is a model development paper and is thus linked to RQ1. The paper describes a new way of looking at downtime rates, by analyzing the cost effect of each downtime occurrence.

4.1.4 Paper 4: Implementation of an economic model to simulate manufacturing costs

This paper describes an implementation of the model presented in Paper 1. The cost model presented in Paper 1 is intended not just to calculate the cost impact of a specific performance loss rate, but also to calculate the costs of the individual loss causes constituting the performance rate. Accordingly, the performance loss data for the model were collected using the production performance matrix (PPM).

Results

When analyzing the collected data, new ways to present the costs were developed inspired by value stream mapping (VSM). In VSM, operations are divided into value-adding (VA), non-value-adding (NVA), and necessary but non-value-adding (NNVA) categories [110], [111]. Accordingly, k_{VA} is the value-adding cost component, describing the cost added in a processing step without considering q_Q, q_S, q_P, and T_{su}; k_{NVA} is the non-value-adding cost component, comprising all costs related to the loss parameters q_Q, q_S, and q_P; and k_{Tsu} comprises the costs related to setup, and is equivalent to NNVA in VSM. The part cost, k, can then be described as:

$$k = k_B + k_{VA} + k_{NVA} + k_{Tsu} \tag{4.16}$$

By dividing the part cost, k, into k_B, k_{VA}, k_{NVA}, and k_{Tsu}, one obtains a quick overview of the cost structure of the product. The size of k_{NVA} indicates the cost reduction made possible by reducing the production disturbances. Furthermore, k_{NVA} can be divided into k_Q, k_S, and k_P: k_Q describes the costs linked to the scrap rate, q_Q; k_S the costs linked to the downtime rate, q_S; and k_P the costs caused by q_P.

As described earlier, during the study, detailed data were gathered using the PPM method for the loss parameters q_S, q_Q, and q_P, including the registered loss causes. The bar chart in Figure 4.5 below shows the part cost, k, together with k_B and these new cost items.

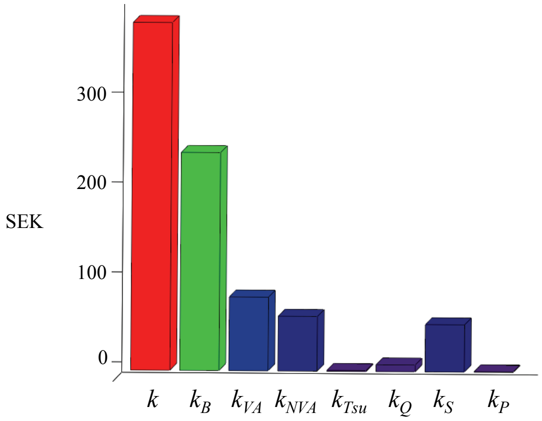


Figure 4.5: The part cost, k, and its division into various types of costs.

Figure 4.6 shows the contributions to the part cost of the most important cost factors of the studied product. Letters A–E in the figure correspond to the factor groups in the PPM method (see Figure 3.3). The figure indicates that, apart from the tool factor, A_2, the major factors underlying the level of k_{NVA} are related to process (C) and organizational (D) issues.

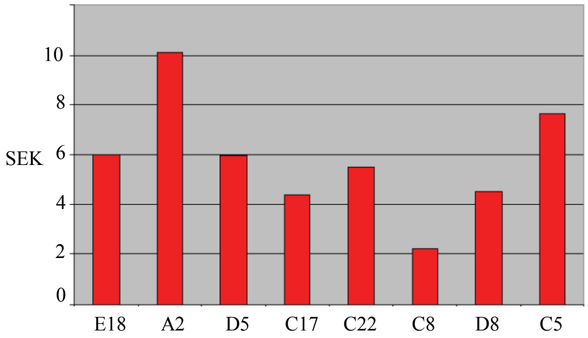


Figure 4.6: Factors having the greatest effects on the part cost of product x.

When the critical parameters and factors connected to these losses are obtained and economically quantified, then cost derivatives can be used to analyze various development scenarios, as demonstrated in Paper 1. Figure 4.7 shows the cost-neutral relationship in the case of product x between an increase in the tool cost, Δk_A, and a decrease in the process development factor, Δx_P. This relationship illustrates the maximum cost increase of improved tooling capable of reducing the cycle time to a certain level. For example, if a new tool can reduce the cycle time by 4% (i.e., $\Delta x_P = -0.04$), the new cost per tool must not increase by more than SEK 4.5, otherwise the cost per part will increase relative to the present situation. The dotted line shows the relationship when new but more expensive tools enable a decrease in x_P, while causing an estimated 0.01 increase in the scrap rate, q_Q. The solid line shows the relationship without any increase in q_Q.

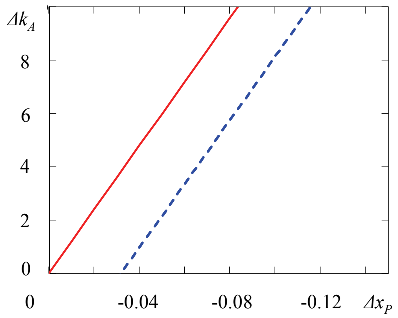


Figure 4.7: Cost-neutral changes between an increase in the tool cost, Δk_A, and a reduction in the development factor, Δx_P (solid line), and between an increase in Δk_A plus a 0.01 increase in q_Q and a reduction in Δx_P (dotted line).

Connection to research questions

The results of this paper relate to both RQ1 and RQ2. The new division of the cost into value-adding, non-value-adding, and setup cost components, as well as the presentation of the costs of specific loss causes, mean that the paper can be categorized as model development and is related to RQ1. The paper also addresses the practical side of the model and demonstrates that the model is applicable in real-world conditions, provided the loss data are collected at a detail level similar to that used here; the paper consequently also addresses RQ2.

4.1.5 Paper 5: Conditions for and development of an IT-support tool for manufacturing costs calculations and analyses

A crucial aspect of increasing cost awareness by using a manufacturing cost model such as the one proposed here is investigating the conditions for implementing the model in an industrial environment. Implementation encompasses two important aspects: availability of input data for the cost model and how the model should be implemented.

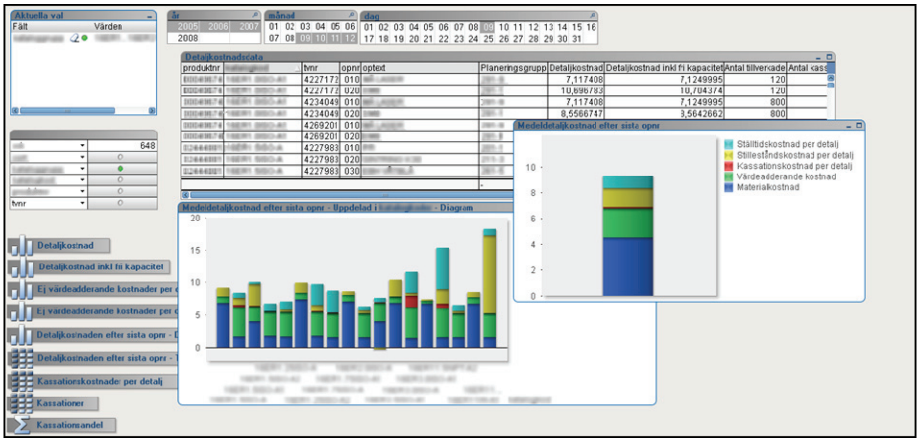
Results

The availability of input data was investigated in two pre-studies. The studies were limited to manufacturing-related data only, i.e., availability of the required cost data was not considered. This limitation was imposed since cost data are more static, and therefore less extensive, and are always gathered in some way by companies. The first study reviewed four software products for collecting data on manufacturing-related parameters, such as performance losses, regarding their ability to collect the required data. The availability of workable software would be advantageous, because then a software application of the cost model would not entail the in-house development of a data collection system, as the application could use data stored by off-the-shelf software products. The study included three dedicated production performance monitoring products and one ERP system. The results of the review indicated that three of these products supported the collection of the manufacturing data needed for the applied model. However, this result does not imply that manufacturing companies are actually exploiting the opportunity to collect the required data. The second study therefore investigated to what extent manufacturing companies are collecting the required data. This study demonstrated that, although the manufacturing companies participating in the study were largely able to collect the needed data, none of them were collecting all the required data.

Based on the results of the pre-studies, it was decided to develop a software application of the cost model jointly with a typical intended application user. The input data for the software should be based on data the company has already collected for other purposes. Before the application was developed, a list of criteria was established that the application had to fulfill, as follows:

- to indicate the cost of every completed order number in cost per part
- to indicate the cost distribution between material, value-added, non-value-added, and support activities
- to indicate the cost distribution between various non-value-added activities
- to visualize the results accessibly
- to provide a user-friendly interface
- to permit "what-if" analyses, i.e., analyses of how the cost is affected by various changes in parameter values

Based on these criteria, the application was initially divided into two sheets, i.e., *Part cost* and *What-if*, but the final version of the application contained two more sheets, i.e., *Batch cost* and *Process cost*. Each sheet contains various tables and charts and a menu in which the user can select the products analyzed and the applicable time horizon. Figure 4.8 shows a screen shot of the part cost sheet.



Detaljkostnadsdata

produktnr	[illegible]	tvnr	opnr	optext	Planeringsgrupp	Detaljkostnad	Detaljkostnad inkl fri kapacitet	Antal tillverkade	Antal kass
[illegible]	[illegible]	4227172	010	[illegible]	[illegible]	7,117408	7,1249995	120	
[illegible]	[illegible]	4227172	020	[illegible]	[illegible]	10,696783	10,704374	120	
[illegible]	[illegible]	4234049	010	[illegible]	[illegible]	7,117408	7,1249995	800	
[illegible]	[illegible]	4234049	020	[illegible]	[illegible]	8,5566747	8,5642662	800	
[illegible]	[illegible]	4269201	010	[illegible]	[illegible]				
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Figure 4.8: Screen shot of the part cost sheet in the cost software.

The purpose of the part cost sheet is to display various calculations linked to the cost per part, *k*. The sheet includes tables and charts showing the cumulative cost per part from raw material to finished part. Information is also available regarding the values of the underlying parameters on which the part cost calculations are based. Figure 4.9 shows an example of a chart available in this sheet. The chart shows the increase in part cost contributed by every processing step, divided into value-added and non-value-added costs.

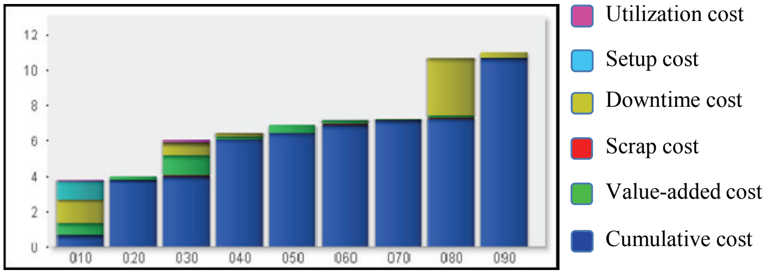

Figure 4.9: The cumulative costs at each processing step, divided into value-added costs and various non-value-added costs.

The batch cost sheet presents the total manufacturing costs of a batch, i.e., part cost multiplied by batch size. The process cost sheet presents the costs linked to machines and machine groups instead of to manufactured parts, indicating where in the plant the costs occur as well as the size of the costs. Figure 4.10 shows a bar chart from the process cost sheet showing the cost per hour of various machine groups.

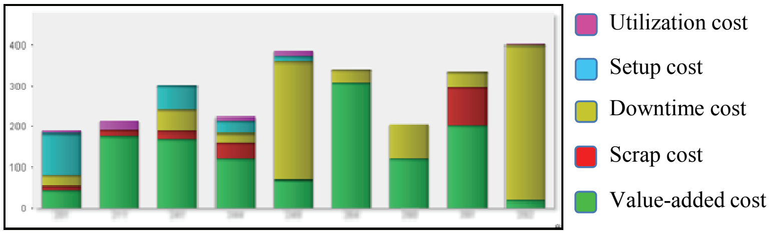

Figure 4.10: Process cost per hour for various machine groups; each bar represents a machine group.

The purpose of the what-if sheet is to make simple simulations that indicate how the cost is affected by changes in input parameter values. The sheet shows the actual part costs and the values of the parameters on which these costs are based, just as in the part cost sheet. The difference is that this sheet also contains input fields in which one can enter new values for the parameters contained in the cost model and examine how the new values alter the part costs.

Connection to research questions

This paper addresses both RQ1 and RQ2. The process cost equations represent model development and thus answer RQ1. The investigations of the industrial conditions necessary for the model and the development of the software prototype represent answers to RQ2.

4.1.6 Paper 6: Availability improvement by structured data collection: a study at a sawmill

This paper explores the role of availability monitoring as a tool for gaining knowledge of availability losses. The purpose is to investigate, first, whether an increase in the detail level of the collected downtime loss data improves the knowledge of what corrective action to implement and, second, how the personnel responsible for reporting the availability losses perceive the increased detail.

Results

The study was carried out in a sawmill company. The company had a system that automatically registered downtime durations, but the operators still needed to choose an appropriate downtime cause from a list available in the system. To investigate how more detailed monitoring affected the knowledge gained, a new list of downtime causes was created, including a new list structure grouping the causes. The original list represented essentially all types of equipment, but only a few downtime cause alternatives were offered for each piece of equipment. The production manager also believed that some downtime causes were missing from the system's lists. There was some dissatisfaction with the list structure, for example, setup time and unplanned tool exchange were found in the same downtime group. A total of 128 downtime causes were available in the system before the implemented changes.

The changes in the downtime monitoring system started with the structure of the downtime cause list. The new structure, based on PPM concept developed by Ståhl [17] (see section 3.1.2.1), is more consistent than the previous one. Now every piece of equipment has essentially the same categories of downtime causes, comprising Tools (only for the equipment incorporating tools), Material, and four machine-related categories. A division was made between processing and material-handling equipment, the former having a more detailed set of downtime causes than the latter. Figure 4.11 shows an example of how the new tree structure of the downtime causes is structured, in which the group *Saw group 1 and its material handling equipment* is expanded.

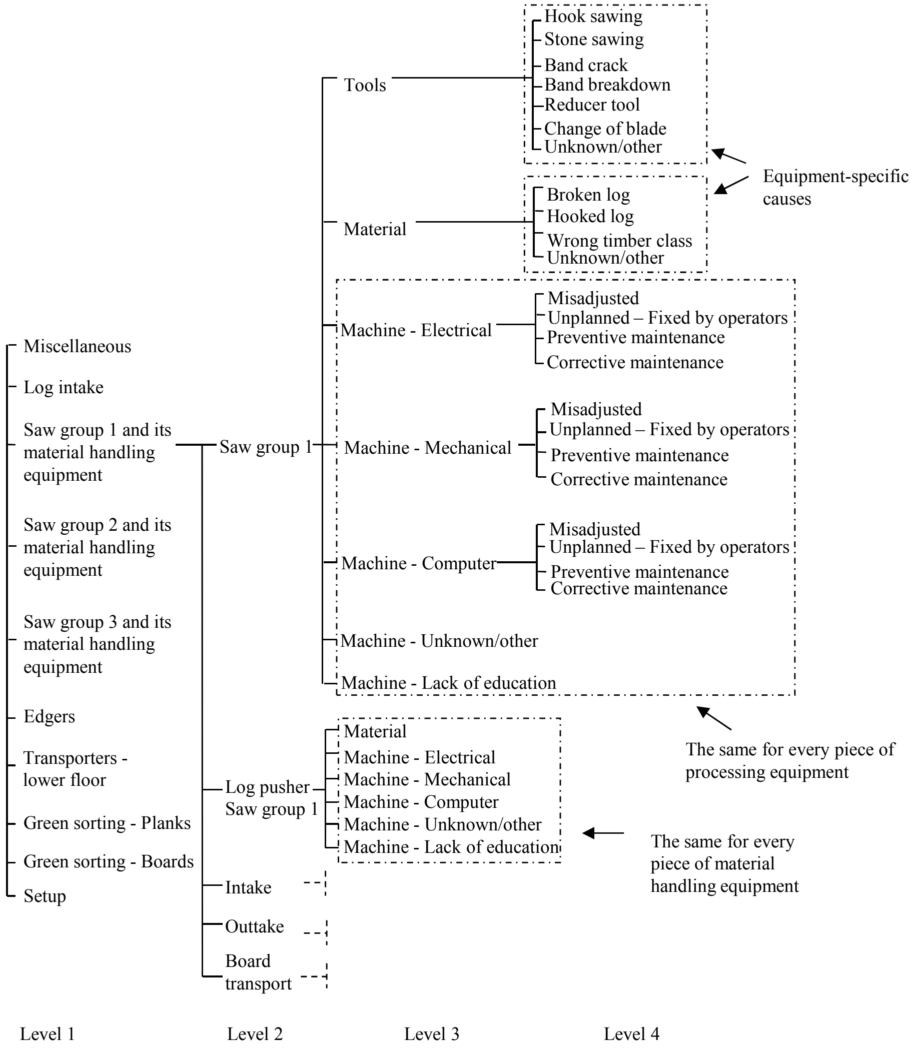

Figure 4.11: Example of the new structure and list of downtime causes.

As mentioned above, the list of downtime causes for the processing equipment has a more detailed structure then the list for the material handling devices. The latter offers only six downtime causes to choose from, as shown in the lower box in Figure 4.11, and they are the same for every piece of material handling equipment. For the processing equipment, the Tools and Material subgroups include specific downtime items for every machine, the other causes (indicated by the large rectangle in the figure) reappearing for every piece of processing equipment. Maintenance-related downtimes consume maintenance resources, so it is useful to highlight and separate them from the other downtimes. It was also decided that preventive and corrective maintenance should be separated, making it possible, for example, to investigate how increases in preventive maintenance affect the amount of corrective maintenance needed. These changes resulted in a downtime monitoring system now containing 292 individual downtime causes.

One question addressed in the paper was whether an increase in the level of detail regarding the specification of downtime causes could improve a company's knowledge of its availability losses. According to the production manager, the changes in the downtime system have improved the usability of the collected data. The data now indicate more precisely what has happened and therefore what needs to be done to improve the situation. Because of the higher level of detail in the list of available downtime causes, the production manager now finds it easier to steer discussions with operators toward specific problems.

The other question raised in the paper was how the personnel responsible for reporting the availability losses perceive the increased level of detail. The interviews with the operators indicated that they generally favored the new list of downtime causes. The new list enables them to choose a downtime cause that actually describes the occurred stoppage, making the monitoring more precise. With more downtime causes to choose from, the operators might feel that the data collection is overly complicated and time-consuming; however, the interview results indicated that they generally did not feel that the new system included too many downtime causes, and that they appreciated the possibility of selecting more correct downtime causes.

Connection to research questions

This paper takes one step backward and addresses the collection of input data for the cost model. Paper 4 demonstrated that the cost model was applicable in an industrial context, provided the company collected data at a level of detail similar to that used in the study. Paper 5 further investigated the conditions for the industrial use of the cost model and demonstrated that existing software products could support the collection of the required data. Finally, Paper 6 demonstrated that the required level of input data detail was manageable under real-world conditions; the paper thus addresses the conditions for industrial use and consequently answers RQ2.

4.2 Cost model – Clarifications and enhanced downtime and equipment cost calculations

The cost model originally published in Paper 1 has since been refined, most of the related changes having been included in papers 2–5. However, some of the refinements were not covered in the appended papers; those will be presented here, together with a more general formulation of the cost model than the one published in Paper 1. The general formulation clarifies that the model describes any processing step in a product's processing chain by formulating the equations in a more general way by using the index *i*, which describes the processing step. The index had already been introduced in papers 3 and 5, but not in all of the equations pertaining to the model.

In the original model presented in Paper 1, the batch size, N_0, describes the nominal batch size, i.e., the ideal number of parts produced in a scenario in which no scrapping occurs. If scrapping does occur, additional parts must be produced to meet customer demands, resulting in the real batch size, N. This formulation of the batch size describes a situation in which the final batch size is not determined before order production starts; instead, it depends on the number of parts scrapped when manufacturing the order. Such a configuration can prevail in a make-to-order situation in which buffers and other types of part stockpiling are undesired. However, companies often adopt a strategy in which the initial batch size is fixed, not varying depending on whether or not scrapping occurs. The size of the batch arriving at a specific processing step then depends on the size of the batch when it left the previous step. This type of configuration is modeled in section 4.2.2.

The original model contains two parameters for equipment costs: k_{CP}, the equipment cost rate during production, and k_{CS}, the equipment cost rate during downtime and idle time. In Paper 1, these two parameters were described only briefly, but section 4.2.2.1 presents a more detailed formulation of k_{CP} and k_{CS} that takes into account the key parameters affecting these costs.

4.2.1 Main principle of the proposed cost model

The focus of the proposed cost model is the influence of each processing step on the total cost of each part. It is a cost center approach in which the cost center comprises every freestanding processing step, i.e., processing steps separated by buffers, in the processing chain. Such a processing step is here referred to as a planning point. Every planning point is represented by a cost equation, which means that every planning point has a specific k_{CP}, k_{CS}, and k_D together with the other parameters included in the cost model. A planning point can consist of several unique process steps, but these steps share a common nominal bottleneck station that determines the common nominal cycle time, t_0, of the planning point. Figure 4.12 illustrates the cost center approach employed. The cost allocation is mainly time driven, which means that the shares of the total equipment and wage costs allocated to the parts are based on the length of time each part resides in each piece of equipment. This time is determined by times related to the equipment capacity, such as processing time and material handling time, and by disturbances causing breakdowns, small stoppages, or reduced production speed. The non-time-driven cost in the model consists of the cost of scrapped parts, which is taken into consideration by defining the part cost as the cost per correctly manufactured part. Hence the cost of the batch in a specific processing step is divided by the number of correctly manufactured parts.

The proposed approach makes it possible to describe how a part's cumulative cost is built up by the processing steps it undergoes. It also makes it possible to determine to what extent these costs are constituted by valued-adding activities and to what extent they are constituted by disturbances, such as downtimes and quality deviations. In addition, the distribution between material, equipment, and wage costs at every processing step can be visualized, illustrated by the bar charts and circle charts in Figure 4.12. Such presentations of the costs involved are intended to foster understanding of how different economic and manufacturing technology-related parameters affect the cost of parts produced in a manufacturing system.

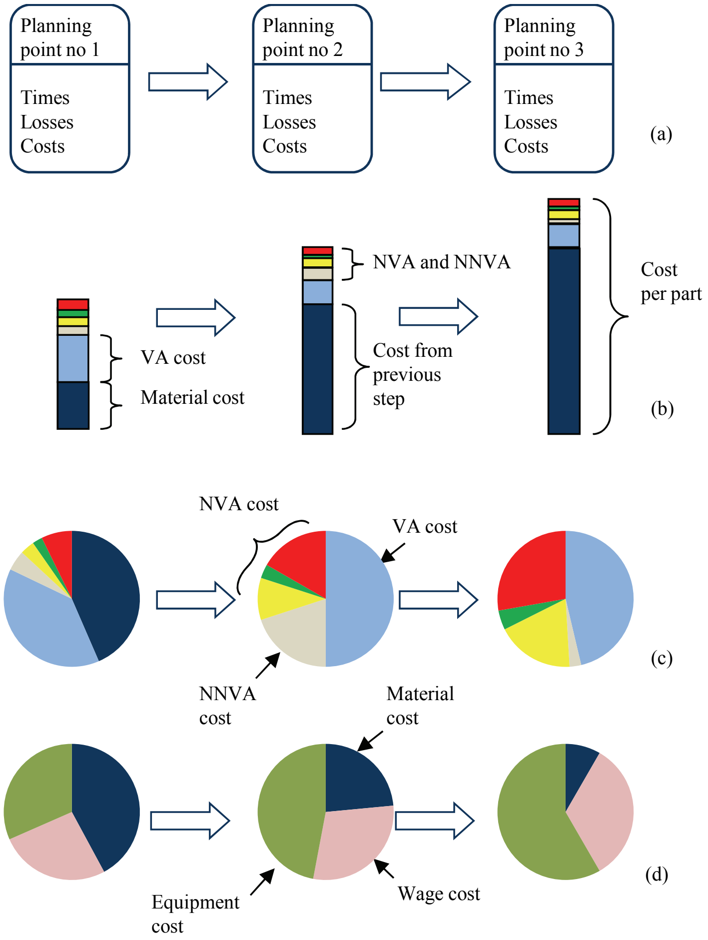

Figure 4.12: (a) The cost center approach and examples of possible analyses. (b) Bar charts showing the added cost associated with a specific processing step. (c) The share of material, VA, NVA, and NNVA costs in each processing step. (d) The cumulative shares of material, equipment, and wage costs.

4.2.2 Modeling the part cost

The nominal processing time (cycle time), t_0, in processing step i for a part comprises machine time, t_m, handling time, t_h, and tool change time, t_{vb}, according to Equation 4.17.

$$t_{0_i} = t_{m_i} + t_{h_i} + t_{vb_i} \tag{4.17}$$

In the original version of the cost model, the downtime rate, q_S, included all planned and unplanned downtime except for setup time and utilization losses. Implementations of the model have revealed the deficiencies of such an approach when it comes to calculating the cost of a specific batch. This is because planned downtime normally often occurs *between* batches, as illustrated in Figure 4.13, so there is no specific batch to which to logically allocate it. A more logical way to handle planned downtime is to allocate its costs not to the parts produced in a specific batch, but to all produced products in relation to the length of each batch time, i.e., according to the same principle as used for machine utilization losses, U_{RP} (see Equation 4.5). This results in the planned downtime being distributed uniformly as an extra cost per unit time during production, unplanned downtime, and setup time.

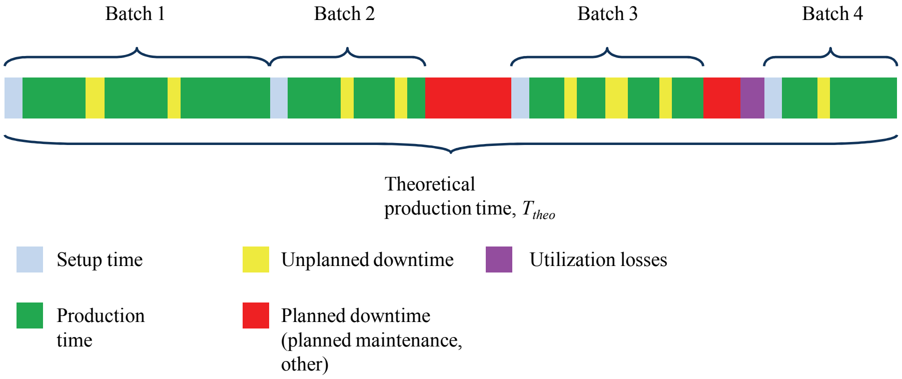

Figure 4.13: Illustrative timeline of hypothetical manufacturing equipment.

Allocating planned downtime costs in a way similar to the allocation of utilization losses costs is logical, because utilization losses are actually a type of planned downtime. Although setup time (T_{su}) is also a planned downtime, the definition of T_{su} will remain unchanged, because setup times are clearly connected to specific batches.

Clearly distinguishing between planned and unplanned downtime is also sound in the sense that there are clear differences between their causes: the former are organizationally related, scheduled by the company, and sometimes carried out to reduce the latter.

As a result of these changes, the downtime rate will be divided into two main types: the planned downtime rate, q_{S1}, and the unplanned downtime rate, q_{S2}. The formulations of these rates, as well as the scrap rate, q_Q, and production-rate loss, q_P, are presented in Figure 4.14, where the rates are calculated by dividing the loss time (indicated in the red square) by the time in the blue rectangle above it. Compared to the OEE performance parameters (i.e., A, O, and P), q_P is equivalent to $1 - P$ and q_Q is equivalent to $1 - Q$; q_{S2} is equivalent to $1 - A$, except that q_{S2} does not include setup time.

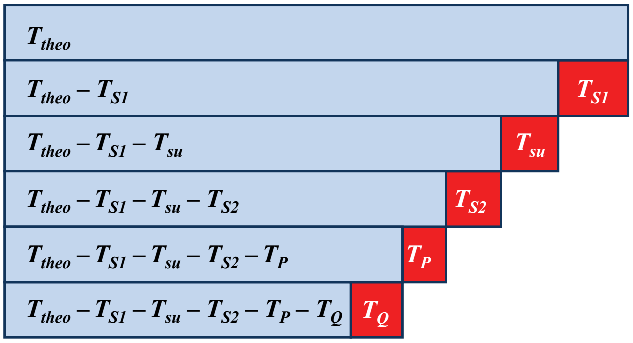

Figure 4.14: The division of the production time that forms the basis for the performance rates.

The planned downtime rate, q_{S1}, for a given planning horizon can be expressed as the ratio between the estimated planned downtime and the theoretical production time for the period, according to Equation 4.18:

$$q_{S1_i} = \frac{T_{S1_i}}{T_{theo_i}} \tag{4.18}$$

T_{theo} is the theoretically available shift time including planned and unplanned downtime, as shown in Figure 4.13.

The planned downtime is further divided into preventive maintenance time, T_{S1EP}, utilization loss time, T_{S1UL}, and other planned downtime, T_{S1O} (e.g., meetings and cleaning), according to Equation 4.19. Maintenance-related time is distinguished from non-maintenance-related time to facilitate analysis of maintenance-related costs, which are treated later in section 4.2.2.1.

$$T_{S1_i} = T_{S1UL\,i} + T_{S1EP_i} + T_{S1O\,i} \tag{4.19}$$

Rates for preventive maintenance, q_{S1EP}, and other planned downtime, q_{S1O}, can be formulated as:

$$q_{S1EP} = \frac{T_{S1EP_i}}{T_{theo_i}} \tag{4.20}$$

$$q_{S1O_i} = \frac{T_{S1O_i}}{T_{theo_i}} \tag{4.21}$$

The original version of the cost model captured machine utilization using the parameter U_{RP}. In accordance with the new downtime definitions presented here, machine utilization is instead expressed as a loss using the utilization loss rate parameter q_{S1UL} defined in Equation 4.22:

$$q_{S1UL\,i} = \frac{T_{S1UL_i}}{T_{theo_i}} \tag{4.22}$$

The total planned downtime rate, q_{S1}, can be expressed by Equation 4.23 using the rates calculated with equations 4.20 to 4.22:

$$q_{S1i} = q_{S1UL\,i} + q_{S1EP_i} + q_{S1O\,i} \qquad 4.23$$

As stated earlier, the planned downtime is allocated to a batch in relation to the total time needed to manufacture a batch. The planned downtime allocated to a batch, T_{S1b}, is defined in Equation 4.24:

$$T_{S1b_i} = \frac{T_{b\,i}}{1-q_{S1_i}} \cdot q_{S1_i} \qquad 4.24$$

The mean unplanned downtime rate, q_{S2}, for a planning horizon is defined as the ratio between total unplanned downtime, T_{S2}, and the theoretical production time minus the planned downtime and setup time for the period, according to Equation 4.25:

$$q_{S2_i} = \frac{T_{S2\,i}}{T_{theo_i} - T_{S1\,i} - T_{su_i}} \qquad 4.25$$

According to the same principle as used for planned downtime, the total unplanned downtime, T_{S2}, is divided into time for corrective maintenance, T_{S2EC}, and other unplanned downtime, T_{S2O}, according to Equation 4.26:

$$T_{S2\,i} = T_{S2EC_i} + T_{S2O\,i} \qquad 4.26$$

The corrective maintenance rate, q_{S2EC}, and the downtime rate for other unplanned downtime, q_{S2O}, are defined by equations 4.27 and 4.28:

$$q_{S2EC_i} = \frac{T_{S2EC_i}}{T_{theo_i} - T_{S1\,i} - T_{su_i}} \qquad 4.27$$

$$q_{S2O\,i} = \frac{T_{S2O_i}}{T_{theo_i} - T_{S1\,i} - T_{su_i}} \qquad 4.28$$

Production-rate loss, q_P, denotes speed losses due to short stoppages and increased cycle times. Equation 4.29 represents q_P, where T_P is the production-rate loss time:

$$q_{P_i} = \frac{T_{P_i}}{T_{theo_i} - T_{S1\,i} - T_{S2_i} - T_{su_i}} \qquad 4.29$$

Equation 4.30 expresses the scrap rate, q_Q, where N_Q is the number of scrapped parts in processing step i and N_i is the batch size for processing step i, excluding scrapped parts, i.e., the number of correctly manufactured units. The scrap rate, q_Q, can also be expressed in terms of time according to Equation 4.31, where T_Q is the nominal production time for the scrapped parts:

$$q_{Q_i} = \frac{N_{Q_i}}{N_{i-1}} = \frac{N_{i-1} - N_i}{N_{i-1}} \qquad 4.30$$

$$q_{Q_i} = \frac{T_{Q\,i}}{T_{theo\,i} - T_{S1_i} - T_{S2_i} - T_{su_i} - T_{P_i}} \qquad 4.31$$

The production time for a batch, T_b, can be expressed in two ways depending on whether or not T_b is affected by the scrap rate, q_Q. In make-to-order situations in which specific quantities of correct units must be produced, T_b will be dependent on q_Q because additional parts must be produced, according to Equation 4.32. On the other hand, in a make-to-stock situation, the production time, T_b, will not be affected by q_Q, according to Equation 4.33:

$$T_{b_i} = T_{su_i} + \frac{N_{i-1} \cdot t_{0_i}}{(1-q_{Q_i}) \cdot (1-q_{S2_i}) \cdot (1-q_{P_i})} \qquad 4.32$$

$$T_{b_i} = T_{su_i} + \frac{N_{i-1} \cdot t_{0_i}}{(1-q_{S2_i}) \cdot (1-q_{P_i})} \qquad 4.33$$

The cost per part is defined according to Equation 4.34. There are several differences between this part cost equation and the one found in Paper 1 (Equation 4.9). Equation 4.34 expresses the cost per part more generally by introducing the processing step index, *i*. It also includes greater detail due to the modified downtime rates described above, and includes rows describing the costs of tools and corrective maintenance (these two costs are described in section 4.2.2.1).

$$\begin{aligned}
k_i = {} & \frac{k_{i-1}}{1-q_{Q_i}} + \left[k_{A_i} \cdot \frac{t_{m_i}}{60 \cdot (1-q_{Q_i}) \cdot (1-q_{P_i})} \right]_A + \\
& \left[\frac{k_{CP_i}}{60} \cdot \frac{t_{0_i}}{(1-q_{Q_i}) \cdot (1-q_{P_i})} \right]_C + \\
& \left[\frac{k_{CS_i}}{60} \cdot \left(\frac{t_{0_i}}{(1-q_{Q_i}) \cdot (1-q_{P_i})} \cdot \frac{q_{S2_i}}{(1-q_{S2_i})} + \frac{T_{su_i} + T_{S1b_i}}{N_{i-1} \cdot (1-q_{Q_i})} \right) \right]_C + \\
& \left[\frac{k_{D_i}}{60} \cdot \left(\frac{t_{0_i}}{(1-q_{Q_i}) \cdot (1-q_{S2_i}) \cdot (1-q_{P_i})} + \frac{T_{su_i} + T_{S1b_i}}{N_{i-1} \cdot (1-q_{Q_i})} \right) \right]_D + \\
& \left[\frac{k_{EC_i}}{60} \cdot \left(\frac{t_{0_i}}{(1-q_{Q_i}) \cdot (1-q_{P_i})} \cdot \frac{q_{S2EC_i}}{(1-q_{S2_i})} \right) \right]_E
\end{aligned} \qquad 4.34$$

The first expression in Equation 4.34 describes the value of a part as it enters processing step *i* and the extra cost resulting from scrapped parts. The cost of a part as it enters the first processing step consists of the material cost, including the raw material and indirect material costs, and is denoted k_B. Equation 4.34 is formulated for an arbitrary production step, which means that if $i = 1$, then $k_{i-1} = k_B$. Indexes *A*–*E* in the cost model relate to different groups of causes in the production performance matrix, described in section 3.1.2.1, i.e., *A* is tool related, *B* material related, *C* machine related, etc. Bracket *A* describes the tool cost, which is defined in section 4.2.2.1. The first *C* bracket expresses the machine cost during the operating time per correctly manufactured part, and the second *C* bracket describes the total downtime cost per correct part. Bracket *D* includes the wage cost per correctly manufactured part; k_D is the wage cost per hour, including social insurance expenditure and other labor taxes, the hourly rate being calculated based on theoretical production time. Only what is traditionally classified as direct labor is included in k_D, i.e., personnel directly connected to the production process, such as machine operators. The wage cost per correctly manufactured part is a function of the total production time including setup time. Bracket *E* describes the cost of corrective maintenance.

4.2.2.1 Equipment costs

Here follows more detailed formulations of the equipment cost parameters k_{CP} and k_{CS} than are found in Paper 1. The equipment cost, which sometimes constitutes much of the manufacturing cost, can be calculated in numerous ways. This leads to the conclusion that the equipment cost must be defined at a higher level of detail than other costs, yielding a precise definition appropriate for the analyses for which the cost model is to be used.

Depreciation and interest costs

All the manufacturing cost models examined in the literature review that include the investment cost of equipment consider only the depreciation cost and sometimes also the installation cost. None of them consider the interest cost—or cost of capital, as it is usually called. Why this cost is neglected is unclear, though it is possibly because there are different opinions as to whether the cost of capital should be regarded as a cost in product costing and equipment cost calculations [39]. For a company applying interest costs in its calculations, a suitable approach for the present cost model is to use the capital recovery factor. This factor results in an evenly distributed yearly cost, enabling fair and convenient comparison of the cost effects of equipment of various ages, independent of how long the equipment has been used. For the same reason, it is recommended that the hourly cost be based on the useful life of the equipment, instead of using a fixed depreciation period. Groover [104] also uses the capital recovery factor in equipment cost calculations; unlike Groover's model, the proposed cost equations include more detailed descriptions of the costs included in the machine cost, instead of using the overhead rate used by Groover.

The initial investment expense is denoted I_0 and also includes, in addition to the investment cost, the costs of equipment installation. The yearly cost of the initial investment, the annuity, is denoted a and the interest rate r. The interest rate should reflect the company's cost of financing the investment. Equation 4.35 defines the annuity, a, where n is the estimated economically useful life of the machine:

$$a = I_0 \cdot \frac{r \cdot (1+r)^n}{(1+r)^n - 1} \tag{4.35}$$

Floor space cost

The equipment occupies a specific floor area, F, in the factory building. The building is associated with certain costs, such as the depreciation, utilities, and maintenance costs, that can be formulated as a cost per square meter, k_{CF}. The product of F and k_{CF} therefore represents the floor area cost of the equipment. This is a standard calculation found, for example, in Son [76].

Cost of preventive maintenance

Preventive maintenance is a planned periodic activity resulting in a periodic cost, normally occurring after a specific number of operating hours. Converting this to a cost not varying in time depending on the specific occurrence of maintenance tasks distributes the costs evenly over the operating time. The preventive maintenance cost per hour is denoted k_{EP} and consists of the labor costs for maintenance personnel and other maintenance department costs, such as the costs of equipment and the computer system for maintenance activity documentation. k_{EP} can be derived by calculating the total cost of the maintenance department, K_E, over the planning horizon, divided by the department's total practical capacity (i.e., number of employees in the maintenance department, n_{Eavail}, multiplied by the practical capacity per employee, T_{Eavail}). This rate is then multiplied by n_{Eused}, which is the average number of workers performing a preventive maintenance task. As shown in equations 4.38 and 4.39, k_{EP} is multiplied by T_{S1EP}, which is the estimated preventive maintenance time for the planning horizon.

$$k_{EP_i} = \frac{K_E \cdot n_{Eused_i}}{n_{Eavail} \cdot \frac{T_{Eavail}}{60}} \tag{4.36}$$

The corrective maintenance cost is described separately in the part cost model, and is not included in the equipment cost parameters.

Variable costs

Equipment operation is associated with energy consumption and often with additives such as cutting fluids and lubricants. These variable costs are denoted k_V, which is defined in Equation 4.37; k_{ep} is the hourly energy cost of the equipment during production and k_{add} is the total cost of additives per hour. How easy these costs are to determine depends on how they are documented and structured by the company. The energy cost per hour can be calculated by measuring the energy consumption of the machines and multiplying the consumption by the energy cost rate. If these cost items cannot be obtained directly, they can be estimated.

$$k_{V_i} = k_{add_i} + k_{ep_i} \tag{4.37}$$

Hourly equipment costs

The part cost model presented earlier in this thesis separates the total equipment cost into the cost of equipment during operation and during downtime (e.g., setup and unplanned downtime). Therefore, two machine cost rates are formulated, one for the cost during operation, k_{CP}, and the other for the cost during downtime, k_{CS}. To calculate the hourly machine cost, the previously noted cost items are divided by the yearly theoretical production time, T_{theo}. Equation 4.38 expresses the hourly machine cost during production, k_{CP}.

$$k_{CP_i} = \frac{a_i + F_i \cdot k_{CF_i} + k_{EP_i} \cdot \frac{T_{S1EP_i}}{60}}{\frac{T_{theo_i}}{60}} + k_{V\,i} \tag{4.38}$$

The hourly machine cost during downtime, k_{CS}, is calculated by reducing the machine cost during production, k_{CP}, by the variable machine costs included in k_V. Machines may consume energy even during downtime, when they may be in standby mode, and this energy consumption is denoted k_{es}.

$$k_{CS_i} = \frac{a_i + F_i \cdot k_{CF_i} + k_{EP_i} \cdot \frac{T_{S1EP_i}}{60}}{\frac{T_{theo_i}}{60}} + k_{es_i} \tag{4.39}$$

Cost of corrective maintenance

The cost of corrective maintenance is not included in the machine cost expressions, but is instead described separately in Equation 4.34. The cost of corrective maintenance is not included in the hourly machine cost expressions because the corrective maintenance cost is viewed as a special type of downtime cost, not an equipment cost. The corrective maintenance cost per hour is denoted k_{EC} and can be derived in the same way as can the hourly cost of preventive maintenance, as described in Equation 4.36. This cost is multiplied by the corrective maintenance time per part using q_{S2EC}. The expression for the corrective maintenance cost per correct part, k_{ec}, is described in Equation 4.40:

$$k_{ec_i} = \frac{k_{EC_i}}{60} \cdot \left(\frac{t_{0_i}}{(1-q_{Q_i}) \cdot (1-q_{P_i})} \cdot \frac{q_{S2EC_i}}{(1-q_{S2_i})} \right) \qquad 4.40$$

Tool cost

A tool or tool system can have different characteristics depending on the type of machine involved. Many types of machines, such as lathes and milling machines, have a tool system consisting of a tool holder and an insert. The cost models of Cauchick-Miguel and Coppini [71] and Branker et al. [78], for example, are based on such a system. The formulation of the tool cost per hour in this thesis is based on the same system, and is shown in Equation 4.41. In this approach, k_{th} is the tool holder cost, which is divided by T_{th}, the estimated tool holder life; k_t is the cost per insert and T_t the insert life. If the insert consists of more than one cutting edge, the parameter n_t, which describes the number of edges, can be applied. Unlike the tool cost as formulated in Cauchick-Miguel and Coppini [71] and Branker et al. [78], Equation 4.41 includes an expression for overhead costs related to the tools, k_{tOH}, which can include the costs of tool sharpening. k_{tOH} is multiplied by the estimated time spent on these activities over a planning horizon, $T_{tOHused}$, and then divided by the time available over the same planning horizon, $T_{tOHavail}$. The hourly costs are multiplied by the machine processing time, t_m, to obtain the cost per part. In addition to scrapped parts, speed losses resulting from increased t_m can be taken into account by q_P, but only the share of q_P resulting from increased t_m and not short stoppages that can also be included in the q_P parameter.

$$k_{A_i} = \left(\frac{k_{th_i}}{\frac{T_{th_i}}{60}} + \frac{k_{t_i}}{n_{t_i} \cdot \frac{T_{t_i}}{60}} + \frac{k_{tOH} \cdot \frac{T_{tOHused_i}}{60}}{\frac{T_{tOHavail}}{60}} \right) \qquad 4.41$$

4.2.3 Connection to research questions

Since the publication of Paper 1, it has been realized that the equipment cost needed to be defined in greater detail, because it can constitute a significant part of the total manufacturing cost in some manufacturing systems, for example, highly automated manufacturing systems. The equipment cost equations presented here can be regarded as a supplement to Paper 1, added to make the cost model more comprehensive, and thus address RQ1. As a result, the model now includes more parameters of interest when analyzing manufacturing cost issues, for example, the relationship between preventive maintenance and unplanned downtime. The other modifications of the cost model introduced in section 4.2.2, for example, the division of the downtime rate into planned and unplanned downtime rates, also address RQ1 and were made so the model would be more applicable. The cost allocation is now more logical, since planned downtime is now distributed evenly over the production time. The introduction of the new downtime parameters describing the rates of preventive and corrective maintenance enables analysis of the impacts of different types of maintenance activities. In addition, the cost model now takes into account the fact that unplanned downtime, the correction of which requires formal maintenance resources, is more costly than downtime handled by the operators themselves.

5 Discussion

This chapter relates the results of the thesis to the literature findings presented in chapter 3. In particular, the cost model is compared with the cost accounting methods described in section 3.2 and with the cost models described in section 3.3.

Companies today use alternative methods to measure their manufacturing performance and to calculate costs related to the manufacturing department and other departments. One popular method for measuring manufacturing performance is OEE. OEE includes many of the parameters found in the proposed model and can be used to address similar issues, for example, how equipment is performing and the distribution of losses between scrap, downtime, and production-rate losses. However, because OEE does not include cost considerations, it cannot provide the same insight into performance as can the proposed model. For example, the definition of OEE results in a 5% quality-rate loss having the same impact on the OEE figures as a 5% downtime-rate loss. OEE consequently neglects the material cost, the value accumulated after each processing step, and the cost rate of the processing step in which scrapping occurred. By expressing performance losses in terms of costs according to the proposed model, improvement activities can be prioritized more accurately than by using OEE.

At the beginning of the literature review, several theories of manufacturing system performance were presented, including the sand cone model. This model claims that improvement work must be conducted in a specific sequence, starting with quality, then dependability, speed, and finally cost, to avoid tradeoffs. Whether or not the sand cone theory is true is debatable, but at least the sequence of the first three layers in the sand cone feels intuitively sound. The fourth layer, i.e., cost, is not necessarily wrong, but the present author believes that cost reduction should not be a final, isolated activity, because, according to the proposed model, costs are linked to the first three layers in the sand cone model. Improvement in quality, for example, may initially entail an investment cost, but the improved quality rate can result in an overall cost reduction per part. Furthermore, reducing the manufacturing cost calls for improvements of some sort, and these improvements may include improvements in quality, dependability, or speed. The cost layer can therefore be regarded as interrelated with the other three layers.

The theory of performance frontiers proposed by Schmenner and Swink [22], partly based on the sand cone model, is interesting in relation to the present work. The asset frontier, describing the frontier determined by equipment, is the maximum performance possible using the equipment in a manufacturing system. Using the proposed model, the asset frontier is equivalent to a situation in which q_Q, q_P, q_{S1}, q_{S2}, and T_{su} must be 0 in the bottleneck process and probably near 0 in other processes in order to minimize the number of operators and the quantity of required maintenance resources. The operating frontier is more difficult to define in general terms. According to Schmenner and Swink [22], the operating frontier is determined by present operating policies; if the company is at this frontier, then performance improvement will result in increased cost, i.e., improving q_Q, q_P, q_{S1}, q_{S2}, or T_{su} will increase the part cost. If the company is somewhere to the left of its operating frontier, then improving q_Q, q_P, q_{S1}, q_{S2}, or T_{su} will lead to a lower or unchanged part cost. This theory can be useful when applied together with the proposed cost model, as it can help explain situations in which improving any of the performance parameters of the model increases the part cost. If the parameters are not close to their optimal values, then the company should consider changes in the operating procedure instead of investing in new equipment.

5.1 The proposed cost model in relation to general cost accounting methods

In this section, the proposed cost model (here referred to as "model A") will be described in relation to the methods presented in section 3.2, namely, traditional cost accounting, activity-based costing (ABC), time-driven activity-based costing (TDABC), throughput accounting (TA), life cycle costing (LCC), kaizen costing, and resource consumption accounting (RCA). The purpose of the comparison is to indentify similarities and differences in terms of purpose, principle, and cost allocation.

Purpose

The purpose of model A is to support decisions regarding improvement activities in manufacturing systems. The model should describe the cost impacts of current manufacturing conditions and of planned decisions. This is realized by including only costs and other parameters affected by decisions made in the manufacturing department. It is a cost concept intended to be used by personnel in the manufacturing department of a company, to raise the cost consciousness of manufacturing personnel. Its focus on manufacturing costs distinguishes the concept from traditional cost accounting, ABC, TDABC, and RCA, all of which are cost accounting concepts applicable to whole organizations and all types of businesses. LCC can also be used in many types of businesses, but its focus is on the costs associated with the buying/making, owning, and disposal of a product, which distinguishes it from the just-mentioned methods and from model A.

TA has a clearer manufacturing focus than do the other mentioned methods. Its focus is on throughput and constraints, for example, a bottleneck station in a manufacturing line, and it is intended to maximize the return in the bottleneck or maximize the relationship between the profit and cost rates of a product. TA is consequently used for bottleneck analysis and profit maximizing, which distinguishes it from model A's focus on the connection between performance and costs in every processing step. However, the impact of the bottleneck station is not neglected, because it affects the cycle time, t_0, in the model. Another major difference between model A and TA is that TA includes revenues and not only costs.

Model A and kaizen costing are also somewhat similar in purpose. Kaizen costing is about cost reduction in the manufacturing phase of a product. Specific cost reduction targets are determined for the whole plant, and these targets are then distributed to specific plant processes. Two similarities are the cost reduction focus and the connection between costs and manufacturing performance. However, there are also important differences. Kaizen costing is largely a top–down approach in which cost reduction targets are determined by top management. It is then the responsibility of the managers in the manufacturing departments to ensure that these targets are realized. Another difference is that the purpose of model A is not solely to support cost reduction, but also to support cost-conscious manufacturing generally, to learn how various manufacturing system parameters affect the manufacturing cost.

Principle

Model A is based on processing steps, each of which is a cost pool. A process drives a specific number of costs due to equipment depreciation, operator wages, energy consumption, etc. These costs are allocated to a manufactured part based on the time needed to process it in the specific step; only costs impinging directly on the processes are included. The purpose of this structure is related to the purpose of the concept itself: the costs of a part in every processing step are made clear in order to learn how the manufacturing costs accumulate as the part undergoes various process steps. In addition to the cycle time, equipment, and wage costs, there may also be non-value-added activities and setup time linked to a process step that add to the cost per part. Section 4.2.1 describes the main principle of model A.

Of the methods included in this comparison, RCA and TDABC are the most similar to model A in terms of the main principle. In RCA, costs are allocated to so-called resource pools, linked to each other based on the cost flow. A resource pool can be a process step in a manufacturing plant, but it can also be a department or another resource group. Like model A, RCA is a time-driven method, even if activities can also be applied as in ABC. RCA differs from model A in that it is a general method lacking, for example, the loss parameters included in model A. TDABC is also based on process steps, and it is time driven, based on the cycle time, as is model A. Like RCA, it is a general model and hence does not include production parameters other than cycle time.

Cost allocation

Because the aim of model A is to connect manufacturing parameters to costs, it was considered important when developing the model to establish logical cost allocations to the cost pools and manufactured parts and thus avoid arbitrary allocations. As with TDABC and RCA, implementing model A takes advantage of the company's ERP and MES systems and other systems the company uses to store data regarding cycle times, equipment performance, costs, maintenance activities, machine utilization, etc. Model A is highly dependent on the IT systems and data available at the company, meaning that the rationality and accuracy of the cost allocation are dependent on these systems. The basic principle of model A, that every process step is a cost pool, makes accurate allocation of the depreciation costs fairly straightforward if the company has specified depreciation costs for all equipment. Other costs related to the equipment, such as maintenance costs, can be more difficult to handle. Maintenance work can be divided into preventive and corrective maintenance. Correct allocation of these costs requires documentation of the quantity of resources and time spent on every cost pool, ideally separating preventive and corrective maintenance.

Energy costs can be divided into fixed and variable costs, the former including the costs of heating the production facilities and the latter the energy consumed by the manufacturing equipment. Because of increasing environmental awareness, companies are becoming more aware of their energy consumption, leading to better allocation of these costs. The energy consumption rate of equipment can be accurately derived using measurement devices. An alternative but slightly less accurate method is to use the energy consumption specified by the equipment supplier. If the fixed energy consumption is not directly available, an estimate may be made. The fixed costs are then allocated to the cost pools based on the occupied area.

In the past, when manufacturing plants were less automated, it was common for one operator to be assigned to each machine. Nowadays, it is not uncommon for one or a group of operators to be responsible for several machines simultaneously, becoming more of an overhead cost, like a support function. In such cases, operator cost can be allocated to the cost pools based on the estimated shares of time the operators or operator groups spend in specific cost pools.

The allocation principles used in model A are similar to those used in two of the most recently developed cost accounting methods, TDABC and RCA. As described above, these methods are based partly on the idea that companies today have considerable data stored in various systems that can be useful in cost accounting. In TDABC, the cost pools are operating departments, or individual processes if the various processes in a department differ significantly in cost. Resources that cannot be directly linked to cost pools should be allocated to cost pools based on rational, cause–effect relationships. These allocations can be made using the same procedure as used to formulate the operation cost rates, i.e., using time equations. The cost of a support department, for example, can be allocated to operating departments by identifying the tasks carried out in the support department and their corresponding "cycle times." The operating departments' demands for these tasks are then quantified, resulting in causal relationships between the departments. This procedure is largely the same as the one used in model A, for example, concerning maintenance costs. The allocation principle in RCA is essentially the same as in TDABC (and model A). Even this method emphasizes allocations based on rational and causal relationships, though preferably not activity based as in traditional ABC.

The second allocation, i.e., from the cost pools to the manufactured parts, is based mainly on time in model A, the exception being the scrap cost. The present author believes that time-based allocation based on the cycle times of individual parts is the most accurate allocation principle and is also feasible in today's manufacturing, in which cycle times for all product types are usually available in the company's ERP or MES system. However, this imposes data maintenance requirements, and nominal times must be updated when modifications in the manufacturing system affect these times. Furthermore, the downtime-rate and production-rate losses must be available, preferably product-specific rates (except for the planned downtime-rate loss). The scrap cost is allocated to the manufactured part level by means of the scrap rate, which is based on the number of scrapped parts in relation to total quantity of parts. The inclusion of the scrap rate means that the cost per part expression describes the cost per non-scrapped part.

In addition to the cycle time (including the unplanned downtime-rate and production-rate losses) and scrap rate, a third allocation principle is used in model A. This principle is used to allocate the planned downtime cost down to manufactured parts, these costs being allocated based on the batch time. In the original version of the model, only the utilization losses were allocated based on this principle, but in the changes introduced into the model in section 4.2, all planned downtime is allocated to the parts in this way. The allocation procedure is similar to the one TDABC uses to allocate planned downtime, the differences being that the planned downtime is formulated as rates and that utilization losses are included. The formulations of the various downtime rates presented in section 4.2 emphasize the planned downtime, which is no longer hidden in the practical production time. In TDABC, as well as in ABC and RCA, the utilization losses are not treated in the same way as is the other planned downtime. The costs related to utilization losses are not allocated to cost objects, because this could lead to a downward spiral in which product prices are constantly increased to compensate for increased utilization loss costs, which in turn result from the reduced production volumes caused by higher prices. However, model A is not intended to be used for product pricing decisions, which makes the allocation of utilization loss costs suitable in this context.

This second allocation procedure in model A has clear similarities to the second allocation procedure in TDABC. TDABC advocates cycle-time-based allocation, although exceptions can be made if other allocation principles are more appropriate. Average cycle times are recommended; any losses in cycle time or losses due to scrapped parts are not considered. As just mentioned, the theory underlying TDABC also includes policies for handling unused capacity, which should be assigned to the person or unit responsible for its occurrence. For example, if idle capacity has occurred due to lower demands than expected for a specific product, then the costs of the resulting idle capacity should be assigned to the person or organizational unit responsible for the product. The costs should not be allocated to individual products, because this could make some products appear unprofitable, leading to the downward spiral just mentioned.

The second allocation procedure in RCA is very similar to the one in TDABC. RCA theory advocates allocation based on quantitative causal relationships. It does not specifically recommend time, but because the theory also says that activity-based rates should be applied only in certain critical cases, it is assumed that time-based allocation is frequently used. In RCA, utilization losses are treated exactly as they are in TDABC, and for the same reasons.

5.1.1 Conclusions

The comparison indicates that model A is somewhat similar to TA and kaizen costing in terms of purpose and focus, mainly because these are more manufacturing related than the other approaches. Kaizen costing is an interesting approach; the idea it uses of setting specific cost reduction targets is also mentioned in Paper 1 as a way of using the proposed model, described as deterministic production development, in contrast to the continuous development normally associated with lean production. Model A could indeed be used in a kaizen costing setting, as the model's causal relationships between manufacturing parameters and costs could be used when determining cost reduction activities. As mentioned earlier, kaizen costing is used together with traditional cost accounting methods, and the method is more like the proposed model in practice than when making cost calculations.

The comparison also revealed similarities between model A and TDABC and RCA, for example, in their use of cost centers and time-driven costs. However, the latter two are more general methods applicable to any type of business and do not include any specific manufacturing-related parameters.

5.2 The proposed cost model in comparison with selected cost models

This section presents a comparison between the proposed cost model (model A) and five selected models described in section 3.3 (models B–F). The models included in the comparison are the models developed by Yamashina and Kubo (B) [75], Özbayrak et al. (C) [68], Son (D) [76], Chiadamrong (E) [77], and Dhavale (F) [70]. These models were chosen because they are more comprehensive models, as shown in the summary presented in Table 3.4. The comparison will relate the parameters and their definitions included in model A to the parameters and definitions in models B–F.

Main model purpose

Model A: To support cost-conscious manufacturing; to describe the link between manufacturing technology, performance, and cost

Model B: To identify production losses to reduce costs

Model C: To estimate the difference in product cost between two planning systems, MRP and JIT

Model D: To estimate the manufacturing cost in advanced manufacturing systems

Model E: To calculate quality-related manufacturing costs

Model F: To calculate manufacturing costs in computer-integrated manufacturing systems

Material cost

In model, A the material cost is the direct material cost for a specific product. Model B distinguishes between direct and indirect material costs (e.g., machining lubricant, a cost found in the variable equipment cost parameter of model A). Models D and E have similar approaches to that in B, but D also includes an ordering cost parameter. The material cost definition in models C and F is similar to that in A.

Equipment cost

In the modified version of model A presented in section 4.2, the equipment cost includes the costs of depreciation, floor space, and preventive maintenance, as well as a variable cost describing extra costs during production, such as energy costs. Corrective maintenance is not included in the equipment cost parameters k_{CP} and k_{CS}, but is included in the model as a separate parameter. In addition, the tool cost is described separately. Section 4.2.2.1 describes the formulation of the equipment cost.

Model B does not have a specific equipment cost parameter, but includes cost items that can be considered equipment costs, i.e., depreciation, tool, die and jig, energy, and maintenance costs. How these costs should be calculated and what they more specifically include are unspecified.

Model C includes costs for the following resources that can be considered equipment related: machines and cutting tool holders, computer system, robot and AGV system, AS/RS system, fixed assets, externally provided resources (e.g., utility costs), cutting tools and fixtures, direct energy consumption, and other services (including maintenance). These costs are allocated to various activity cost centers, each consisting of a direct and an indirect cost pool. The indirect costs (e.g., externally provided resources) are distributed to the cost centers based on utilization levels obtained from simulation runs of the manufacturing system. In addition, the allocations from the cost centers to the products are based on simulations in which the percentage of the total time a product occupies a certain operation (i.e., activity center) determines the product's share of the total operation cost. The depreciation cost is calculated based on the initial investment price and is formulated as an hourly rate based on the estimated useful life. The depreciation costs of the buildings are allocated to machines based on the floor space they occupy. Tool costs are allocated to the machines based on the number of tools consumed by each machine, assuming each tool has an average cutting life of 60 minutes.

Model D includes a machine cost comprising utility, maintenance, repair, insurance, and property tax costs. These costs are, except for property tax, formulated as hourly costs without any description of how these rates should be calculated. In addition, the model includes cost parameters for tool, floor space, and computer software costs. The tool cost is calculated as the cost per tool times the number of tools changed over a planning horizon. Depreciation costs are considered but no equation is formulated for it.

Model E includes a machine cost comprising utility costs and a material handling cost. The model also includes costs for preventive maintenance. Corrective maintenance is not directly mentioned, but it can be assumed that this is included in another parameter called "failure repairing cost." Other equipment-related costs such as depreciation and tool costs are not considered because they are not regarded as affecting the cost of quality, which is the focus of this model.

Model F has no specific equipment cost item, but includes the following equipment-related costs: machine cost including depreciation, installation and preparation costs, utility and building depreciation costs, and cost of accessories (e.g., tools, computers, and fixtures). The machine cost is formulated as an hourly cost based on estimated hours of use. The cost of accessories is allocated to specific machine centers based on their fractions of the total investment cost in machine centers. The costs of utilities and building depreciation are allocated to the machine centers based on the floor space occupied by the machines.

It can be concluded that the models are somewhat similar in terms of this cost item. The main differences between model A and the other models are the inclusion of cost of capital in model A and its clear division between preventive and corrective maintenance costs.

Personnel cost

Model A includes personnel costs only for workers near the production, for example, machine operators and assembly workers, and, besides wages, also includes the social insurance expenditure and other labor taxes. Such wage costs have traditionally been denoted direct labor, though, for example, Dhavale [70] and Özbayrak et al. [68] claim that these costs have become more indirect in today's more automated production. In model A, these costs are formulated as an hourly rate, the denominator being the theoretical production time for a specific period.

Model B has separate parameters for direct and indirect labor, the latter being exemplified by maintenance. Model C includes labor and salary costs for non-manufacturing departments. These costs are divided by machine hours to obtain an hourly rate. The definition of machine hours is unspecified.

Son (model D) also claims that direct labor has declined, though direct and indirect labor cost parameters are still included in his model. The direct labor cost is formulated as the cost per unit time, though the period on which the calculation should be based is not mentioned. The indirect labor cost is formulated as the salary for a specific job over a planning horizon. Model E uses exactly the same definitions as does model D.

Model F includes direct and indirect labor and other manufacturing personnel in a cost group referred to as "personnel cost." The cost model is machine center based, and these personnel costs are allocated to the machine centers based on the individual centers' shares of total machine investments.

Cycle time

Model A is basically a time-driven model in which the cycle time is an essential parameter. Cycle time is defined as the nominal (theoretical) cycle time for a specific product in a specific processing step; cycle time losses are considered in separate parameters.

Like model A, model B distinguishes between the theoretical cycle time and losses in cycle time. In model C, it is unclear whether the cycle time is the theoretical or an average time. Model D does not include a cycle time, these costs instead being calculated over a planning horizon; the same procedure is used in model E. In model F, as in model C, it is unclear whether the cycle time is the theoretical time or an average time including losses.

Batch size

Model A considers two situations, one with a fixed starting batch size, i.e., the batch size is not increased to compensate for scrapped parts, a situation common in make-to-stock situations. The other situation is when a certain output batch size is required, which means that the batch size will increase if parts are scrapped; this can occur in make-to-order situations.

Models B, D, and E do not take batch size into consideration. Model C includes a batch size parameter used to distribute the setup time over the produced parts, as in model A. How scrapped parts in a batch are handled is not described in model C. Model F does not include a batch size parameter; however, the model uses the example of a product having a specific batch size, which is used to calculate both the total batch and unit costs. Adjustments for scrapped parts are not made in model F.

Setup

Model A includes a setup time parameter that is multiplied by the equipment and wage costs; the resulting cost is then divided by the number of correct produced parts to obtain the setup cost per correct part. In the original version of the model, the parameter is defined as a mean value because companies do not usually have a nominal setup time. However, in a situation in which a nominal setup time exists, a nominal setup time in combination with a setup time loss parameter can be applied, according to the same principle as used for the downtime, scrap, and speed losses. The setup time parameter in combination with the batch size parameter describes the flexibility in switching between product types (i.e., process flexibility).

Model B also includes a setup loss parameter that describes both the setup time cost and the cost of any scrapped parts attributable to the setup activity. In model A, the latter loss is considered in the scrap rate, which consists of the material, labor, and machine costs. Model C includes a setup parameter describing the average setup time. This parameter is multiplied by a parameter describing the overall setup cost rate; the kinds of costs included in the setup cost rate are unspecified. The sum of these costs is divided by the batch size to obtain a cost per unit. Model D has a parameter describing the total setup time for a machine over a planning horizon; this time is multiplied by a setup cost per unit time, though the model does not specify what costs constitute the setup cost. Model E has a setup cost parameter, which distinguishes between setup costs for correct and reworked parts. Model F does not include a setup time parameter.

Utilization losses

Idle capacity in a machine can be viewed in various ways depending on the context. Some idle capacity is needed to cope with demand fluctuations, but the present author believes that long-term excessive idle capacity needs to be addressed in some way. The original version of Model A includes a parameter describing the utilization rate of a specific processing step, U_{RP}. In the modified version presented in section 4.2, the idle capacity is instead captured by the utilization loss parameter, q_{S1UL} ($= 1 - U_{RP}$). The costs of utilization losses are dependent on whether any personnel are affected by these losses. If idle capacity means that personnel are also idle, then the wage cost should be included, otherwise the equipment cost will be the only cost parameter included in the utilization loss cost calculations. The idle time is distributed among all batches in relation to their production times.

Model D includes an idle cost consisting of parameters for idle cost per unit time and for total idle time per machine; the costs included in idle cost per unit time are unspecified. Even model E includes an idle cost expression, consisting of an idle opportunity cost per unit time and the total idle time of the equipment. The idle opportunity cost consists of the cost of capital tied up during the idle time, which can be based on the cost of capital or the company's internal rate of return. Models B, C, and F do not include a utilization loss parameter.

Scrap rate

Model A includes a quality parameter describing the rate of scrapped parts in a specific process step. The scrap rate influences the material cost as well as the equipment and wage costs for the cost per part in this model, because the model describes the cost per correctly manufactured part. The model also takes into consideration the processing step in which the scrapping occurs, i.e., a scrap will be more costly after each processing step because the part's value increases after each step it undergoes. Regarding cost of quality and the PAF concept (see section 3.4.1), model A directly considers the failure cost. The appraisal cost is indirectly considered by the equipment and wage costs and by the cycle time, which can include the time needed for quality control. The prevention cost is considered partly by the preventive maintenance cost expression, but more product-related prevention costs are not included.

Model B includes a defective loss cost, which comprises the direct and indirect material, tool, die and jig, and energy costs; equipment and wage costs are not included and the product's added value in later processing steps is not considered. Regarding model C, Özbayrak [68] mentions that scrapped parts are considered in the simulation model in which the cost model is used, but how the cost of the scrapped parts is calculated is not described. Model D includes two quality costs, prevention and failure costs, the former defined as the cost of both prevention and appraisal. The prevention cost is based on the costs of control charts and process capability. The control chart cost includes the costs of sampling and of assignable causes, while the process capability cost includes sampling and improvement costs. The failure cost includes the costs of reworking, scrapping, and selling defective parts. Model E's quality costs are similar to those of model D. Its expression for material cost includes the cost of defective units and income from scrapped material. Like model D, it includes the costs of prevention and appraisal (formulated in a way similar to that of model D) and a cost of external failure. Model E's expression for failure repairing cost contains a separate cost of repairing defective units, which is not included in model D. Both models D and E include rework costs. Model F does not include any quality costs.

It can be concluded that models D and E include more quality-related cost parameters than does model A. The inclusion of prevention and appraisal costs is interesting, but the presentations of these costs lack descriptions of what is included in the cost parameters, which could make them somewhat ambiguous and difficult to implement. The reworking cost can be taken into consideration in model A by including the extra time needed for reworking in the production-rate loss parameter.

Downtime rate

The modified version of model A presented in section 4.2 contains two main downtime rates: the planned downtime rate, q_{S1}, and the unplanned downtime rate, q_{S2}. The estimated planned downtime over a planning horizon is distributed evenly among all parts produced, whereas unplanned downtime can be based on a specific order number, product, or period. The downtime rates affect the equipment and wage costs per manufactured part.

Model B includes a loss called breakdown loss, which includes labor, depreciation, tool, die and jig, energy, and maintenance costs. This model also takes into consideration the losses due to blocking and idling occurring in the process steps before and after the step in which the breakdown occurs. In addition, the cost of any parts scrapped due to the breakdown is included. The model also includes a separate cost expression for short stoppages.

As in the case of the scrap rate, the paper on model C mentions that downtimes are accounted for in the simulation model, but does not present any specific cost expressions.

Model D does not include a downtime cost, but it does include a waiting cost capturing the cost of parts waiting to be processed, i.e., a work-in-process cost, based on an opportunity cost per unit time. Model E includes a failure repairing cost based on the failure repairing cost per unit time, but exactly what costs constitute this parameter are not mentioned. This model also contains a waiting cost, defined similarly to the one in model D. Model F does not include any downtime costs.

Production-rate loss

The production-rate loss parameter of model A includes losses for short stoppages and speed losses. These losses influence the real cycle time and thereby also the equipment and wage costs.

Model B includes a speed down loss and a loss for short stoppages. The speed down loss is based on the costs of time lost, depreciation, and direct labor; alternatively, it can be based just on the energy cost, depending on whether the equipment has idle capacity. Models C, D, E, and F do not include costs for production-rate losses.

5.2.1 Conclusions

The comparisons made in the previous section between the proposed cost model and the models found in the literature suggest there are related models, especially the Son (D) [76], Chiadamrong (E) [77], and Yamashina and Kubo (B) [75] models. The first two are similar in many ways: Son's model is referenced by Chiadamrong, and they both describe the total manufacturing cost over a specific period or planning horizon.

Why is a new model required when existing models already include similar parameters? This question can be answered in several ways. First, the proposed model, model A, is clearly connected to the OEE parameters, as q_Q, q_{S2}, and q_P are almost identical to the three rates in OEE, the main difference (besides the fact that the q parameters describe the losses and not the remaining parts) being that the setup time is a separate parameter of the proposed model. Model A is mainly cycle time driven and its focus is on the cost per correctly manufactured part, while the Son and Chiadamrong models calculate the total cost over a specific period without considering the cycle time. The Yamashina and Kubo model focuses on the costs of specific losses, not on how these losses affect the cost of the manufactured products. The cycle time and part cost perspective of model A makes it possible to analyze the cost impact of the cycle time, for example, how an improvement in a specific processing step leading to a shorter cycle time affects the cost of the parts produced.

Models B, D, and E do not take into consideration the increased value of the manufactured part after each processing step. Every process step adds value to the part, making it more costly to scrap a part the more process steps the part has passed. Model A takes this into consideration.

Another difference is the intended use of the proposed model. Model A focuses on the connection between the particular loss causes and their impacts on the part cost. Detailed monitoring of the losses in terms of quality, downtime, and production rate is proposed. This monitoring aims to combine detailed knowledge of the performance loss causes with high cost consciousness, thereby facilitating improvement work by fostering better knowledge of what to do and prioritize. This link between loss causes and costs is not found in the other models. The proposed model is intended to be applied using a software application, like the one presented in Paper 5. This should be a software product for use by manufacturing management, and it would benefit from the IT systems currently available in companies to handle the highly detailed data needed. The papers on the other models lack real-world implementation examples and descriptions of how to use the models. As for Son's model, no real or illustrative implementation examples of the model can be found, and Son [76] only mentions that the model can be used as a productivity measure and in a cash flow model. Yamashina and Kubo [75] succinctly examine the application of their model in a case study in which their proposed method and cost model are compared with TPM; they conclude that their approach leads to a greater cost decrease than does TPM. It should be added that the comparison is poorly described and its implementation unclear. The Chiadamrong model [77] is illustrated using a hypothetical example in which the results indicate the specific cost items in various categories. The categories are: invisible production costs, visible quality costs, opportunity costs, and total costs of quality-related activities. Chiadamrong's model is extensive, but includes no examples or discussion of how to obtain the needed data in real-world settings. Consequently, there are few examples of when or how to use these other models. Papers 2–5 include implementations of model A in real-world settings and present various possible analyses, for example, dividing the cost into VA, NVA, and NNVA costs (papers 4 and 5), cost derivatives (papers 1 and 4), process costs (Paper 5), what-if analyses (Paper 5), volume flexibility (Paper 2), and dynamic manufacturing costs (Paper 3). This thesis presents analytical examples not linked to the other models. In summary, the three "competitive" models are similar to the proposed model in many ways; however, in addition to the differences between the models themselves (e.g., model A's cycle time and part cost perspective, performance rates, and division between preventive and corrective maintenance costs), another crucial difference is in how the models are intended to be used.

5.3 Conditions for industrial use

One aspect of the conditions for industrial use is the availability of the necessary data in the companies. The most critical parameters are the loss parameters, i.e., quality, downtime, and production-rate losses. This is because they have to be collected continually by the company, as opposed to the more static parameters, such as the cost parameters and nominal cycle time. Companies using OEE collect data on all three of these performance losses (and the setup time), but the detail level of the data, i.e., the classification of the individual loss occurrences to specific types of losses, differs between them. In the OEE implementation examples described in the literature review in section 3.1.2.3, the detail level was generally low. The proposed cost model is intended to describe costs related to losses at a higher detail level, because it should be possible to evaluate the cost of each specific loss. If these losses were grouped into only a few types of losses, it would be impossible to know what actions were needed to reduce these losses and the costs related to these actions. In the implementation described in Paper 4, highly detailed performance loss data were collected using the production performance matrix (PPM), and, as shown in Figure 4.6, this permitted the cost contributions of specific types of loss to be obtained. This detail level, however, was based on data collected by pen and paper specifically for this study and not on the company's ordinary downtime monitoring system. As demonstrated in Paper 6, however, it is both possible and advantageous in practice for companies to collect highly detailed performance loss data.

Another implementation consideration is how the cost model should be applied in practice in industry. Paper 5 presented a software application of the model in which all required data were retrieved from existing databases. It allowed data on every order to be automatically available to the software after registration, without any need for manual data input. Such an implementation is of course advantageous, but it requires that the company store all the needed data in databases. Although some companies still use pen and paper to register performance losses, computerized systems are common today and will probably be even more common in the future.

The improved version of the cost model, presented in section 4.2, requires that the times used for preventive and corrective maintenance also be registered, and linked to each processing step. Preventive maintenance is fairly static and easy to register, but corrective maintenance is more difficult. Paper 6 demonstrates how this can be done by making a distinction in the downtime monitoring system between unplanned downtimes corrected by operators and unplanned downtimes corrected by maintenance personnel.

6 Conclusions

Here are the most important conclusions based on the research results presented. The conclusions relate mainly to the research questions described in chapter 1.

The first research question (RQ1) concerned how a general cost model should be designed to take into consideration the most important process-near parameters influencing the performance of a manufacturing system. This thesis has proposed a general cost model for cost analyses of a manufacturing system. One aim of the model is that it should include the most important cost parameters of a manufacturing system, together with the parameters linking these costs to the manufactured parts. The model is intended to form the basis of a decision support tool for the manufacturing department, with which performance and future improvement activities can be analyzed. Using the model and applications presented in papers 1–3 and section 4.2, analyses can be conducted of, for example, how the manufacturing cost accumulates in every processing step, which steps are the most costly, which steps exhibit the most non-value-added costs, how much a specific loss cause contributes to a part cost, and how a specific investment will affect the cost per part.

Papers 2 and 3 present cost analyses based on the cost model, but with some modifications to accommodate specific cases. Paper 2 demonstrates how the model can be used for analyzing volume flexibility by including parameters describing the effects of varying numbers of assembly workers. Paper 3 demonstrates how downtime variability can be analyzed from a cost perspective by calculating downtime rates for each failure cycle.

The second research question (RQ2) concerned how such a cost model could be used in practice, i.e., what the requirements and conditions are for industrial use. Papers 4–6 address this question. Paper 4 describes an implementation of the model in the automotive industry. In this study, the performance loss data for the cost model were collected manually using a proposed performance analysis procedure, the same procedure as implemented in the study described in Paper 6. The study described in Paper 4 indicated that the model was applicable in the described case and that detailed information on manufacturing costs, for example, the size of the loss-related costs and of the costs of the individual loss causes, could be acquired using this method. However, this level of detail could only be achieved using manual data collection carried out specifically for this study. It was therefore decided to further investigate the conditions for the applicability of the cost model in industry, resulting in Paper 5. This paper demonstrated that software products exist for collecting manufacturing loss data of the proposed level of detail, but that the manufacturing companies participating in the study did not collect as detailed data as proposed. The demonstration program developed based on the available databases in the collaborating company indicated how the cost model could be used practically in a company. The results of this study indicated that companies do not fully collect loss data of the proposed level of detail, leading to questions as to the pros and cons of collecting highly detailed performance loss data. Two questions were raised as to whether companies specifically benefit from collecting highly detailed data and whether such data are difficult to collect due to increased workload and complexity for the operators responsible for registering the losses. These two questions were addressed in Paper 6. The results indicate that highly detailed data offer more advantages than disadvantages: the production manager believed that the increased level of detail led to improved knowledge of the performance losses and the operators did not perceive any particular difficulties gathering more detailed data.

7 Future research

This chapter makes suggestions for future research activities related to the research questions posed in this thesis.

This thesis addressed two questions, the first concerning the development of a cost model and the second issues regarding the conditions for implementing the model in industry. Future research can be suggested linked to both these questions. Regarding model development, the ongoing PROLOC research project is developing better decision support for production localization decisions. In this project, the cost model presented here represents one of several cost modules that together cover all parameters of interest in a localization decision, for example, various manufacturing overhead costs.

Manufacturing system dynamics is another area of interest for further research. Paper 3 addressed such issues, and a next step would be to investigate how the cost model could be implemented in a DES model. Detailed cost analysis could then be combined with other types of analyses, such as buffer dimensioning and bottleneck analyses, enabling more comprehensive analysis of proposed investments and of other changes in the manufacturing system than could be conducted using the cost model alone.

Most of the implementations of the cost model were conducted in discrete manufacturing systems in which processing activities were carried out mainly by machines. The cycle times were consequently guided by the length of time the part resided in the equipment. Further studies in which the cycle times consist of manual work, for example, in assembly lines, would be of interest. Paper 2 addressed volume flexibility in assembly lines; additional studies could investigate that issue further by making more detailed cost calculations regarding various strategies for creating volume flexibility.

With regard to implementation issues, longer case studies of the implementation and use of the model in industry would be beneficial. Paper 4 describes a test of the model in industry and Paper 5 deals with the user interface, among other matters. An appropriate next step would be to address aspects of model application in companies using the model in their improvement work. Such studies could provide more insight into how the model could be used in organizations, for example, for analyzing investment proposals, and into how the results should be presented to the user.

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Paper 1

M. Jönsson, C. Andersson, and J.-E. Ståhl, “A General Economic Model for Manufacturing Cost Simulation,” *Proceedings of the 41st CIRP Conference on Manufacturing Systems*, pp. 33-38, 2008.

A General Economic Model for Manufacturing Cost Simulation

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Abstract

The described technical-economic model clarifies the influence of different production technological factors on the processing cost of a part. Influential factors can be weighted against each other, which leads to different production development scenarios and their effects on the processing cost can be studied. This implies a way to generate a basis of decision by which a company can base their production related development goals. The model describes influence of technical factors on the manufacturing cost and thereby represents the important link between technical development and economy.

Keywords:
Manufacturing Economy; Cost Model; Deterministic Production Development

1 INTRODUCTION

A majority of all manufacturing companies are working with production development and improvements to meet the global competition of today. There are a number of methods and philosophies for working with continuous improvements, where the success of lean production [1], is the most widely spread. An important question is if considerations and decisions made regarding investments and development actions are based on correct and adequate knowledge in order to achieve the highest efficiency benefits.

The outsourcing debate has been going on for some time now [2], [3]. Decisions made about moving production-units to low-wage countries are often based on limited information, giving wages too big influence over the decisions. Existing economic models are inadequate in utilizing estimation of the development potential of a production system and possible development actions.

There are many questions to be asked when considering major improvement changes in a production facility. The most common questions the company management would like to have answered are:

- How much better do we have to be to compete with for example low-wage countries and what and where in the production facility do we have to improve?
- What are the bases of decision required to formulate goals for production development, and what are reasonable goals for the actual production system?

The economic model presented in this paper can help to give answers to these questions, if the required data about the production performance is known.

2 PURPOSE AND LIMITATIONS

The purpose of this economic model is to describe the costs added to the cost of a part at every processing step. The model is not intended to be used only to describe the present cost situation, but also to function as a simulation tool to simulate different development scenarios and their effect on the part cost. Thereby it can be used as a support tool in manufacturing development activities.

The economic model presented is defined to comprise the direct production cost. The overhead costs are excluded at this level, because they have little to do with developing the production system. Factors tied to the income side of the production are not considered in the model. The model primarily describes batch production and is summarised to describe one processing step or a so-called planning point (a planning point is a set of machines and robots where the cycle time is determined by the slowest machine in the line). This simplification enhances the principle of comparing the influence of different cost items on the total production cost. These factors influence on the production cost can therefore constitute the foundation for choosing research and development actions.

3 LIST OF SYMBOLS

The parameters in the list of symbols are partly tied to the factor groups described above. The economic parameters are described in the Swedish currency krona (kr).

Table 1: List of symbols

t_0	Nominal cycle time per part.	min
t_m	Machine time	min
t_h	Handling time	min
t_{vb}	Tool switch time	min
t_p	Production time per part	min
t_S	Average down time per part	min
q_S	Down time rate	-
N_0	Nominal batch size	unit

N	Total amount of required parts to be able to produce N_0 parts	unit
N_Q	Amount of scrap parts in a batch of N_0 parts	unit
q_Q	Scrap rate	-
t_{0v}	Cycle time including production rate losses	min
q_P	Production rate	-
T_{su}	Set up time of a batch	min
T_{pb}	Production time of a batch	min
t_{pb}	Production time per part of a batch with N_0 parts	min
k	Part cost	kr/unit
k_B	Material cost per part including material waste	kr/unit
k_{CP}	Hourly cost of machines during production	kr/h
k_{CS}	Hourly cost of machines during down time and set up	kr/h
k_D	Wage cost	kr/h
K_B	Material cost of a batch including scrapped parts and material waste	kr/batch
k_{B0}	Material cost of the manufactured part without material waste	kr/unit
q_B	Material waste factor	-
m_{tot}	Total consumption of material per part	weight
m_{part}	Remaining material in the machined part	weight
U_{RP}	Degree of occupation	-
n	Rational number > 0	-
∂z	Partial change in arbitrary variable.	-
Δz	Change in arbitrary variable	-
x_p	Process development factor for the cycle time	-
x_{su}	Process development factor for set up time	-

4 LITTERATURE REVIEW

Several different models have been developed for the purpose of calculating the manufacturing cost. According to Tipnis, *et al*. [5], the models can be divided in microeconomic and macroeconomic models. In the microeconomic models specific process parameters influence on the part cost is described. Microeconomic models dealing with machining has been described by Colding [6], [7] and Alberti, *et al*. [8] among others and Knight, *et al*. [9] has developed a corresponding model for forging. Within the field of machining a microeconomic model can describe how for example the cutting rate, feed or working margin influence the part cost. In a macroeconomic model several parameters are aggregated. An example of a macroeconomic model is when the cost calculations are based on the cycle time and not the factors influencing the cycle time. The fundamental principles for developing macroeconomic models are described by Kaplan and Anderson [10]. The authors have not developed any models that are directly applicable to calculate the part cost but leaving these activities to the reader.

Macroeconomic models have previously been illustrated by Groover [11]. In this model only one production loss parameter is taken into consideration; the scrap rate. Ravignani and Semeraro [12] have developed a model that combines the micro- and macroeconomic views by noticing both cutting technological conditions and the batch size. Non production loss parameters are regarded.

It can be stated that the microeconomic models are specific for different processing methods. Numerous models have been developed to describe the cutting cost of machining. The models are describing the connection between the cutting rate, the wear rate of a cutting tool and the tool switch time. In these models the tool cost is highly prioritized. Costs of down time and the scrap rate are not often taken into consideration.

A cost model for assembly is introduced by Teng and Garimella [13]. This model is based on inventory costs, assembly costs and costs associated with diagnostic and rework activities. The model has a high resolution concerning cost of different types of equipment in the assembly line. The model is based on average cycle times where also the scrap rate is considered. Boothroyd [14] is describing a specific cost model for robot assembly which is noticing the down time costs in the assembly line.

Production cost regarding design has been discussed by Locascio [15], Liebers and Kals [16] and Shehab and Abdalla [17]. Locascio is assuming that all cycle times of the processing steps is known in advanced. Any specific connection to production loss parameters is not considered. Shehab and Abdalla is describing an interesting model that estimate the manufacturing cost of machining for different choices of material where both the material cost and the processing cost is taken into consideration.

The model described below is general and can be regarded as a macroeconomic model but with the possibility to consider the microeconomic parameters. The model is intended to describe the part cost of various specific or aggregated processing methods without any major modifications.

5 MODELLING OF THE PART COST

The nominal processing time (cycle time) t_0 for a part is comprised of machine time, handling time and tool change time:

$$t_0 = t_m + t_h + t_{vb} \tag{1}$$

The equation assumes that the events are performed in a sequential order and can be considered as a planning point. The real processing time t_p will be longer than the nominal time due to disturbances and downtime. The rate of the disturbance and downtime can be expressed as the quotient between the downtime t_S and the observed production time t_p described in equation 2. The sum of the downtime and nominal processing time gives the real processing time t_p according to equation 3. Combining equation 2 and 3 the processing time can be determined based on the nominal cycle time and the downtime rate q_S:

$$q_S = \frac{t_S}{t_p} = \frac{t_p - t_0}{t_p} \tag{2}$$

$$t_p = \frac{t_0}{1-q_S} = t_0(1+\frac{q_S}{1-q_S}) \tag{3}$$

To obtain N_0 number of correct parts, N number of parts has to be manufactured due to scrapped parts. The rate of scrapped parts is expressed by q_Q:

$$q_Q = \frac{N_Q}{N} = \frac{N - N_0}{N} \tag{4}$$

$$N = \frac{N_0}{1-q_Q} = N_0\left(1+\frac{q_Q}{1-q_Q}\right) \tag{5}$$

Losses in production rate are a fact when the cycle time has to be increased from t_0 to t_{0v} to maintain the quality level or avoid unplanned downtime. The relative loss in production rate is described as:

$$q_P = \frac{t_{0v} - t_0}{t_{0v}} \tag{6}$$

$$t_{0v} = \frac{t_0}{1-q_P} \tag{7}$$

To changeover the production from manufacturing part A to part B a certain amount of setup time T_{su} is required. The production time for a batch including the setup time is:

$$T_{pb} = T_{su} + N \cdot t_p = T_{su} + \frac{N_0 \cdot t_0}{(1-q_Q)(1-q_S)(1-q_P)} \tag{8}$$

The average production time for a batch of N_0 number of correct parts is calculated as:

$$t_{pb} = \frac{T_p}{N_0} \tag{9}$$

In the presented model there are primarily three cost items specified; equipment costs k_C, wage costs k_D and material costs k_B. Equipment costs for a machine or a production line can be split up into a cost during production k_{CP} and a cost k_{CS} when the machine or production is not running. For the case in question both these cost items include all of the costs that can be related to the equipment as investment cost, local cost, cost of maintenance, tool costs etc. The cost of wages per hour k_D are presumed to be independent of if the machine is running or not and also presumed to be unchanged during setup.

To study the material cost including scrapped parts and material waste, a material waste factor q_B is introduced:

$$K_B = \frac{N_0 \cdot k_{B0}}{(1-q_B)(1-q_Q)} \tag{10}$$

$$q_B = \frac{m_{tot} - m_{part}}{m_{tot}} \tag{11}$$

where k_{B0} is the material cost of the manufactured part and K_B is the material cost of the batch including scrapped parts and material waste. The material waste factor q_B consider the total consumption of material m_{tot} per part and comprises also material that are machined or cut off as for example chips during turning or milling and retainer surfaces during sheet metal forming. The remaining material in the machined part is denoted m_{part}.

Reduced occupation in a manufacturing system leads to consequences for all manufactured parts. This situation can be considered in different ways, hence the free production resource can be considered both as an economic asset and a disadvantage depending on the situation. In a long term view the manufactured parts must carry the costs for the over capacity. The over capacity time can be distributed over all the batches in relation to their production time T_{pb} by introducing a degree of occupation U_{RP}, calculated as the quotient between real production time T_{prod} and planned production time T_{plan}:

$$U_{RP} = \frac{T_{prod}}{T_{plan}};\ T_{plan} = T_{prod} + T_{free} \tag{12}$$

The extra free capacity $T_{free,b}$ to be added to a specific batch is calculated according to equation 13. The free time can be considered as a setup time at the same time as the equipment is available for manufacturing:

$$T_{free,b} = \frac{1-U_{RP}}{U_{RP}} T_{pb} \tag{13}$$

The manufacturing costs per part k, including the previously described parameters and assumptions can be expressed as:

$$\begin{aligned} k = {} & \frac{K_{sum}}{N_0} + \left(\frac{k_B N_0}{N_0(1-q_Q)(1-q_B)}\right) + \\ & \left(\frac{k_{CP}}{60N_0} \cdot \frac{t_0 N_0}{(1-q_Q)(1-q_P)}\right) + \\ & \frac{k_{CS}}{60N_0}\left(\frac{t_0 N_0}{(1-q_Q)(1-q_P)} \cdot \frac{q_S}{(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}} T_{pb}\right) + \\ & \frac{k_D}{60N_0}\left(\frac{t_0 N_0}{(1-q_Q)(1-q_S)(1-q_P)} + T_{su} + \frac{1-U_{RP}}{U_{RP}} T_{pb}\right) \end{aligned} \tag{14}$$

In some cases it can be necessary to introduce a disturbance factor q_{Ssu} to handle spreading in the nominal setup time.

The cost item K_{sum} in equation 14 comprises different types of costs that are not described separately in the model. A more complete economic model has a higher resolution and includes more of the separate terms that are now included in K_{sum}. A developed model can for example consider tool costs, cost of maintenance, remainder value of waste material, fixture costs, stock/buffer and transportation costs, surrounding equipment, costs arising due to environmental or recycling actions for example to eliminate cutting fluids or oils.

6 DETERMINISTIC PRODUCTION DEVELOPMENT

To be able to manage production development efficiently, clear goals has to be established for the development activities. Many companies today have implemented lean manufacturing to some degree, or they are by other methods developing and improving the manufacturing process. With this model those activities can be performed in a more deterministic, goal oriented way. The reasons for this is that an implementation of this model for every product in every processing step, enables the most critical factors from a cost perspective to be acquired. When you have this information it will be possible to establish concrete economic goals and to simulate the consequences these goals have on the parameters constituting the part cost. The consequences could for example be how much a given parameter must be changed to reach the established goal.

The development activities can be performed in relation to the present production conditions of the company or in relation to the competitors and other terms of the market. Example of production development goals are reduction of the manufacturing costs with 20% for a certain part type, a 50% reduction of setup time or an increase of production rate from 100 to 120 parts per week with unchanged cost parameters.

Considering that a lot of factors, isolated or in cooperation, influence the cost of a specific part, different changes in these factor can lead to same cost effects. To be able to separate the influence of these different factors on the part cost, different development factors are introduced to the parameters in equation 14.

$$
\begin{aligned}
k = {} & \frac{K_{sum}}{N_0} + \left(\frac{k_B \cdot N_0}{N_0(1-q_Q)(1-q_B)} \right) + \\
& \left(\frac{\kappa_C \cdot k_{CP}}{N_0 60} \cdot \frac{x_p \cdot t_0 \cdot N_0}{(1-q_Q)(1-q_P)} \right) + \\
& \frac{\kappa_C \cdot k_{CS}}{60 N_0} \left(\frac{x_p \cdot t_0 \cdot N_0}{(1-q_Q)} \cdot \frac{q_S}{1-q_S} + x_{su} \cdot T_{su} + \frac{1-U_{RP}}{U_{RP}} T_{pb} \right) + \\
& \frac{k_D}{60 N_0} \left(\frac{x_p \cdot t_0 N_0}{(1-q_Q)(1-q_S)} + x_{su} \cdot T_{su} + \frac{1-U_{RP}}{U_{RP}} T_{pb} \right)
\end{aligned}
\qquad (15)
$$

In equation 15 the development factor x_p operates on the cycle time and enables therefore analysis of changes in cycle time. The development factor x_{su} operates on the setup time and enables therefore studies of changes in setup time. The cycle time and setup time are the most important parameters describing the capacity and flexibility of a production system. A development factor given a value less than 1.0 result in a reduction in cycle time and setup time, if the factors are given for example the value 0.5, the production time and setup time has been reduced to half of the original size. The development factors can therefore be regarded as improvement variables in a goal function.

A cost development factor κ_C is introduced to describe an investment cost that can be connected to a change in cycle time. The cost factor operates on the equipment costs k_{CP} and k_{CS}. This factor is used to model changes in costs in primarily existing equipment, and can be used to determine the limit of investment justified by for example a decrease of the downtime rate to a certain value. For example does κ_C = 1.20 corresponds to an increase in equipment cost with 20%.

7 COST DERIVATIVES

Changes in part cost caused by a limited change in an arbitrary variable *z,* is calculated by partial derivative, and is described in linear form as:

$$\Delta k_i = \frac{\partial k_n}{\partial z} \cdot \Delta z \qquad (16)$$

The changes in part costs can be calculated with respect to different parameters as for example changes in wage costs and share of downtime Δq_{Si}. Equation 17 is exemplifying changes in part costs due to changes in different governing parameters.

$$\Delta k_i = \frac{\partial k_i}{\partial k_{Di}} \cdot \Delta k_{Di} + \frac{\partial k_i}{\partial q_{Si}} \cdot \Delta q_{Si} \qquad (17)$$

Cost neutral changes in each variable can be studied by putting the change in part costs $\Delta k_i = 0$. Equation 17 is written in a cost neutral form in equation 18, describing the size of the reduction in downtime share required to compensate for a change in wage costs.

$$\Delta q_{Si} = -\Delta k_{Di} \cdot \frac{\dfrac{\partial k_i}{\partial k_{Di}}}{\dfrac{\partial k_i}{\partial q_{Si}}} \qquad (18)$$

The influence of a specific variable can be studied by calculating cost derivatives. A change in a variable giving a large influence on the part cost also gives large cost derivative values. It is hazardous to uncritically compare different cost derivatives with each other since the possibility of changing each variable is different. A weighting of the cost derivative can be made by multiplying the cost derivative with its functional value. A weighted cost derivative is a better indication of the impact each variable has on changes in the cost derivatives. All changes Δz in the variable *z* becomes relative with respect to the absolute value of the variable. By introducing a relative variable $\Delta z_0 / z_0$, the changes expressed as a percentage for a specific variable can be compared with changes expressed as a percentage for another variable. This principal is expressed in equation 19.

$$\Delta k = \frac{\partial k(z_0)}{\partial z} \cdot z_0 \cdot \frac{\Delta z_0}{z_0} \qquad (19)$$

8 MODEL EXAMPLE

In the present section the usefulness of the model will be shown by implementing the model using fictive input data. The example will illustrate what kind of analyses that could be performed and what decision-making bases you can get.

The costs for two different production cases can be studied by introducing an index *i* tied to the parameters and variables in equation 16 in order to separate them. In the following examples the part costs k_1 and k_2 are calculated for the presumption valid for each case. Below the developed model is exemplified by inserting technical and economic data according to Table 2.

Table 2: Applied data for the model.

t_0	10	min
T_{su}	100	min
k_{Cp}	1000	kr/h
k_{CS}	700	kr/h
k_{D1}	200	kr/h
k_{D2}	50	kr/h
k_B	20	kr/part
q_B	0	-
K_{sum}	0	kr/batch

Figure 1 illustrates the part cost *k* as a function of the nominal batch size N_0 with two separate values of the wage cost. In case 1 (dotted graph) is the wage cost unchanged, i.e. k_{D1} = 200 kr/h and in case 2 (continous graph) is the wage cost reduced; k_{D2} = 50 kr/h. The difference in wage cost can for example illustrate two manufacturing plants in different countries with different wage costs. All other parameters are unchanged. In the figure you can see that the value of *k* is clearly higher for case 1 because of the higher wage cost.

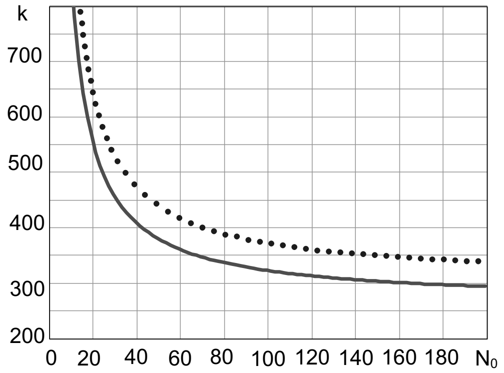

Figure 1: The part cost of the productio ıses 1 (dotted graph) and 2 (continuous graph) as a function of the nominal batch size N_0. In both case 1 and 2 is q_Q = 5 % and q_S = 40 %, x_p and x_{su} is 1.0.

For the plant in case 1 to be able to compete with the plant in case 2 it must take actions to alter one or more of the parameters building up the cost *k*. In Figure 2 has the plant in case 1 managed to decrease the down time losses from q_S = 40 % to q_S = 35 % and the process development factor x_{p1} has decreased from 1.0 to 0.95. By these changes the difference in part cost between the two cases has more than halved, even if it differ a factor 4 in wage cost.

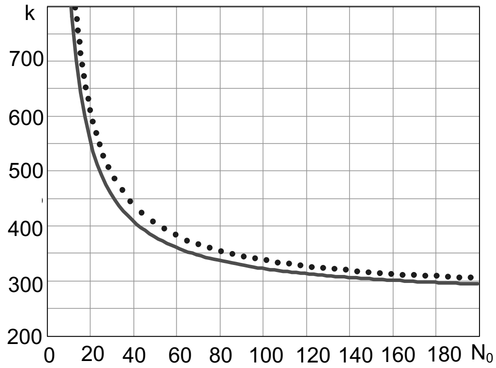

Figure 2: The part cost of the production cases 1 (dotted graph) and 2 (continuous graph) as a function of the nominal batch size N_0. In both case 1 and 2 is q_Q = 5 % and q_S = 40 % for case 2 and 35 % in case 1, x_p is 1.0 in case 2 and 0.95 in case 1.

In Figure 3 below, the down time factor q_{S1} has been further decreased with 5 % to 30 % and the process development factor x_{p1} is reduced to 0.80. In this situation the part cost for the plant in case 1 has been reduced and becoming 30 kr lower than the plant in case 2 for batches larger than 100 parts.

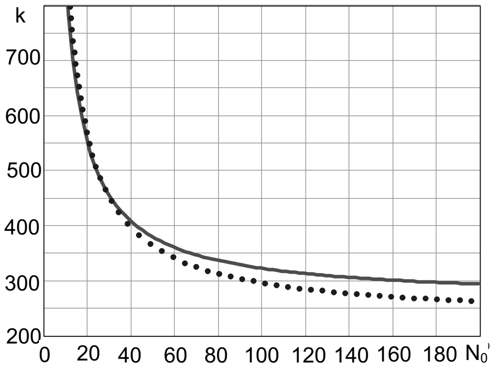

Figure 3: The part cost of production cas dotted graph) and 2 (continuous graph) as a function of the nominal batch size N_0. In both case 1 and 2 is q_Q = 5 %. q_S = 40 % for case 2 and 30 % in case 1, x_p is 1.0 in case 2 and 0.80 in case 1.

In Figure 4 the cost derivative is exemplified. The cost change Δk_1 is illustrated as a function of change in down time loss Δq_{S1} and change in relative wage cost $\Delta(k_{D1}/k_{D1})$. In the figure you can observe that a increase in part cost by 40 kr can either be received by increasing the down time loss 10 % or the wage cost by 70 %. In this linear model the corresponding decrease applies in the described variables.

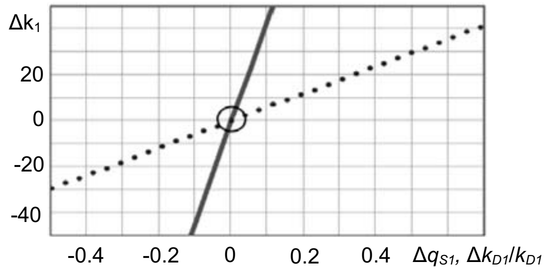

Figure 4: The relationships between the cost change Δk_1 and change in down time loss Δq_{S1} and change in relative wage cost $\Delta k_{D1}/k_{D1}$. In this case is q_Q = 5 % and q_S = 40 %, x_p and x_{su} is 1.0, the batch size 200 parts.

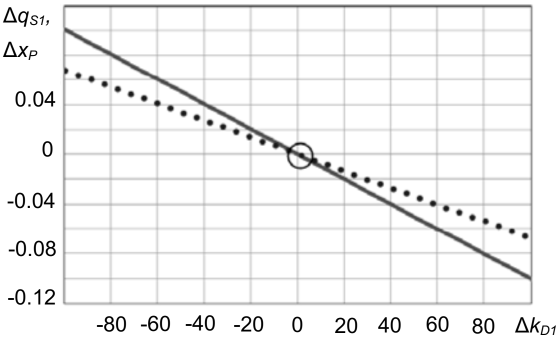

Figure 5: Cost neutral changes in wage cost and in down time losses (dotted graph) and also in wage cost and process development factor (continuous graph). In this case is q_Q = 5 % and q_S 40 %, x_p and x_{su} is 1.0 and batch size N_0 = 200 parts.

In Figure 5 the cost neutral changes are shown, which illustrate the balance for a change in wage cost and down time loss and also a change in wage cost and process development factor. In the figure it can be established that a wage increase by 40 kr per hour i.e. 20 %, corresponds a cost neutral improvement i the process development factor

Δx_p by about 4 % or a decrease in down time losses Δq_S by almost 3 %.

9 DISCUSSION AND CONCLUSIONS

The developed model enables analyses and economic estimations of various technical and organisational development alternatives. The model example shown in the section above illustrates for example how a higher wage cost can be compensated by technical and organizational improvements. Through studies of cost derivatives different alternatives related to production development can be judged. High cost derivatives shows the strength of a certain variable. The investment cost in research and development necessary to reduce x_{p1} from 1.0 to 0.80 and q_{S1} from 0.40 to 0.30 can for instance be weighted against alternative costs. The theoretical and practical possibilities to realize the necessary development for example in the case above must of course be estimated in each specific case. The conditions are highly governed by the present level of development and the belonged remaining development potential.

The difficulties of using the described model are that the model demands accurate input data. A systematic registration of the disturbances building up the parameters q_Q, q_S and q_P and parameters such as the set up time is of great importance. From experience the equipment costs represent though the greatest difficulties. These problems are dealt with by Ståhl (2007) among others.

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Paper 2

M. Jönsson, C. Andersson, and J.-E. Ståhl, “Relations between Volume Flexibility and Part Cost in Assembly Lines,” *Robotics and Computer-Integrated Manufacturing*, vol 27, no 4, pp. 669-673, 2011.

Robotics and Computer-Integrated Manufacturing 27 (2011) 669–673

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Relations between volume flexibility and part cost in assembly lines ☆

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ARTICLE INFO

Article history:
Received 16 December 2010
Accepted 20 December 2010
Available online 2 February 2011

Keywords:
Volume flexibility
Manufacturing costs
Assembly

ABSTRACT

This paper presents a strategy for achieving volume flexibility in assembly lines, so that varying production demands can be met. The strategy involves providing assembly lines inherent cycle-time flexibility, through creating the possibility for operators to handle multiple work stations. A basic part-cost model serves as a basis for analyzing the cost effects of different staffing alternatives, its taking account of different performance parameters and numbers of operators. Use of the part-cost model is illustrated by analyzing two specific cases differing in the number of operators assigned to the assembly line, the operators being partly permanent and partly temporary workers. It is shown how the costs are affected by the production performance of the work force in question, temporary operators being expected to display a somewhat lower level of performance than permanent workers.

1. Introduction

Flexibility has received a lot of attention the last decades [1]. There are different types of flexibility, such as product flexibility, production flexibility, volume flexibility and machine flexibility [2]. Present paper is concerned primarily with volume flexibility and its relations to manufacturing costs.

Many of the external factors associated with the current economic situation are ones that no individual company has any appreciable control over, although under such conditions, if faced with increased competition or a decrease in incoming orders, a company may pursue a survival strategy based on increasing its flexibility and/or cutting costs. The recent financial crisis has highlighted the importance of both cutting costs and of designing manufacturing systems such that they have a high degree of flexibility, volume flexibility in particular. There are often two alternatives to meeting a decreasing (or varying) inflow of orders: shutting down manufacturing lines and instead buying from a subcontractor, or manufacturing with a reduced number of operators. Decisions regarding this can be difficult to make, since shutting down parts of a manufacturing system can result in a loss of knowledge that could be important for survival in a time of rapid changes in the market situation.

Many assembly systems are based on rigid automation involving fixed cycle times. When this is the case, an adjustment of the production pace to fit the demands of customers through altering the number of operators in an assembly line, can lead to balance delay. Other possible losses, such as those due to difficulties in moving between assembly stations or to increased setup times, can add to the manufacturing costs. In designing a new (or redesigning an old) assembly line it is important to take account of the degree of flexibility found in the system as a whole, so as to be able to create a cost efficient assembly line that can readily adjust to customer demands. The present article aims at analyzing relations between volume flexibility and manufacturing costs in this context.

2. Aim and limitations

The article takes up the question of the strategy to employ in dealing with fluctuations in customer demands with the aim of remaining competitive. Since a major factor in remaining competitive is to establish flexibility in production volume at a minimum of cost, the article includes a part-cost model that can be used to analyze changes in manufacturing costs brought about by variations in cycle times and in number of operators. The model is referred to as a part-cost model, since it enables estimates to be made of the manufacturing cost per part.

It is assumed in connection with the model that personnel not occupied in the assembly line in question can be engaged in activities of different kind in some other part of the production system

In comparison with many other volume flexibility and capacity-cost models described in the literature, such as those regarding Aggregate production planning (APP), the part-cost model to be presented can be considered quite simple and straightforward. Its aim is to examine volume flexibility from a cost-per-part perspective, asking how costs per part are affected by volume

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☆ The author gratefully acknowledges the CSU East Bay University for support of the project.

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doi:10.1016/j.rcim.2010.12.002

flexibility. The results in this article are based on a case study in a just-in-time environment in which inventory levels and work-in-progress levels consequently were correspondingly low. It was found that in such an environment the costs related to inventory and work in progress were often negligible from a cost-per-part perspective. Since the products produced in the assembly line that was studied are all very similar in terms of cycle times and performance parameters, no consideration is taken of product-specific conditions that can affect the manufacturing costs.

3. List of symbols

The economic parameters are described in terms of US Dollars (Table 1).

4. Volume flexibility

Flexibility can be divided into several categories, how they are defined differing slightly between different authors. This paper deals with volume flexibility, sometimes also denoted capacity flexibility in the literature. Here are the definitions of volume flexibility by two widely cited authors within the area:

- The ease with which changes in the aggregate amount of production of a manufacturing process can be achieved (Gerwin [3]).
- The ability to manufacture profitably in spite of changing manufacturing volume (Browne et al. [4]).

Capacity management has received considerable attention recently. Wijngaard and Miltenburg [5] present an approach to the use of resources for promoting sales opportunities when operator capacity is flexible and machine capacity is fixed, their using primarily two parameters: *r*, the reward achievable by accepting additional sales opportunities and c, the capacity required to produce the additional products. Tang [6] presents a dynamic model for planning capacity and for flexibility over a finite period of time, a model that includes parameters for equipment and processing cost, but no performance parameters. Also, no application of the model is presented.

Alp and Tan [7] refer to capacity flexibility as the ability to adjust the total production capacity during a given period of time when having the option of utilizing contingent resources in addition to permanent resources. In their study, they consider a tactical-level capacity planning problem in which production and inventory decisions are to be made. They present a model for balancing out variations in backlog, the hiring of temporary workers and the selection of inventory strategies. The model parameters include fixed production costs and the ordering of contingent capacities. The cost parameters are aggregated at a system level, and not all of the manufacturing costs are included in the fixed costs.

Aggregate production planning (APP) is a technique for determining the minimal costs for handling a specific future demand that has been prognosticated. Research on APP started in the 1950s and since then there have been numerous contributions to the field, much of the research being based on the groundbreaking work by Holt et al. [8,9]. The general idea is to calculate the minimal manufacturing costs for a prognosticated demand by finding the optimal balance between different sources of volume flexibility such as hiring and firing, inventory levels and overtime [10]. Although considerable work has been carried out within the field, it has had only a limited impact upon the industry [10,11]. There has been said to be various reasons for this gap between theory and practice. One reason is that of the underlying preconditions inherent in APP models, e.g. that different products can be grouped together and be viewed as a single aggregated product and the complexity that use of the technique involves.

In an investigation surveying factors that affect volume flexibility, Oke [12] found there to be three major factors of this type: demand variability, demand uncertainty and the influence customers have on the lead time. Volume flexibility can be dealt with in a variety of ways: Jack and Raturi [13] conducted a survey of the main sources of volume flexibility. They found there to be both short term and long term sources of it. The major short-term sources were overtime, inventory buffers and capacity buffers. The major long term sources were plant networks, outsourcing, the ability to increase or decrease plant capacity, and the ability to increase or decrease the current labor force or the number of shifts.

The models involving cost estimates consider cost factors either at an aggregated level or without taking account of production system performance. Production performance is conceived in terms of parameters that define production losses, such as downtime rate and rate of loss in speed and in quality. The setup time is also treated as a performance parameter.

5. Number of operators and ideal cycle time

One way of achieving volume flexibility in an assembly line is to reduce or increase the number of operators as the need arises. This can be done in either of two ways. The one way is to keep the total production capacity constant in terms of operators, but to effect any changes in local production capacity that are called for (i.e. in individual production cells or assembly lines) by moving operators, already employed by the company, to where they are needed. This produces no change in labor costs since the same operators as before are involved. The other way is to hire additional workers on a temporary basis to the extent needed. This increases the labor costs, both generally and per worker, the latter because of temporary workers not being familiar with the

Table 1
List of symbols.

a_i	Factors, $i=1,2$		n_{op}	Number of operators	unit
k	Part cost	US $/unit	N_0	Nominal batch size	unit
k_B	Material cost per part including material waste	US $/unit	N	Total amount of parts required to be able to produce N_0 parts	unit
k_{CP}	Hourly cost of machines during production	US $/h	t_0	Ideal cycle time	min
k_{CS}	Hourly cost of machines during downtime and setup times	US $/h	$t_0(n_{op})$	Ideal cycle time depending upon the number of operators	min
k_D	Wage cost	US $/h	t_p	Production time per part	min
K_{sum}	Sum of remaining costs	US $/batch	T_{su}	Setup time for a batch	min
q_B	Material waste rate	–	$T_{su}(n_{op})$	Setup time depending upon the number of operators	min
q_Q	Scrap rate	–	T_{pb}	Production time for a batch	min
q_P	Production-rate loss	–	U_{RP}	Machine utilization	–
q_S	Downtime rate	–			

work tasks involved and thus needing to be trained in order to perform the tasks as quickly as experienced operators.

A situation of either of two differing types is often encountered dealing with volume flexibility. The one type of situation is that of a decrease in incoming orders for a particular product. A company may cut costs and reduce the number of operators. This may also be the case if additional operators are needed in some part of the company manufacturing products that have been given high priority.

The other type of situation is one in which there is an increased demand for some product, requiring that more parts per time unit be produced. A short term solution to this is to introduce overtime. Another alternative is to hire extra production equipment and temporary workers so as to increase the production capacity. If the increase in demand for a product is expected to be long-lasting, the best solution may be to introduce an extra shift because of difficulties in adding more operators to the assembly line.

A consequence of a situation of the first type, if the number of operators in a line is reduced is that the remaining operators have to perform more tasks than before or are responsible for additional work stations. This tends to increase the downtimes, unless the work stations and the cycle times are adjusted to the decrease in the number of operators. A consequence of a situation of the second type if a new shift is added can be an excess in capacity.

One way of increasing the volume flexibility is to design an assembly line in such a way that there is an inherent system flexibility and flexibility in the number of operators in the line, inherent flexibility meaning that the assembly line that is able to function effectively with varying numbers of operators. Under such conditions the assembly line often functions best if U-shaped, since this facilitates an operator's handling multiple work stations. Such inherent flexibility makes it possible to alter the cycle time of an assembly line in accordance with demand, through changing the number of operators [14]. As already indicated, it is preferable if the flexible staffing can be managed within the company through personnel being transferred to production lines and locations where they are needed most.

5.1. *An example of volume flexibility in an assembly line*

The following example illustrates the functioning of an assembly line containing a total of 18 work stations, 10 of which are operated automatically and 8 are operated manually. The example is based on a real assembly line, although the cycle times have been modified here. The cycle times in the manually operated work stations are 17–42 s and those for the automatically operated stations 22–40 s in length. The assembly line is operated in 2 shifts. The workshop is available a total of 76 h/week. When the time spent on breaks and meetings has been deducted a total of 70 h of production time is available. If production takes place during the entire 70 h that are available the maximum ideal production capacity is 6000 parts/week or a production rate of 86 parts/h. The assembly line operate at a weekly average of OEE$=$75%, due to a downtime rate of $q_S=10\%$, a speed-loss rate of $q_P=15\%$ and a quality loss of $q_Q=2\%$. The current performance level indicates the real production capacity to be 4500 parts/week, corresponding to a production rate of 64 parts/h. Table 2 lists the work stations in the order in which they come. It is assumed that the distribution of separate tasks across the workstations as a whole is optimized in terms of balance delay.

If there are 8 operators in the assembly line here, this means there being one operator for each manual work station. As the number of operators decreases, each operator can come eventually to perform the tasks for two or more work stations. The assembly line can be operated by anywhere between 1 and 8 operators, each new staffing setup resulting in a different ideal cycle time for the assembly line as a whole, see Fig. 1.

Table 2
The work stations in the assembly line.

Station no.	Ideal cycle time t_0	Manual (M), automatic (A)	Station no.	Ideal cycle time t_0	Manual (M), automatic (A)
1	34	M	10	25	A
2	40	A	11	17	A
3	28	A	12	38	M
4	23	M	13	22	A
5	30	A	14	32	M
6	33	A	15	34	A
7	38	A	16	19	M
8	25	A	17	22	M
9	42	M	18	35	M

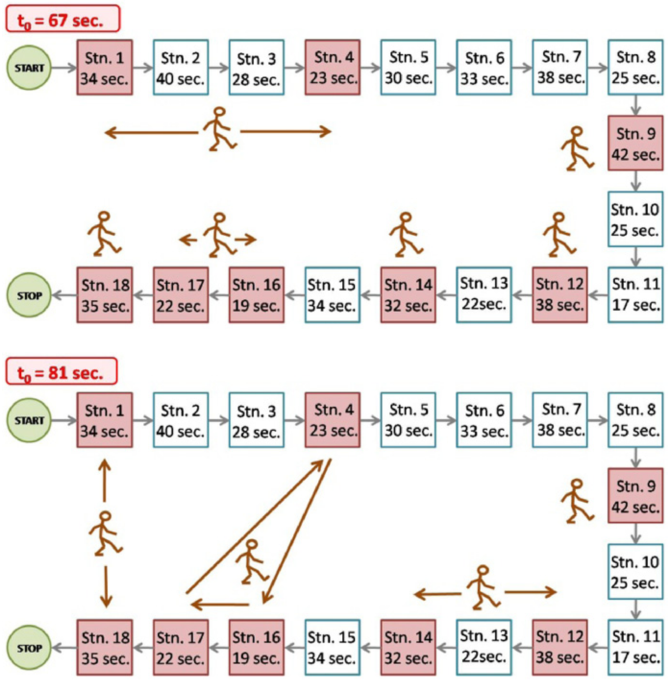

Fig. 1. Examples of workstation configurations for different capacity levels.

The strategy in allocating workstations to operators for a specific level of demand is to minimize the balance delay. If the number of operators is reduced to 7, one operator has to perform the tasks for two workstations rather than one. If the two successive manual stations in question are those with the shortest ideal cycle times the balance delay is minimized. In the example presented, it is stations 16 and 17 that would be best chosen to be operated by a single operator if the number of operators is decreased from 8 to 7.

Table 3 shows the ideal cycle time t_0 for different numbers of operators. From the variations in ideal cycle times for the different staffing alternatives, one can see that the ideal production capacity varies between 85 and 12 parts/h. For the OEE of 75% that was obtained here, the real production capacity varies between 9 and 64 parts/h. If there are fewer than 8 operators, the operators need to walk between different manual work stations. An average transfer time of 5 s is thus included in the ideal cycle times shown in Table 3. The values for the production capacity shown in Table 3 are the ideal values, no account being taken there of any losses in performance.

Table 3
The ideal cycle times, production rates and balance delays for the presence of different numbers of operators.

No. of operators n_{op} (unit)	Ideal cycle time t_0 (s)	Production capacity P_C (unit/h)	Balance delay D (%)
8	42	85	0.29
7	51	70	0.37
6	67	53	0.49
5	80	45	0.57
4	81	44	0.49
3	116	31	0.62
2	155	23	0.69
1	285	12	0.82

The total range of flexibility for the ideal capacity here is between 12 and 85 parts/h. Varying customer demands can be met by a different number of operators being contracted for the daytime shift than for the evening shift. In the example here, a weekly customer demand of 3000 parts can be dealt with adequately by having 7 operators on the daytime shift and 6 operators on the evening shift, both shifts operating of OEE=75%, yielding a total real capacity of 3228 parts/week. The same weekly demand can also be met by having 8 operators on the daytime shift and 3 operators on the evening shift resulting in a total real capacity of 3045 parts/week. It is of interest to note that the manufacturing costs would probably be substantially lower for the second staffing alternative, due to the lesser number of operators totally and also due to lesser operators with shift allowances.

To address issues of this sort, a part-cost model for analyzing the differences in cost produced by differences in the number of operators will be presented in the next section.

6. Modeling volume flexibility and part cost

In this section a part-cost model for determining the total part cost for manufacturing a specific product, taking account of variations in cycle time and work force, is presented. A basic part cost model was presented by Jönsson et al. [15] with the aim of being able to calculate the real manufacturing costs of a given processing step as affected by such production-performance parameters as downtimes, production-rate losses and scrap. The model attempts to take account of all major factors, both technical and economic, that contribute to the part costs of any given production step. A production step typically involves a machine or an automated cell or line with a fixed cycle time. The total part cost is obtained by summing the part costs for all of the manufacturing steps, from the raw material to the finished product. The manufacturing cost per part, k, is modeled in Jönsson et al. [15] as

$$k=\frac{K_{sum}}{N_0}+\left(\frac{k_B N_0}{N_0(1-q_Q)(1-q_B)}\right)+\left(\frac{k_{CP}}{60N_0}\frac{t_0 N_0}{(1-q_Q)(1-q_P)}\right)+\frac{k_{CS}}{60N_0}\left(\frac{t_0 N_0}{(1-q_Q)(1-q_P)}\frac{q_S}{(1-q_S)}+T_{su}+\frac{1-U_{RP}}{U_{RP}}T_{pb}\right)+\frac{k_D}{60N_0}\left(\frac{t_0 N_0}{(1-q_Q)(1-q_S)(1-q_P)}+T_{su}+\frac{1-U_{RP}}{U_{RP}}T_{pb}\right) \quad (1)$$

The model contains terms for material cost (index B), equipment costs during the run time (index CP) and downtimes (index CS), wage costs (index D) and remaining costs, represented by K_{sum}. The q-parameters represent production losses, the index S denoting downtimes, P production-rate losses and Q losses in quality.

Studying how costs are affected by changes in capacity requires an additional set of parameters. In Eq. (2), the fixed ideal cycle time t_0 is replaced by a varying ideal cycle time, dependent upon the number of operators, $t_0(n_{op})$:

$$k=\frac{K_{sum}}{N_0}+\left(\frac{k_B N_0}{N_0(1-q_Q)(1-q_B)}\right)+\left(\frac{k_{CP}}{60N_0}\frac{t_0(n_{op})N_0}{(1-q_Q)(1-q_P)}\right)+\frac{k_{CS}}{60N_0}\left(\frac{t_0(n_{op})N_0}{(1-q_Q)(1-q_P)}\frac{q_S}{(1-q_S)}\right)+\frac{k_{CS}}{60N_0}\left(T_{su}(n_{op})+\frac{1-U_{RP}}{U_{RP}}T_{pb}\right)+\frac{k_D n_{op}}{60N_0}\left(\frac{t_0(n_{op})N_0}{(1-q_Q)(1-q_S)(1-q_P)}\right)+\frac{k_D n_{op}}{60N_0}\left(T_{su}(n_{op})+\frac{1-U_{RP}}{U_{RP}}T_{pb}\right) \quad (2)$$

If the operators share the setup tasks, the setup time is dependent upon the number of operators. If the number of operators is reduced, the setup tasks need to be performed by fewer persons, resulting in longer setup times. This is taken into account by introducing the operator-dependent setup time $T_{SU}(n_{op})$. The total time for manufacturing an entire batch (T_{pb}) is calculated as

$$T_{pb}=T_{su}+Nt_p=T_{su}(n_{op})+\frac{N_0 t_0(n_{op})}{(1-q_Q)(1-q_S)(1-q_P)} \quad (3)$$

Applying this part-cost model to the example given in the previous section provides an idea of how different staffing alternatives can affect the manufacturing costs per manufactured part. These costs are presented for two cases:

- Case 1: the line is staffed by 4 operators who are regular company employees.
- Case 2: the line is staffed by 8 operators, 4 of whom are temporary workers.

Because of no other workers, from other parts of the workshop, being available at that time, the company has to hire temporary workers. The salary costs for the temporary workers are higher, as shown in Table 4. Since they need to be trained so as to be able to carry out the assembly tasks insofar as possible at the same speed and proficiency level as the permanent workers, there is net loss in speed due to the extra time needed to provide the temporary workers the knowledge and skills required. A certain loss in quality can also be expected.

The performance and cost parameters in the example are chosen from Table 4. Since the operators all work on the same assembly line, regarding the cost parameters there is only a difference in wage costs. The downtimes are largely equipment-dependent in this case, and accordingly these are presumably not affected by the fact that the equipment is partly being operated by temporary workers. In the case of 4 permanent workers, the

Table 4
Cost parameters and production performance parameters for the assembly line example presented earlier.

Parameters	Case 1: $n_{op}=4$	Case 2: $n_{op}=8$
k_B (US \$/unit)	10	10
k_{CP} (US \$/h)	110	110
k_{CS} (US \$/h)	100	100
k_D (US \$/h)	35	45
$t_0(n_{op})$ (sec)	81	42
$T_{SU}(n_{op})$ (min)	12	8
q_Q	0.02	0.04
q_S	0.25	0.25
q_P	0.15	0.25
U_{RB}	1	1
N_0 (unit)	60	60

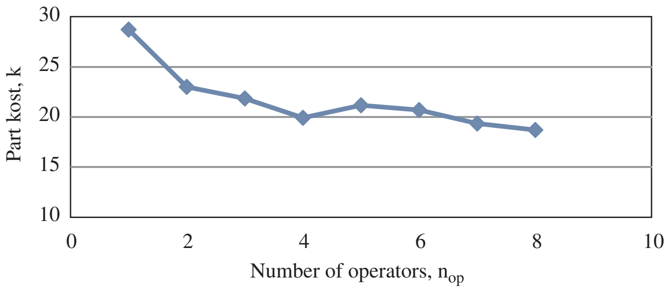

Fig. 2. The relationship between the part cost k and number of operators n_{op}.

setup time is 12 min, the operators needing to set up an average of two manual stations and two automatic stations. Although one could expected, other things being equal, that when the line is operated by 8 operators the setup time should be half that required when there are only 4 operators, the fact that 4 of the 8 are not fully trained from the start means that the time needed can be reasonably estimated as 8 min.

The rest of the parameters in Eq. (2) are set to zero. The part costs calculated using Eq. (2) are as follows for the two cases presented:

- Case 1: k=$19,9 US $/part.
- Case 2: k=$21,5 US $/part.

If Case 2 is compared with a third case, one involving there being free work-force capacity at the company, 4 trained operators replacing the 4 temporary ones, and if it is assumed that this yields the same performance parameters as for the regular operators, then the part cost k is $18.1 US $/part. If one assumes instead that making use of the 4 extra in-house operators results in the same decrease in performance as for the temporary work force, then k is $19.6 US $/part. The results obtained indicate the importance of taking account of the performance parameters in cost analyses concerned with volume flexibility.

Fig. 2 shows the part cost k as a function of the number of operators n_{op}, using the same parameter values as in case 1. The setup time in Fig. 2 is considered as being independent of n_{op}. The figure indicates that this line is operated most cost effectively either with use of 4 operators or with use of more than 6 operators.

7. Conclusions

The volume flexibility of assembly lines can be increased by designing them so that they possess an inherent cycle-time flexibility. This makes it possible to adjust the cycle time so as to meet the current demands. In order to carry this out in the most cost-effective way, it is best, insofar as possible, to make the staffing adjustments needed by using only the regular company staff.

A part-cost model for analyzing real manufacturing costs under varying production-capacity conditions was presented. The model was applied in comparing the manufacturing costs involved in two cases differing in terms of the customer demands, in the one case the company staffing the assembly line with 4 permanent workers and in the other case the company needing to choose between hiring a workforce from outside and using an extra work force available in-house. The cases show how the cost model can be applied for analyzing the costs per manufactured part in different staffing cases.

Acknowledgments

This work was supported by SPI, Sustainable Production Initiative, Chalmers & LTH, and is financed by VINNOVA.

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Paper 3

M. Jönsson, P. Gabrielson, C. Andersson, and J.-E. Ståhl, "Dynamic Manufacturing Costs - Describing the Dynamic Behavior of Downtimes from a Cost Perspective," *Proceedings of the 44st CIRP Conference on Manufacturing Systems*, 2011.

Dynamic Manufacturing Costs -
Describing the Dynamic Behavior of Downtimes from a Cost Perspective

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Abstract

Downtimes in a manufacturing cell, line or individual machines are characterized by a stochastic behavior that their frequency and their duration display. A method is presented here for analyzing this dynamic behavior from a cost perspective. An important element of the method is statistical analysis of downtimes, including empirical distribution functions pertaining to downtimes of specific types. For demonstrating this, use is made here of genuine downtime data obtained from the Swedish company Alfa Laval.

Keywords:
Manufacturing costs, Downtime, Variability

1 INTRODUCTION

Manufacturing plants need to be operated at a high level of efficiency in order to succeed in the global competition of today. An essential parameter in this respect is the availability of machines. High availability means high utilization of the available resources and thus contributing to a more sustainable production. Availability can be calculated in numerous ways, in terms of the times to include in the calculations, its essence is the share of time the equipment involved is available for the work to be performed. Availability is thus dependent upon the amount of time the machines in question are down. The literature is not unequivocal regarding the question of whether downtimes should include planned alongside unplanned downtimes (see [1], for example). As Patty and Watson [2] point out it can be tempting to measure downtimes in terms of the total downtimes occurring during a specific period, without considering the variability of their frequency and duration. In addition to the effects this variability can have on the flow in serial production systems, as described by Patty and Watson [2], the lengths of time between successive downtimes and the length of the downtimes themselves have an impact on the costs of the parts produced.

The aim of the present paper is to present a method by which this variability can be described in terms of costs, specifically dynamic manufacturing costs, as they will be termed. The paper explores the relevance this has as a method for analyzing the actions which should best be taken in order to improve performance and lower the costs.

2 LITERATURE REVIEW

2.1 Downtime

An influential management approach within the field of maintenance and waste management is the Total productive maintenance (TPM) philosophy presented originally by Nakajima [3]. He divides the losses that occur in manufacturing processes into six major groups, “the six big losses”, those of equipment failure, setup and adjustment, idling and minor stoppages, reduced speed, process defects and reduced yield. These losses can involve many different types of incidents and causes, which need to be registered in order to be followed up and analyzed. The gains that can be achieved if data regarding them is registered and is analyzed are discussed by De Smet et al. [4], who describe how the information thus obtained can be used as a support for learning and for improvement of the manufacturing processes.

Another popular manufacturing philosophy concerned with losses in manufacturing and how these should best be handled is the Six sigma philosophy [5]. Six sigma deals mainly with how variations in different processes, such as variations in the cycle time can be reduced. The variations are measured and are analyzed by means of some set of statistical tools, such as the Seven quality control tools (7QC) and factorial experiments. Such statistical tools are also used in assigning priorities to improvement projects of different types. According to a review by Banuelas [6], cost-benefit analysis is the method most often utilized in giving priorities to different Six sigma-projects, although how such cost-benefit analyses are carried out is not dealt with here. It was found in that study that brainstorming, Critical-to-quality CTQ trees, focus groups and interviews were the methods used most commonly for indentifying Six sigma projects.

The size and frequency of the failures that occur in a manufacturing system can be described statistically by means of distribution functions. Vineyard et al. [7] analyzed failure-rate distributions in a Flexible manufacturing system (FMS). They collected failure data and classified it in terms of six different failure types: human, software, electrical, mechanical, hydraulic and electronic. For each of these failure types they calculated the time between failure (TBF) and the time to repair (TTR) for each failure that occurred. They investigated then what types of distributions best fitted the TBF and TTR values. They found that the TBF values for all types of failure except for electrical ones could be described by a Weibull distribution, the electrical failures having a lognormal distribution. Regarding results for the TTR values, all the failure types except for hydraulic and electronic failures had lognormal distribution. For hydraulic failures the TTR values were found to be gamma distributed whereas the TTR values for electronic failures were found to display a Weibull distribution. Yazhou et al. [8] analyzed the failure distributions at machine centers. Studying 24 such centers during a one-year period, they found that the failure distribution could be fitted to an exponential distribution. In the literature, exponential distributions are commonly assumed to apply in modeling failures [9], [10]. Dallery [10] argues that, although an exponential distribution can be properly employed in modeling the time distribution of failures, it is not equally useful in modeling repair-time distributions. He considered that failure times can be described by generalized exponential (GE) distributions. Mohanty [11], in turn, argues that whereas failure times are often modeled in terms of exponential distributions due to constant failure rates is suitable for describing overstresses in electronic components, the weibull distribution is more suitable for describing fatigue. For the modeling of repairs, Mohanty considers the lognormal distribution to be the best choice in many cases.

Additional views concerning the handling of failure data are to be found within the realm of discrete event simulation (DES) research. In the literature there, it is often argued that TBF and TTR data is best described by a theoretical distribution, to which the chi-square test, the Kolmogorov-Smirnov test and the Anderson-Darkna test [12], [13] can be applied.

Questions in connection with calculation of performance rates can be raised concerning such matters as sample size, and the lengths of time samples should encompass in order for reliable results to be obtained. Lamberson and Wasserman [14] have developed models concerning the relationship between sample size, the occurrences of failures and the standard deviations obtained for different degrees of availability. Their models are based on the assumption that TBF and TTR values have exponential distributions.

2.2 Downtime costs

Various studies of manufacturing costs recently, such as those concerned with analyzing different manufacturing systems from a cost perspective, such as [15], [16] and [17], have made use of the activity-based costing (ABC) method. This method is often used for the purpose of obtaining as accurate estimates as possible of the overhead costs of products, rather than for calculating the costs of losses in performance.

Non-ABC-related work on the costs of losses in performance has also been carried out recently. Das [9] has developed a multi-objective mixed integer programming (MIP) model that takes into account both the reliability and the costs of a manufacturing cell. One aim of his model is to create the basis for a trade-off between system availability and system costs when alternative processing routs are available, involving different machines, the availabilities of which are also different. There are two versions of the model, one of them for exponentially distributed reliability and the other for Weibull distributed reliability. Several papers have presented models of the relationship between availability and maintenance costs. Murty and Naikan [18] developed an optimization model regarding the optimal availability level in terms of the costs associated with improving availability, assuming that the costs of improving it increase exponentially with the level of availability aimed at. In this model, the profit per time unit is maximized. Calabria et al. [19] also modeled an exponential cost function, but treated the mean time between failures (MTBF) and the mean time to repair (MTTR) as being separate from one another, assuming that an improvement in one of these does not affect the other. Their cost model thus contains two cost expressions, the one for MTBF and the other for MTTR. Jones et al. [20] discuss similar issues and present a model for calculating optimal inspection intervals, i.e. optimal preventive maintenance intervals in terms of keeping the costs at a minimum. The failure rate is assumed to have an exponential distribution.

Life cycle costing (LCC) commonly includes downtime costs based on use of mean values for TBF and TTR in the cost calculations [21].

It can be concluded from this literature review that there are research made with the aim of statistically describing failures and there are also papers which include cost expressions that takes availability and its variability into consideration. The cost analyses described in section 4 aims to describe the dynamic behavior of failures from a cost perspective by investigating how variability affects the manufacturing cost per part. This way of analyzing the variability was not found in the literature review.

3 PART COST MODEL

The aim of the present paper is to connect statistical analyses of downtimes with costs. The cost calculations described in the paper are based on a cost model described by Jönsson et al. [22] concerning manufacturing costs per part as based on performance parameters, on economic parameters related to material, to equipment and to wages along with other manufacturing-related parameters such as cycle time and batch size. The aim of the part cost model used is to analyze and simulate part costs on the basis of information of high resolution from each manufacturing step, from raw material to the finished product. The calculations result in US $/part. A basic version of the model is shown in Equation 1.

$$
\begin{aligned}
k = {} & \frac{k_{B0}N_0}{N_0(1-q_Q)(1-q_B)} + \frac{k_{CP}}{60N_0}\cdot\frac{t_0N_0}{(1-q_Q)(1-q_P)} + \\
& \frac{k_{CS}}{60N_0}\left(\frac{t_0N_0}{(1-q_Q)(1-q_P)}\cdot\frac{q_S}{(1-q_S)} + T_{su} + \frac{1-U_{RP}}{U_{RP}}T_{pb}\right) + \qquad (1) \\
& \frac{k_D}{60N_0}\left(\frac{t_0N_0}{(1-q_Q)(1-q_S)(1-q_P)} + T_{su} + \frac{1-U_{RP}}{U_{RP}}T_{pb}\right)
\end{aligned}
$$

The cost parameters in Equation 1 are following: k_{B0} (US $/unit) is the material cost, q_B the material waste rate, k_{CP} (US $/h) the machine costs during production, k_{CS} (US $/h) the machine costs during downtimes and set-up and k_D (US $/h) the wage costs. The production parameters are: N_0, the nominal batch size, t_0 the nominal cycle time and T_{su} the set up time. The equation also includes parameters describing quality losses due to scrapped parts q_Q, downtime losses q_S, production-rate losses q_P and machine utilization U_{RP}.

Equation 2 describes the scrap rate q_Q, where N_Q is the number of scrapped parts and N the total batch size, the scrapped parts included, i.e. N_0 plus N_Q.

$$q_Q = \frac{N_Q}{N} = \frac{N - N_0}{N} \qquad (2)$$

The downtime rate q_S is described in Equation 3, where t_s is the downtime per part and t_p the total cycle time including downtimes, i.e. t_0 plus t_s.

$$q_S = \frac{t_S}{t_p} = \frac{t_p - t_0}{t_p} \tag{3}$$

Production rate losses q_P describe losses in speed due to factors such as machine instability for example. Equation 4 defines q_P, t_{0v} being the nominal cycle time plus the extra time caused by losses in speed.

$$q_P = \frac{t_{0v} - t_0}{t_{0v}} \tag{4}$$

Machine utilization U_{RP} can be dealt with in various ways, although the present authors consider that long term free capacity should be regarded as a cost. Equation 5 describes the expression for U_{RP}, where T_{plan} is the planned production time and T_{prod} the actual production time. Planned production time is the practical capacity including downtimes and setup time. Actual production time is planned production time minus utilization losses.

$$U_{RP} = \frac{T_{prod}}{T_{plan}} \tag{5}$$

In the part cost equation, the costs of the free capacity are distributed over the parts produced in relation to the production time for the batch, T_{pb}. T_{pb} is given in Equation 6.

$$T_{pb} = T_{su} + N \cdot t_p = T_{su} + \frac{N_0 \cdot t_0}{(1-q_Q)(1-q_S)(1-q_P)} \tag{6}$$

4 DYNAMIC MANUFACTURING COSTS

If downtime data collected for a processing step is categorized in terms of the types of downtimes or downtime causes involved, a strategy of some type can be used for determining what downtime category has the strongest impact on the total downtime. Manufacturing companies usually adopt a strategy of this sort. Another way of analyzing downtime data is to analyze the dynamic behavior of downtimes with the aim of developing improvement strategies for reducing variability. In the sections that follow a method for analyzing such variability in terms of costs is described.

4.1 Method description

This method will be described here and be exemplified using data from a sheet-metal forming and cutting line.

Description of the production line and the products

The serial production system in question starts off with the processing of a sheet metal coil and ends up with a product consisting of advanced thin plate of stainless steel. The production line is a modern one possessing a high level of automation. The different steps involve uncoiling of the material, straightening of it, pre-cutting of holes at numerically controlled cutting stations, lubrication of the plates, centering of them, the forming of two plates in each cycle, automatic testing of the plates and stacking of them. The material is handled by a transfer system between different stations. All production stops are logged into a downtime collection system. Stops longer than five minutes are coded by an appropriate downtime description being selected from a list, stops shorter than five minutes being coded automatically as “short stops”.

The non-downtime data pertaining to the line needed as input data is presented in Table 1.

PARAMETER	VALUE
Number of operators	1.5
Wage cost per operator (k_D)	36 US $/h
Cycle time (t_0)	0.167 min
Hourly equipment costs during production (k_{CP})	160 US $/h
Hourly equipment costs during downtime (k_{CS})	140 US $/h
Material cost (k_B)	6 US $/unit

Table 1: Input data to the cost calculations

The major part of the data made of use in the paper is TBF and downtime (DT) data pertaining to the process just described. The data constitute of approximately 260 production hours, consisting of 1164 TBF-DT cycles. The data was extracted from the downtime collection system. It represents data concerning one of the products.

The variability analyses provide a description of the DT and TBF data obtained and a classification of it, calculation of the dynamic downtime rates and presentation of the dynamics of the manufacturing costs.

Empirical distributions of the TBF and DT data

The empirical distributions of the TBF- and DT data are calculated first, the TBF being defined here as the time between two successive downtimes, each TBF being linked with the DT that follows it, as shown in Figure 1. A TBF here is thus not the time between two downtimes of a specific type or category.

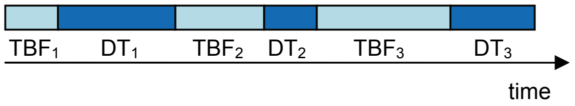

Figure 1: Each TBF value referred to here is linked with the DT value that follows it.

Figure 2 shows the empirical distributions of the TBF and DT data. The continuous line represents the TBF data and the broken line the DT data. As can be seen most of the TBF- and DT times are relatively short, particularly the DTs. One conclusion to be drawn is that the process is fairly instable, its being characterized by short TBF periods followed by short DT periods. The mean downtime (MDT) is 5.8 min and mean time between failures (MTBF) 7.5 min. The DT data can be described by an exponential distribution, having an absolute deviation of less than 3 %. The TBF graph is more complex and involves several different distribution functions. The exponential distribution is characterized by the fact that the events are independent of each other in time. This relation can lead to exponential distributed downtimes being more difficult to take care of than for example Weibull distributed.

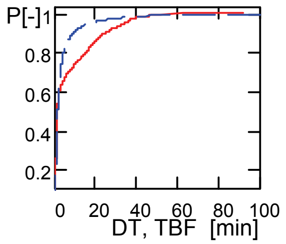

Figure 2: Empirical distributions of all the TBF data (continuous line) and the DT data (broken line).

In Figures 3-6 the DTs and their TBFs are grouped into 7 different downtime categories, those of inspection, short stops, change of coil, cutting line, change of material, gripping tool and miscellaneous. This grouping is based on the fact that most of the DTs could be attributed to only one of these categories. Downtimes caused by meetings, training and other such planned staff-related activities are not included in the calculations. As can be seen in these figures, the various downtime categories differ in their distribution characteristics for both DT and TBF.

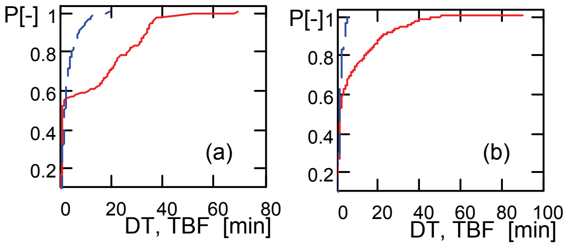

Figure 3: Empirical distributions of TBF data (continuous line) and DT data (broken line) for (a) inspections and (b) short stops.

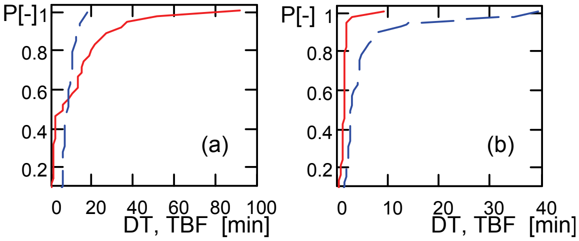

Figure 4: Empirical distributions of TBF data (continuous line) and DT data (broken line) for (a) change of coil and (b) cutting line.

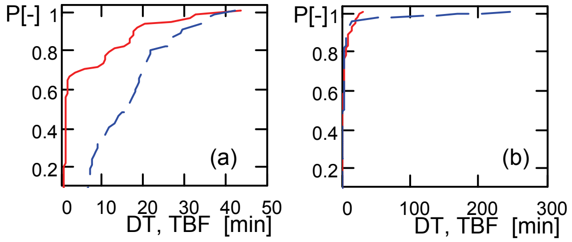

Figure 5: Empirical distributions of TBF data (continuous line) and DT data (broken line) for (a) change of material and (b) the gripping tool.

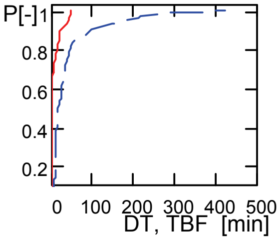

Figure 6: Empirical distributions of TBF data (continuous line) and DT data (broken line) for miscellaneous.

Downtime rate

For a given series of TBF and DT the downtime rate for each failure cycle can be calculated using equation 7.

$$q_{S_j} = \frac{DT_j}{TBF_j + DT_j} \qquad (7)$$

This approach differs from the normal procedures for downtime rate calculations, based on mean values for DT and TBF. Equation 7 is employed in the cost calculations described in the next section.

Figure 7 shows empirical distributions of downtime rates for each of the downtimes and for each of the downtime categories, the latter differing from each other in their characteristics. The downtime categories in Figure 7 (a) show a preponderance of low downtime rates (circled area), whereas Figure 7 (b) shows a preponderance of high downtime rates (circled area). It is possible to indentify to some extent connections between the TBF and DT values. The downtime categories in Figure 7 (a) show the possibility of their extending down to a downtime rate of less than 0.05, whereas the downtime rates in Figure 7 (b) display higher starting values.

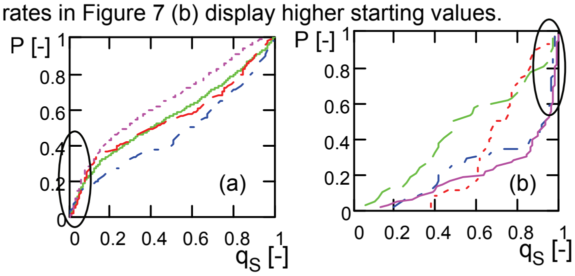

Figure 7: (a) Empirical distributions of downtime rates as a whole (continuous line), inspections (broken line), short stops (dotted line) and gripping tool (broken and dotted line) (b) Empirical distributions of cutting line (dotted line), change of material (broken and dotted line), change of coil (broken line) and miscellaneous (continuous line).

Costs

In previous use of the cost model described in equation 1, the parameters q_Q, q_S, q_P and T_{su} were usually based on mean values for specific periods. A mean part-cost provides general insight into the conditions for the manufacturing of a product, but says nothing regarding the degree of variation in the processes in question.

In the present paper, each TBF-DT cycle is treated individually. The downtime rate q_S is thus calculated by use of equation 7, which result in the part costs being the same for each part produced during a given TBF-DT cycle. In the analyses described in this paper, the downtimes caused by setup activities are not described separately from the parameter T_{su} as in equation 1, but are viewed as “ordinary downtimes” and are thus calculated by use of equation 7. The cost equation can be formulated then in accordance with equation 8. The batch size N_0 is only affecting how many parts the setup time is allocated to, can thus be excluded from the equation. In the analysis presented here q_Q, q_P, q_B are set to 0 and U_{RP} is set to 1.

$$\begin{aligned} k_j = {} & \frac{k_{B0}}{(1-q_Q)(1-q_B)} + \frac{k_{CP}}{60} \cdot \frac{t_0}{(1-q_Q)(1-q_P)} + \\ & \frac{k_{CS}}{60}\left(\frac{t_0}{(1-q_Q)(1-q_P)} \cdot \frac{q_{S_j}}{(1-q_{S_j})} + \frac{1-U_{RP}}{U_{RP}} T_{pb}\right) + \qquad (8) \\ & \frac{k_D}{60}\left(\frac{t_0}{(1-q_Q)(1-q_{S_j})(1-q_P)} + \frac{1-U_{RP}}{U_{RP}} T_{pb}\right) \end{aligned}$$

During a TBF period a specific number of units is manufactured. The number of parts N_c that are manufactured during a TBF period can be calculated as the integer of the ratio of TBF to the cycle time t_0 by use of equation 9. If the part can be completed after the downtime without a loss in speed, N_c can be expressed in decimals.

$$N_{cj} = trunc\left(\frac{TBF_j}{t_0}\right) \qquad (9)$$

The maximum number of parts that can be manufactured during a follow-up period is obtained by the ratio of the sum of all TBFs to the cycle time t_0 of the part in question.

Figure 8 shows the number of parts produced during a TBF_j at cost k_j. Several TBF periods can produce the same amount of parts N_c, but at differing costs k_j. In the figure the minimal part costs k_{min} and the mean part costs k_{mean} are plotted. k_{min} is the part costs with q_S=0 and k_{mean} the part cost with the mean value of q_S.

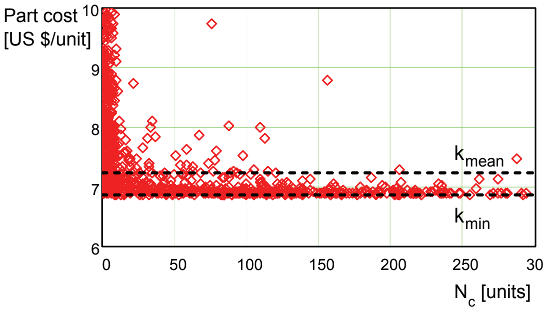

Figure 8: The part costs k_j shown as a function of the number of parts manufactured during a TBF period, N_c.

Figure 9 shows the part costs as a function of DT. As it is evident, there is no clear relationship between part costs and the lengths of the downtimes.

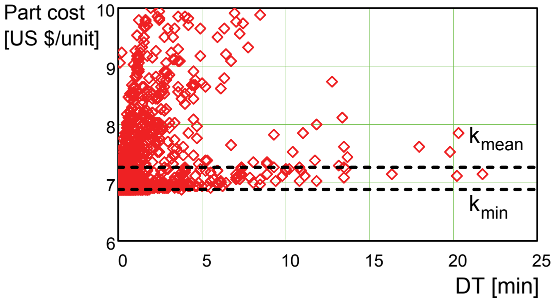

Figure 9: The part costs k_j as a function of DT.

To increase the performance of a manufacturing system, actions to lower k_{mean} should be carried out. Lowering k_{mean} can be achieved in various ways, depending on the strategy employed. For example, k_{mean} can be lowered by lowering k_{min}, thus reducing the part costs by considering parameters other than q_S. It can also be lowered by lowering the highest k_j values. This way of looking at production development can also be illustrated by considering the graph in Figure 10, in which the empirical distribution function for part costs is plotted. k_{mean} can be lowered both by lowering the high part costs shown at the right in the figure or by making changes that affect all the parts, thus pulling k_{min}, so to speak, to the left. No general advice or conclusions can be formulated, each case needing to be studied in a thorough way individually.

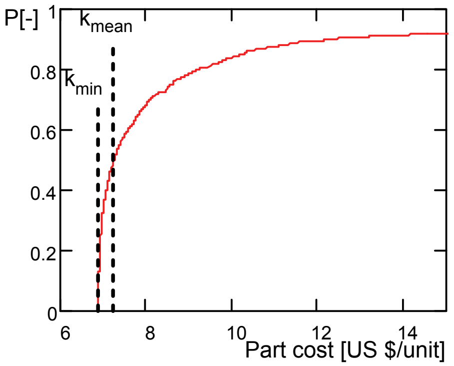

Figure 10: The empirical distribution of all part costs.

Figures 11-14 show the empirical distributions of the part costs related to each of the downtime categories.

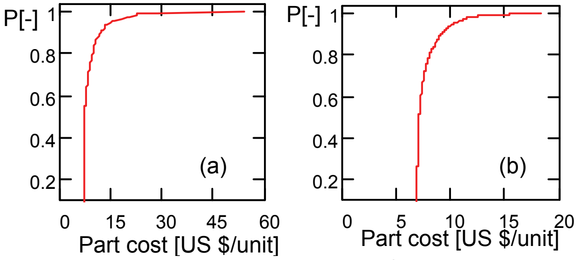

Figure 11: The empirical distributions of part costs related to (a) inspections and (b) short stops.

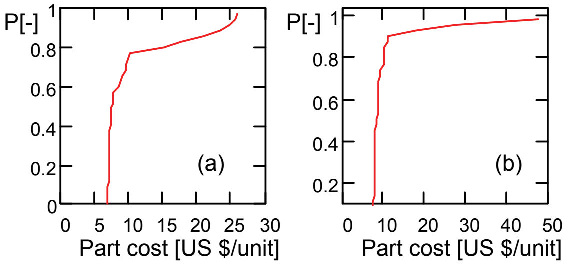

Figure 12: The empirical distributions of part costs related to (a) change of coil and (b) cutting line.

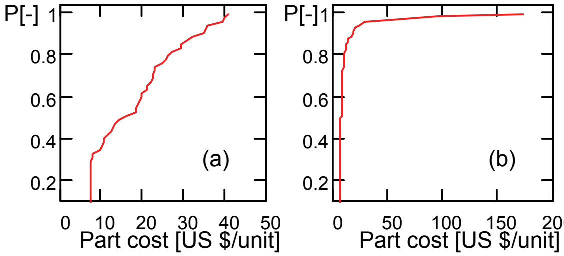

Figure 13: The empirical distributions of part costs related to (a) change of material and (b) gripping tool.

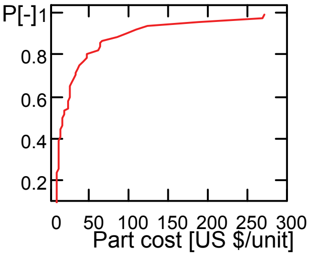

Figure 14: The empirical distributions of part costs related to the miscellaneous category.

The cost calculations above show how part costs vary as a function of downtimes. In selecting projects aimed at improvement, it is important not only to know how the costs vary but also to know the total cost reduction potential. Figure 15 (a) shows the total downtime costs for every downtime category and Figure 15 (b) shows the downtime costs as a histogram. It can be stated from the figures that the shorter stops are dominating, but they are on the other hand consisting of several different downtime categories. From Figures 11-14 and Figure 15 (a) it is clear that the miscellaneous category from a cost point of view is the largest category. This category constitutes of different kinds of stops that occur relatively seldom, making it presumably more complex and difficult to reduce the costs for this category. The possible measures to take to reduce the costs also must be analyzed together with the expenditures associated with them.

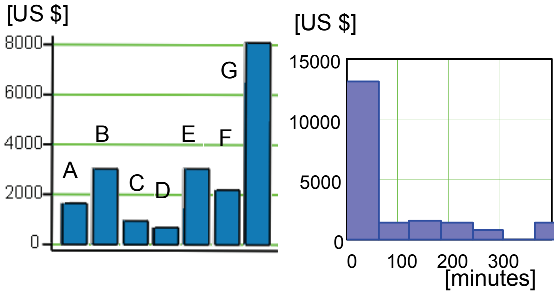

Figure 15: The total downtime costs for every downtime category (a) where A is inspections, B short stops, C change of coil, D cutting line, E change of material, F gripping tool, G miscellaneous and (b) the total downtime costs divided into a histogram.

5 DISCUSSION AND CONCLUSIONS

The authors have endeavored to illustrate here, by use of the concept of dynamic manufacturing how manufacturing costs can be used to describe the variability of a manufacturing process. Translating variability to costs serves to make it particularly evident how important it is to reduce variability.

In this work a TBF period is connected to the successive DT period. The authors are aware of the fact that there not always exist a clear relation between the TBF period and the DT period, a downtime can for example be caused by wear, starting many TBF periods before the downtime occur.

6 FURTHER WORK

Reduction in downtime can be carried out in two ways, either by reducing DT or by increasing TBF. In this paper the TBF is defined as the time between two successive downtimes. Further work will be focused on the time between failures of the same kind and investigate variables affecting this time.

7 ACKNOWLEDGEMENTS

This work has been carried out within the Sustainable Production Initiative.

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Paper 4

M. Jönsson, C. Andersson, and J.-E. Ståhl, “Implementation of an Economic Model to Simulate Manufacturing Costs,” *Proceedings of the 41st CIRP Conference on Manufacturing Systems*, pp. 39-44, 2008.

Implementation of an Economic Model to Simulate Manufacturing Costs

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Abstract

An economic model describing manufacturing costs is implemented within the frame of a case study. The implemented economic model is developed to enable analyses of the cost items and parameters influencing the cost of a part or a batch and also to make simulations for the purpose of investigating the economic outcome of future development activities. The aim of the case study was to identify activities in a production unit that could lead lower manufacturing costs by using the method described in this paper.

Keywords:
Manufacturing Economy; Cost Model; Economic Simulation

1 INTRODUCTION

The globalisation has influenced the manufacturing sector considerably; it has become more important than ever to constantly increase the productivity in the manufacturing plants to be able to meet the increasing competition, especially from companies in low-wage countries. Many companies deal with these circumstances by offshoring or by offshore outsourcing. These types of relocations are solely based on cost reductions, in contrast to relocations based on market aspects for the purposes of getting closer to a certain market for competitive reasons. But to relocate the manufacturing plants to low-wage countries doesn't have to be the only way out to maintain a high competitiveness for companies in countries with high wages. Focusing on the optimal production development regarding organizational issues and production technology can in many cases compensate the higher level of wage costs.

In order to make the right decisions concerning the offshoring based on cost reductions, it is necessary to be able to make correct analyses of the performance in the manufacturing plant from an economic point of view. One approach is to analyse the manufacturing costs of the products produced in the plant. Common methods to calculate the manufacturing costs are the traditional full costing methods and Activity-Based Costing (ABC). Traditional full costing is mostly used for cost-price calculations and is not an equally suitable method to use when seeking detailed and accurate information solely about the manufacturing costs, essentially because of the methods volume based approach. One of the main purposes behind the development of ABC was to in a more accurate way than traditional full costing allocate the overhead costs [1]. A lot of research has been done over the years since ABC was first introduced with the intention of implementing and analyzing the method, for example Thyssen, *et al*. [2].

The model presented in this paper is developed with the purpose of calculating and analysing the part cost associated with the manufacturing. The model has some similarities to ABC, for example when it comes to recognising the cost of unused capacity and the different types of parts individual consumption of the manufacturing resources. The main differences are that the model presented here only describes costs related to manufacturing. The focus of this model is to describe the relations between economy and manufacturing performance. Another difference is that this model allocates batch level activities to the unit level and also allocates cost of unused capacity to products.

Models describing the manufacturing cost can roughly be divided into a micro- and macroeconomic approach according to Tipnis, *et al*. [3]. The macroeconomic models are essentially based on aggregated information while the microeconomic models include process data like cut rate, gas flow, current intensity etc. For example Colding [4], [5], Alberti, *et al*. [6] and Knight and Poli [7] have all described microeconomic models while Groover [8] has described a macroeconomic model.

The model applied below can be described as a macroeconomic model. The applied model differs from the models presented in the previous section by the inclusion of all the production loss parameters; scrap rate, down time rate and production rate.

2 PURPOSE

The performance of a defined production unit that manufactures gearwheels will be analysed, using a manufacturing economic model described in section 6. The purpose was to identify activities in the production unit that can lead to lower manufacturing costs by using the method described in this paper.

3 METHOD

To be able to test the model in real a context a case study at a company was considered as the most appropriate choice of method. The case study was chosen to be limited to one section at the factory in order to make the data collection manageable from a practical perspective and it was also considered sufficient in order to to comply with the purpose of the study. The case study began with a careful study of the chosen production unit to get an understanding about its characteristics regarding the process and function. The accuracy of the economic data obtained by the cost model is dependent on the accuracy of the collected data. Therefore a systematic data collection was made regarding the scrapped parts, down time, production rate and the set up time.

4 SYSTEMATIC PRODUCTION ANALYSIS

The systematic data collection mentioned in section 3 was performed by implementing a method called Systematic Production Analysis (SPA) [9]. The method has been developed to determine the existing production condition. In this method the result parameters downtime rate, scrap rate and production rate are measured for each processing unit involved in the manufacturing of a specific product. The possible downtime, scrapped parts and loss in production rate are related to a factor found in one of the following factor groups: A Tool and tooling system; B Work piece material; C Manufacturing process and process data; D Personnel, organization and outer logistics; E Maintenance and wear tied to A, C, D and G; F Special process behavior/factors; G Surrounding equipment and inner logistics; H Unknown or unspecified factors

Table 1 shows a method of presenting a SPA. Q_1 to Q_n describe different quality deviations leading to scraped parts, where every Q has a separate column. Analogous to the quality parameters, S_1 to S_n describe different types of down time losses and P_1 to P_n describe different production rate deviations. The factor groups describe causes leading to the different result parameters. Every factor group contain individual factors, for example factors A_1 to A_n, where every individual factor has a separate row. After an implantation of this method, where every disturbance has been registered in the right place in the table, you can sum up the result for every row and column and then find critical result parameters and factors for the specific processing unit. This method makes it possible to directly get an indication towards which of the result parameters and which of the individual factors that causes losses in the production efficiency. Coupling this to economic parameters it is possible to determine the part cost under the influence of the result parameters. In section 6 it will be shown how these result parameters together with time and batch size parameters and also economic data build up the part cost in a specific processing step.

Table 1: Systematic production analysis.

	Result parameters			
Factor groups	$Q_1,..,Q_n$ (unit)	$S_1,...,S_n$ (min)	$P_1,...,P_n$ (min)	Σ
$A_1,...,A_n$				
$B_1,...,B_n$				
$C_1,...,C_n$				
$D_1,...,D_n$				
$E_1,...,E_n$				
$F_1,...,F_n$				
$G_1,...,G_n$				
H				
Σ				

5 LIST OF SYMBOLS

Table 2: List of symbols used in this paper. The economic parameters is described in the Swedish currency krona (kr).

Parameter	Description	Unit
t_0	Nominal cycle time per part	min
t_m	Machine time	min
t_h	Handling time	min
t_{vb}	Tool switch time	min
N_Q	Amount of scrap parts in a batch of *N* parts	unit
N	Total batch size, including scrap parts	unit
N_0	Amount of correct produced parts in a batch	unit
q_Q	Scrap rate	-
t_p	Production time per part	min
t_S	Average down time per part	min
q_S	Down time rate	-
q_P	Production rate	-
t_{0v}	Cycle time including production rate losses	min
T_{su0}	Nominal set up time	min
T_{su}	Set up time including deviations from nominal set up time	min
q_{Ssu}	Ratio between the nominal set up time T_{su0} and the real set up time T_{su}	-
k	Part cost	kr/unit
k_A	Tool cost	kr/unit
k_B	Material cost	kr/unit
k_{CP}	Equipment cost during production	kr/h
k_{CS}	Equipment cost during downtime and set up	kr/h
k_D	Wage cost	kr/h
x_p	Process development factor for the cycle time	-

x_{su}	Process development factor for set up time	-
κ_c	Equipment cost development factor	-
Δz	Change in an arbitrary variable z	-
k_{VA}	Value added part of the part cost	kr
k_{NVA}	Cost of non value added activities	kr
k_{Tsu}	Costs related to set up	kr
k_Q	Costs connected to the scrap rate	kr
k_S	Costs related to the down time rate	kr
k_P	Costs connected to the production rate	kr

6 ECONOMIC MODEL

The economic model is priviously described in [9]. In this section a summerized description is presented.

The nominal cycle time t_0 in a machine or a line is defined in equation 1, t_m is the machine time, t_h handling time and t_{vb} tool change time.

$$t_0 = t_m + t_h + t_{vb} \tag{1}$$

The scrap rate q_Q is defined in equation 2, where N_Q is the number of scrap parts, N is the batch size and N_0 the number of correct, non scrapped parts of the batch.

$$q_Q = \frac{N_Q}{N} = \frac{N - N_0}{N} \tag{2}$$

The down time rate q_S is defined in equation 3, where t_s is the down time per cycle and t_p the actual cycle time.

$$q_s = \frac{t_s}{t_p} = \frac{t_p - t_0}{t_p} \tag{3}$$

The production rate q_P describes the ratio between the nominal cycle time t_0 and the real cycle time t_v and is defined in equation 4.

$$q_P = 1 - \frac{t_0}{t_{0v}} \tag{4}$$

The downtime rate during set up q_{Ssu} describes the ratio between the nominal set up time T_{su0} and the real set up time T_{su}, see equation 5.

$$q_{Ssu} = 1 - \frac{T_{su0}}{T_{su}} \tag{5}$$

The production time for a batch including the setup time can then be defined as in equation 6:

$$T_{pb} = \frac{T_{su0}}{(1 - q_{Ssu})} + \frac{N \cdot t_0}{(1 - q_S)(1 - q_P)} \tag{6}$$

Reduced occupation in a manufacturing system leads to consequences for all manufactured parts. This situation can be considered in different ways, hence the free production resource can be considered both as an economic asset and a disadvantage depending on the situation. In a long term view the manufactured parts must carry the costs for the over capacity. The over capacity time can be distributed over all the batches in relation to their production time T_{pb} by introducing a degree of occupation U_{RP}, calculated as the quotient between real production time T_{prod} and planned production time T_{plan} according to according to equation 7 and 8. T_{free} is the time for the free, non occupied production time.

$$T_{plan} = T_{prod} + T_{free} \tag{7}$$

$$U_{RP} = \frac{T_{prod}}{T_{plan}} \tag{8}$$

The extra free capacity $T_{free,b}$ to be added to a specific batch is calculated according to equation 9. The free time can be considered as a setup time at the same time as the equipment is available for manufacturing:

$$T_{free,b} = \frac{1 - U_{RP}}{U_{RP}} T_{pb} \tag{9}$$

With these parameters together with economic data, the cost of production per part can be calculated. The economic parameters included in the model is the following :

- Tool cost k_A
- Material cost k_B
- Equipment cost during production k_{CP}
- Equipment cost during down time and set up k_{CS}
- Wage cost k_D

The cost of production per par can then be calculated using equation 10.

$$\begin{aligned}
k = {} & \frac{k_A \cdot N}{N \cdot (1 - q_Q) \cdot (1 - q_P)} + \frac{k_B \cdot N}{N \cdot (1 - q_Q)} + \\
& \frac{k_{CP} \cdot t_0 \cdot N}{60 \cdot N \cdot (1 - q_Q) \cdot (1 - q_P)} + \\
& \frac{k_{CS}}{60 \cdot N \cdot (1 - q_Q)} \cdot \frac{t_0 \cdot N}{(1 - q_P)} \cdot \frac{q_S}{(1 - q_S)} + \\
& \frac{k_{CS}}{60 \cdot N \cdot (1 - q_Q)} \left(\frac{T_{su0}}{(1 - q_{Ssu})} + \frac{1 - U_{RP}}{U_{RP}} T_{pb} \right) + \\
& \frac{k_D}{60 \cdot N \cdot (1 - q_Q)} \left(\frac{t_0 \cdot N}{(1 - q_S) \cdot (1 - q_P)} \right) + \\
& \frac{k_D}{60 \cdot N \cdot (1 - q_Q)} \left(\frac{T_{su0}}{(1 - q_{Ssu})} + \frac{1 - U_{RP}}{U_{RP}} T_{pb} \right)
\end{aligned} \tag{10}$$

To be able to simulate the effect of an improvement of the production process, a number of factors are introduced. The development factors are x_p, x_{su} and the cost factor κ_c, where x_p describe the improvement in cycle time that is achieved due to the development of the process. Likewise, x_{su} describes the improvement in set up time. κ_c is used to model changes in costs in primarily existing equipment, and can be used to determine the limit of investment justified to for example a decrease of the downtime rate to a certain value.

The manufacturing economic model including development and cost factors is described in equation 11.

$$
\begin{aligned}
k = {} & \frac{k_A \cdot N}{N \cdot (1-q_Q) \cdot (1-q_P)} + \frac{k_B \cdot N}{N \cdot (1-q_Q)} + \\
& \frac{\kappa_C \cdot k_{CP} \cdot x_P \cdot t_0 \cdot N}{60 \cdot N \cdot (1-q_Q) \cdot (1-q_P)} + \\
& \frac{\kappa_C \cdot k_{CS}}{60 \cdot N \cdot (1-q_Q)} \cdot \frac{x_P \cdot t_0 \cdot N}{(1-q_P)} \cdot \frac{q_S}{(1-q_S)} + \\
& \frac{\kappa_C \cdot k_{CS}}{60 \cdot N \cdot (1-q_Q)} \left(\frac{x_{su} \cdot T_{su0}}{(1-q_{Ssu})} + \frac{1-U_{RP}}{U_{RP}} T_{pb} \right) + \\
& \frac{k_D}{60 \cdot N \cdot (1-q_Q)} \left(\frac{x_P \cdot t_0 \cdot N}{(1-q_S) \cdot (1-q_P)} \right) + \\
& \frac{k_D}{60 \cdot N \cdot (1-q_Q)} \left(\frac{x_{su} \cdot T_{su0}}{(1-q_{Ssu})} + \frac{1-U_{RP}}{U_{RP}} T_{pb} \right)
\end{aligned}
\qquad (11)
$$

Changes in part cost caused by a limited change in an arbitrary variable *z*, is calculated by partial derivative, and is described in linear form in equation 12.

$$\Delta k_i = \frac{\partial k_n}{\partial z} \cdot \Delta z \qquad (12)$$

Cost neutral changes in each variable can be studied by putting the change in part costs $\Delta k_i = 0$. Equation 12 is written in a cost neutral form in equation 13, describing the size of the reduction in downtime share required to compensate for a change in wage costs.

$$\Delta q_{Si} = -\Delta k_{Di} \cdot \frac{\dfrac{\partial k_i}{\partial k_{Di}}}{\dfrac{\partial k_i}{\partial q_{Si}}} \qquad (13)$$

7 THE CASE STUDY

The implementation of the method SPA resulted in data connected to a number of products produced at the factory at the choosen manufacturing unit. This paper will present an analysis of one of these products, called product x. Besides as an analysis of this product, this case study presentation also can be viewed as an example of how you can apply the cost model described in equation 11, when an SPA has been made and other necessary production data is available.

From the data collection phase of the case study, including a systematic registration of scrap, down time and production rate according to the method described in section 4, the values of the parameters in equation 10 was obtained and is presented in Table 3. In this case study the cost of reduced occupation has not been considered and there is no data for the deviation from the nominal set up time for this product. Inserting the values of the parameters in Table 3 into equation 10, the cost of production per part *k* equals 386,8 kr, which implies that this processing step adds 144,27 kr to the cost of the product.

Table 3 : Calculated values of the parameters in the economic model

q_Q	q_S	q_P	q_{Ssu}	T_{su0}	t_0
0.0230	0.4273	0	0	120	7.2
N_0	k_A	k_B	k_{CP}	k_{CS}	k_D
1000	13.7	242.53	420	420	150

During the analysis of the collected data, new ways to present the costs was developed. This was done by starting out from equation 10 and then divide the cost *k* into the different parts that add costs in the chosen processing step. The chart in Figure 1 below shows the part cost *k* together with k_B and these new cost items; k_{VA}, k_{NVA} k_{Tsu}, k_Q, k_S, and k_P, where *k* equals the sum of k_B, k_{VA}, k_{NVA} and k_{Tsu}, see equation 14.

$$k = k_B + k_{VA} + k_{NVA} + k_{Tsu} \qquad (14)$$

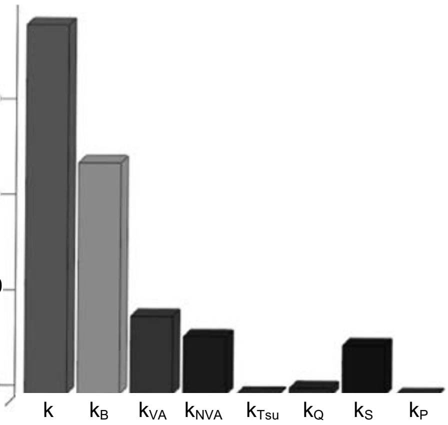

Figure 1: The part cost *k* and different parts of *k*.

k_{VA} is the value added part of the cost and is defined in equation 15. k_{VA} describes the cost added in this processing step, without considering q_Q, q_S, q_P and T_{su}.

$$k_{VA} = k_A + (k_{CP} + k_D) \cdot t_0 \qquad (15)$$

k_{NVA} is the cost of non value added activities and constitutes of all costs related to the loss parameters q_Q, q_S and q_P, and is defined in equation 16.

$$k_{NVA} = k_Q + k_S + k_P \qquad (16)$$

k_{Tsu} constitutes of the costs related to set up and is defined in equation 17.

$$k_{Tsu} = \frac{k_{CS} + k_D}{60 \cdot N \cdot (1-q_Q)} \cdot \frac{T_{su0}}{(1-q_{Ssu})} \qquad (17)$$

By dividing the part cost *k* into k_B, k_{VA}, k_{NVA} and k_{Tsu} you get a quick overview of the cost condition of the product. The size of k_{NVA} indicates the potential cost reduction by decreasing the disturbances in the production. k_{NVA} make up 42.3 % of the total cost added in this processing step, or 61.0 kr per part. Correspondingly, k_{VA} make up 56.9 % of the total cost added, or 82.1 kr expressed in cost per part. k_{Tsu} is calculated to 1.2 kr per part. The combination of a large batch size and a long cycle time makes k_{Tsu} relatively insignificant regarding the part cost of product x at this chosen processing step.

A division of k_{NVA} can be made into k_Q, k_S and k_P, with the purpose to find out the specific costs contributed by each result parameter q_Q, q_S, q_P. k_Q describes the costs connected to the scrap rate q_Q and is defined in equation 18.

$$k_Q = \frac{N \cdot q_Q}{N \cdot (1-q_Q)} \cdot \left(k_A + k_B + \frac{k_{CP} \cdot t_0}{60} + \frac{k_D \cdot t_0}{60} \right) \tag{18}$$

The largest part of k_{NVA} consists in this case of costs related to the down time rate q_S. This cost is named k_S and is defined in equation 19. k_S was calculated to 52.7 kr per part and constitutes 86.3 % of k_{NVA}.

$$k_S = \frac{k_{CS} \cdot t_0 \cdot N \cdot q_S}{60 \cdot N \cdot (1-q_Q) \cdot (1-q_S) \cdot (1-q_P)} + \frac{k_D \cdot t_0 \cdot N \cdot q_S}{60 \cdot N \cdot (1-q_Q) \cdot (1-q_S) \cdot (1-q_P)} \tag{19}$$

k_P describes the costs caused by q_P and is defined in equation 20 and was calculated to 0.7 kr per part.

$$k_P = \frac{k_A \cdot N \cdot q_P}{N \cdot (1-q_Q) \cdot (1-q_P)} + \frac{k_{CP} \cdot t_0 \cdot N \cdot q_P}{60 \cdot N \cdot (1-q_Q) \cdot (1-q_P)} + \frac{k_D \cdot t_0 \cdot N \cdot q_P}{60 \cdot N \cdot (1-q_Q) \cdot (1-q_P)} \tag{20}$$

The size of k_{NVA} for this product at this production unit implies that there is a substantial amount of money to be saved if k_{NVA} can be reduced, if the total annual volume of the product is considered. The annual volume of product x is estimated to 9300 units by the company. If assuming that the value of k_{NVA} is intact over a year, the theoretical cost reduction becomes roughly: $k_{NVA} \cdot 9300 = 61 \cdot 9300 = 567300$ kr.

To reduce k_{NVA} you have to know the result parameters and the factors connected to these parameters that together constituting the value of k_{NVA}. When combining the result from the SPA and the parameters calculated from this data, it will be possible to obtain the influence on the manufacturing cost of every result parameter and factor registered in the SPA. In Figure 2 the factors having the largest effect on the part cost of product x as a result of the performed SPA are shown as their cost per part. The figure illustrates that apart from the tool factor A2, the major factors behind the size of k_{NVA} are related to the process C and organizational issues D.

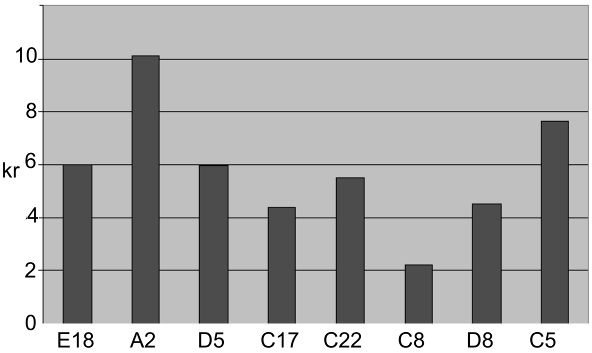

Figure 2: The factors having the largest effect on the part cost of product x

After quantifying the cost of the production disturbances and the factors in the different units or cells of the manufacturing plant, it will be possible to compare different disturbances influence of the manufacturing cost and thereby for example be able to make priorities between different development projects concerning the manufacturing process.

At this stage, when the critical parameters and factors connected these losses are obtained and economically quantified, then cost derivatives can be used to analyse different development scenarios. Figure 3 illustrate the cost neutral relationship between a change in the development factor $\Delta\kappa_C$ and a change in downtime rate Δq_S for product x. The figure shows for example that if the down time rate can decrease by 0.15, you get $\Delta\kappa_C$ to 0.35. This means that the equipment costs, k_{CS} and k_{CP}, can be increased by up to 35 % without increasing the part cost if the decrease in q_S can be accomplished.

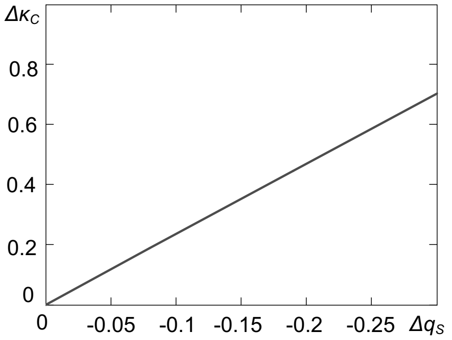

Figure 3: Cost neutral change between an increase in equipment cost factor $\Delta\kappa_C$ and reduction of down time rate Δq_S.

As Figure 2 illustrates, the largest cost factor for product x is A2, which is a factor connected to the tools in the machine. Figure 4 shows the cost neutral relationship for product x between an increase of the tool cost Δk_A and a decrease of the process development factor Δx_P. This relationship illustrates the maximum cost increase of improved tooling capable of reducing the cycle time to a certain level. The dotted graph shows the relationship when new but more expensive tools enables a decrease in x_P, but at the same time causes an estimated increase in the scrap rate q_Q by 0.01. The continuous graph shows the relationship without any increase in q_Q.

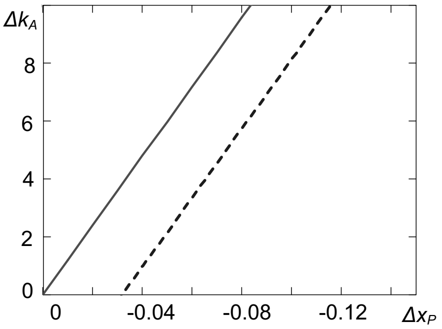

Figure 4: Cost neutral changes between an increase in tool cost Δk_A and reduction of the development factor Δx_P (continuous graph) and an increase in Δk_A plus a 0.01 increase of q_Q and a reduction of Δx_P (dotted graph).

This analysis is made for a single product in a processing step where several other products is produced. These other products and the costs connected to them must of course be taken into consideration to get a general picture of the costs in this processing step.

8 DISCUSSION AND CONCLUSIONS

To sum up the analysis described in the previous section, the high value of q_S is making a significant impact on the manufacturing cost of this product at this processing step. This case study shows that there is a potential in analysing the manufacturing performance of today and alternative simulated scenarios with the method described in this paper. An important prerequisite for these analyses to be reliable is the accuracy of the input data and how detailed this data is. If the model is implemented at every unit or cell at a factory it will then be possible to obtain which cost items that builds up the total manufacturing cost of a part or a group of parts and size of these items. Figure 5 shows the division of the part cost k made in section 7. This division makes it easy to get a clear view of the costs added in a processing step. Having this detailed information accessible for products in all processing steps would enabeling a greater insight and understanding about where in the manufacturing process there is the highest potential to lower the costs and thereby function as a basis for prioritys concerning production development activities.

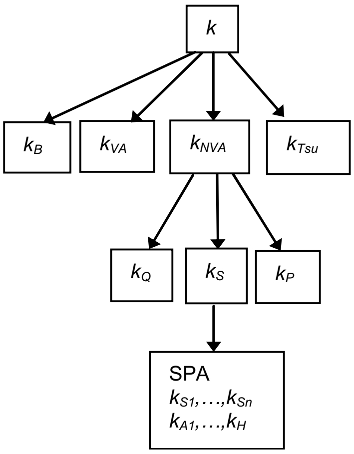

Figure 5: The division of k made in the presented case study analysis.

By combining production data and economic data into this economic model it is also possible to establish manufacturing economic development goals. A development goal could for example be to reduce the cost of manufacturing per part with 10 % for a product or a group of products. By the implementation of this model a plan to reach that goal could be established.

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Paper 5

M. Jönsson, C. Andersson, and J.-E. Ståhl, “Conditions for and development of an IT-support tool for manufacturing costs calculations and analyses,” Under 2nd review at *International Journal of Computer Integrated Manufacturing*.

Conditions for and development of an IT-support tool for manufacturing costs calculations and analyses

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Abstract

Collecting data on manufacturing performance and making the results known to those involved could support efforts to improve manufacturing processes. This paper describes the conditions for and development of manufacturing cost software developed for analyzing connections between manufacturing performance parameters and economic parameters. The conditions for the software were investigated in two pre-studies. The first found that there are commercial software products for manufacturing data collection that support the collection of the data needed for the applied model. The second study demonstrated that the manufacturing companies participating in the second study were largely able to collect the needed data. The developed software, preliminary in character and needing further development, provides information on how the manufacturing performance of a company affects its manufacturing costs. It takes account of six categories of manufacturing cost. A what-if section is included, making it possible to alter the values of various parameters that affect costs in order to analyze how the part cost of a certain component changes with the use of new parameter values compared with historic values.

Keywords: cost analysis, cost improvement, performance measures, manufacturing management

1. Introduction

Staying competitive in a global market is a necessity for any manufacturing company today. Success in doing so is strongly dependent on the ability to develop innovative products and to design flexible and optimally performing manufacturing systems. A manufacturing system represents a highly complex system consisting of a variety of components, such as machines, tools, material-handling equipment, control systems, and operators. The management and improvement of such complexity requires true and relevant data on the performance and outcome of the system and its individual components. A widely used performance measure in the manufacturing industry is overall equipment effectiveness (OEE), originally introduced by Nakajima (1988). The monitoring of OEE often involves the use of data collection software of some sort for collecting data and calculating performance in terms of, for example, quality rate, equipment availability, and equipment utilization.

The challenges of global competition for manufacturing companies require that they increase their cost awareness. Differences in wage levels between various parts of the world have led many companies in the western world to turn to offshore production or to outsource their production to countries with lower wage levels. Such relocation is inevitable in the case of, for example, non-complex products with low value added or when striving for new market shares. However, outsourcing might not have been done to the extent it was in the early 00s if a complete set of factors (not only wage costs) influencing the total manufacturing cost had been considered. In fact, factories paying fairly high wages can be competitive, through using appropriate manufacturing strategy and by excelling in productivity and performance. Production development with high cost awareness can provide opportunities to set appropriate priorities regarding the development activities having the largest impact on cost efficiency. This requires correct information about all the parameters that drive costs in the production system.

There is a lack of adequate cost models describing the links between performance parameters and the manufacturing costs involved. Most cost models presented in the literature contain too little detail regarding the parameters that affect various manufacturing costs. There are however exceptions, for example the models by Son (1991), Chiadamrong (2003), and Yamashina and Kubo (2002) are quite comprehensive, but they lack a clear link to performance parameters. Also the practical aspects of these models are not considered, i.e. the conditions for industrial implementation of the models and how the models should be used by the practitioner in the industry.

The authors of this paper have developed a cost model (2008a,b) that links production performance parameters with economic parameters, enabling detailed analysis of the manufacturing costs of specific parts or products. The model is intended for use by plant management as a tool for strategic decisions regarding priorities for manufacturing development action, production sourcing and to generally increase the cost awareness in the manufacturing department of a company.

2. Research questions and method design

As stated above there are detailed cost models in the literature, but practical aspects regarding usability are often treaded rather briefly. A cost model indented to be used in the industry is of limited value if it is not practicably usable. It was therefore considered necessary to take account of these aspects, i.e. to investigate the conditions for implementing the cost model (2008a,b) in an industrial environment.

Implementation encompasses two important aspects: availability of input data for the cost model and how the model should be implemented. This paper addresses both issues by investigating whether the needed input data can be collected from existing company databases. Using a detailed manufacturing cost model to analyze manufacturing costs makes considerable demands of the data collection systems in place and of company data collection routines, in order to provide the analysis with correct information about the manufacturing process being analyzed.

The paper also addresses the design of the manufacturing cost software to meet requirements for usability, result visualization, and simulation capability. The aim of this research can be formulated in two research questions:

- RQ1: What are the conditions for a successful industrial implementation of the cost model in terms of the functionality of data collection systems available on the market, and to what extent do companies already collect the needed data?
- RQ2: What are the specific requirements for user-friendliness for an industrial implementation of the cost model, what analysis and simulation capabilities should be provided for the user, and how should the results be presented and visualized?

To answer the first question, we reviewed various commercial data collection systems concerning their support for collecting the required data. A case study involving five companies was also performed to consider the extent to which these data were collected at the studied companies. These pre-studies were conducted by means of interviews and by examining the systems in place.

To answer the second question, we performed a case study to develop a manufacturing cost software application together with one of the manufacturing companies participating in the pre-study. According to Yin (2006) case studies enable phenomena to be studied in their real-world contexts, and it was precisely the real-world context we wanted to consider by the above stated research questions. It was therefore decided that the best way to find out how such a software application should be designed was to develop one, and to do so in collaboration with a company that was an intended user of the software. The advantages with incorporating prototype development in the research process is for example discussed by Nunamaker et al. (1991), which argue that a prototype can both constitute a proof of a concept and also form a base for continued research.

3. Frame of reference

A performance measurement system (PMS) is defined by Neely et al. (1995) as a 'set of metrics used to quantify both the efficiency and effectiveness of actions'. Despite an extensive PMS literature related to manufacturing extending many decades back, there has been a marked increase in publications in this field over the last 20 years (Neely 2005). According to Ghalayini and Noble (1996), the PMS literature can be divided into two main phases, the first extending from the 1880s to the early 1990s and the second, or current phase, covering the period since then. In the first phase, financial measures were emphasized. In the current phase, considerable emphasis is placed on the shortcomings of traditional financial measures; the use of non-financial measures is advocated, although there is no clear consensus among authors as to which non-financial measures companies should select.

Neely et al. (1995), in reviewing the PMS literature, distinguish four dimensions of performance measures, those of quality, time, flexibility, and cost. These four dimensions describe what these authors found that the literature regarded as the most important dimensions in defining manufacturing performance. White (1996), in his survey of performance measures, proposes a similar division, but his also includes, along with the four dimensions just referred to, delivery reliability as a major dimension. White classifies these five dimensions as competitive capability, and adds four additional dimensions that describe various aspects of the measures, such as data source and type, as shown in Table 1.

Table 1. White's (1996) five dimensions of a PMS.

Competitive capability	**Data type**
Cost	Subjective
Quality	Objective
Flexibility	**Reference**
Delivery reliability	Benchmark
Speed	Self-referenced
Data source	**Orientation**
Internal	Process input
External	Process outcome

White concludes that most measures used by companies are internal, objective, and self-referenced, and have a process–outcome orientation. At the same time, he argues for the importance of companies' also obtaining externally based, subjective, benchmark, and process input-oriented measures and of not simply focusing on cost capabilities, as many companies have traditionally done.

Arguing as White does for multidimensional measures is common in the second phase of PMS research. Gomes et al. (2004), in their review of the PMS literature, have constructed a five-phase framework for the evolution of PMS. The framework they advocate suggests that development is headed towards multidimensional, balanced, and integrated measures, as well as towards acceptance of the importance of non-financial measures and of the connection between these measures and company strategy.

One measure that manufacturing companies commonly employ is OEE. Nevertheless, the PMS literature seldom treats this measure, possibly because of the previously described emphasis on multidimensional measures in the PMS literature. OEE focuses on what Nakajima (1988) calls the ‘six big losses’ due to equipment failure, required setup time, idling and minor stops, reduced speed, quality defects, and reduced yield. As can be seen, OEE measures the performance of equipment on the shop floor. OEE is calculated by multiplying the availability rate, *A*, by performance efficiency, *P*, and quality rate, *Q*. These rates are defined in equations (1) to (4) below.

$$Q = \frac{\text{processed amount} - \text{defect amount}}{\text{processed amount}} \tag{1}$$

$$A = \frac{\text{operating time}}{\text{loading time}} \tag{2}$$

$$\text{operating time} = \text{loading time} - \text{unplanned downtime} \tag{3}$$

Loading time is the total production time minus planned downtimes, such as planned maintenance and morning meetings. Unplanned downtimes involve downtimes resulting, for example, from failures, setup times, and time for die exchange.

$$P = \frac{\text{processed amount} \cdot \text{ideal cycle time}}{\text{operating time}} \tag{4}$$

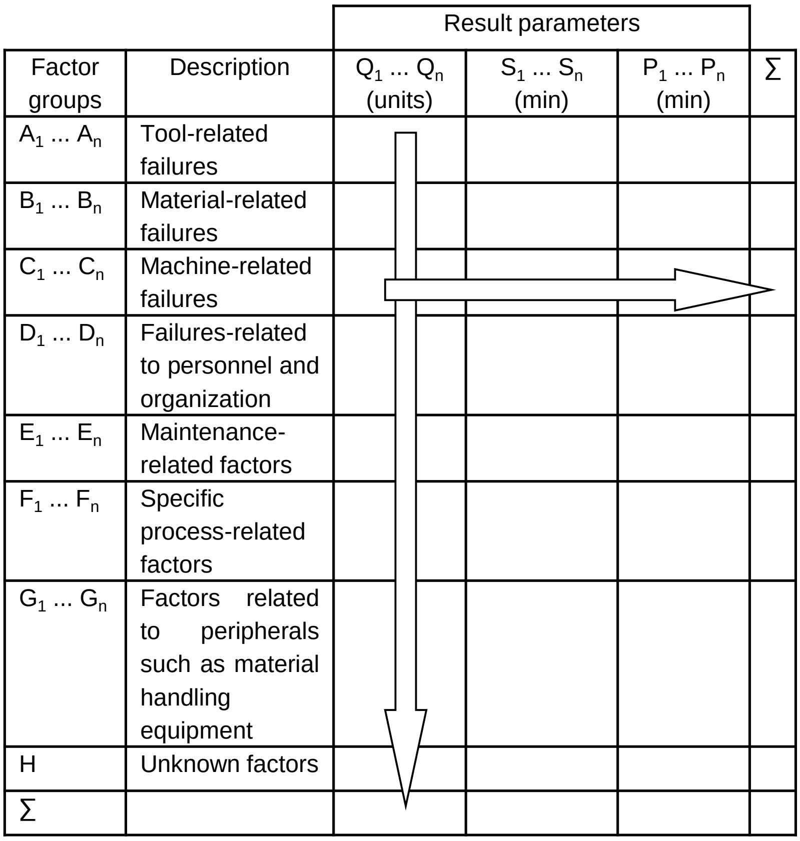
Using White’s categorization as shown in Table 1, OEE then measures various aspects of quality, flexibility, and speed. OEE is also internal, objective, and self-referenced and measures process outcome. It fails, however, to use all the proposed dimensions of a measurement system and needs to be complemented with additional measures, as has also been noted by Jonsson and Lesshammar (1999). Another shortcoming of OEE is that it measures only the performance of individual pieces of equipment as such, failing to take account of the linkages between various machines and the flow of materials within the manufacturing system. This shortcoming of OEE has been identified by Jonsson and Lesshammar (1999), Muchiri and Pintelon (2008), and Muthia and Huang (2007). Muthia and Huang (2007) propose a solution to the insufficiency of measuring pieces of equipment individually, introducing the term overall throughput effectiveness (OTE). OTE is based on OEE and can be described as a factory-level version of OEE that takes the dependability of equipment into account. OTE is expressed in four ways, depending on the characteristics of the machine layout, such as whether they function in series or parallel.

In their review of the OEE literature, Muchiri and Pintelon (2008) consider various suggested modifications of OEE, all of which attempt to overcome its various insufficiencies. The modified measures include production equipment effectiveness (PEE), overall asset effectiveness (OAE), overall plant effectiveness (OPE), and OTE. Muchiri and Pintelon (2008) believe that the absence of a cost dimension is a serious shortcoming of OEE and that future research should explore the translation of equipment effectiveness into costs. They also believe that future research should investigate the benefits of investing in automated data collection systems to gather the data needed for OEE calculations.

As stated in the introduction chapter there is a lack of manufacturing cost models which link performance parameters with costs. Some of the cost models found in the literature are based on activity based costing (ABC), for example the models by Özbayrak (2004) and Koltai et al. (2002). ABC models have a tendency on focusing on correct ways to handle overhead costs and not on how the performance of the manufacturing system affects the cost. There are also manufacturing cost models not based on ABC, for example the models by Dhavale (1990), Cauchick-Miguel and Coppini (1996), Branker et al. (2011). The first two focus on the same aspects as ABC models commonly do, i.e. allocation of overhead costs. The model by Branker has a clear focus on environmental costs. The three models mentioned in the introduction chapter, i.e. the models by Son (1991), Chiadamrong (2003), and Yamashina and Kubo (2002) include costs related to performance, but not as integrated as the model by Jönsson et al. (2008a,b) in which the performance losses are formulated as rates. Additionally, these three models describe the cost only as a period cost, not how the cost of the various products are built up in the processing steps they undergoes.

4. Cost model and data collection method

The cost model to be considered represents the further development of a method for production data collection and analysis described in detail by Ståhl (2010) and depicted in Figure 1. The aim of this data collection method is to enable the connections between a specific production performance parameter (scrap rate, downtime rate, or production-rate loss) and the factors affecting it to be studied. The factor groups A to H in the figure represent the causes of the disturbances involved, the Q parameters various quality deviations, the S parameters downtimes of various types, and the P parameters speed losses of various types. Converting the Q parameters to loss of time allows sums to be obtained both for separate rows and columns and for the rows and columns taken together. Collecting the manufacturing input data for the cost analysis software in accordance with this enables the various considered parameters and factors to be compared in terms of their impact on manufacturing cost per part produced. This makes it possible to assign appropriate priorities, based on their effects on cost, to the various improvement measures that can be undertaken.



Factor groups	Description	Result parameters			
		Q_1 ... Q_n (units)	S_1 ... S_n (min)	P_1 ... P_n (min)	Σ
A_1 ... A_n	Tool-related failures				
B_1 ... B_n	Material-related failures				
C_1 ... C_n	Machine-related failures				
D_1 ... D_n	Failures-related to personnel and organization				
E_1 ... E_n	Maintenance-related factors				
F_1 ... F_n	Specific process-related factors				
G_1 ... G_n	Factors related to peripherals such as material handling equipment				
H	Unknown factors				
Σ					

Figure 1. An overview of the factor- and result-based principles involved in the data collection procedures.

4.1. Cost model

The developed cost model (Jönsson 2008a,b) takes account both of production performance parameters corresponding to those included in OEE and of cost-related parameters such as material, equipment, and wage costs. The results of the calculations are expressed in USD/part. Equation 5 is the version of the model used in the developed software. Because of the specific configurations of individual manufacturing systems, it is impossible to develop a completely general model, so the model presented in equation 5 could need modification from case to case. Compared with the versions included in Jönsson *et al.* (2008a,b), equation 5 illustrates how the model is to be used in cases involving more than one processing step. Index i describes the various processing steps; if $i = 1$, then $k_{i-1} = k_B$. k_B being the material cost (USD /unit).

$$
\begin{aligned}
k_i &= k_{i-1} + \frac{k_{i-1}\cdot q_{Q_i}}{(1-q_{Q_i})} + \frac{k_{CP_i}}{60}\cdot\frac{t_{0_i}}{(1-q_{Q_i})\cdot(1-q_{P_i})} + \\
&\frac{k_{CS_i}}{60}\cdot\left(\frac{t_{0_i}}{(1-q_{Q_i})\cdot(1-q_{P_i})}\cdot\frac{q_{S_i}}{(1-q_{S_i})}\right) + \\
&\frac{k_{CS_i}}{60}\cdot\left(\frac{T_{su_i}}{N_{i-1}\cdot(1-q_{Q_i})} + \frac{1-U_{RP_i}}{U_{RP_i}}\,\frac{T_{pb_i}}{N_{i-1}\cdot(1-q_{Q_i})}\right) + \\
&\frac{k_{D_i}}{60}\cdot\left(\frac{t_{0_i}}{(1-q_{Q_i})\cdot(1-q_{S_i})\cdot(1-q_{P_i})} + \frac{T_{su_i}}{N_{i-1}\cdot(1-q_{Q_i})}\right)
\end{aligned}
\tag{5}
$$

The parameters in equation 5 are described in Table 2.

Table 2. Description of the parameters in equation 5.

Parameter	Description	Parameter	Description
k (USD /unit)	Cost per part	T_{pb} (min)	Production time for a batch
k_{CP} (USD /h)	Hourly machine cost during production	T_{su} (min)	Setup time
k_{CS} (USD /h)	Machine cost during downtimes, setup times, and idle times	q_Q (-)	Quality losses due to scrapped parts
k_D (USD /h)	Wage cost	q_S (-)	Downtime losses
N (units)	Batch size	q_P (-)	Production-rate losses
t_0 (min)	Nominal cycle time		

Costs k_{CP}, k_{CS}, and k_D are expressed in cost per hour and t_0, T_{su}, and T_{pb} are expressed in minutes, hence the division by 60 in equation 5 and in some of the equations described below.

Equation 6 concerns the expression for the scrap rate, q_Q where N_Q is the number of scrapped parts in processing step i and N_i is the batch size for processing step i excluding scrapped parts, i.e. the number of correctly manufactured units in step i.

$$q_{Q_i} = \frac{N_{Q_i}}{N_{i-1}} = \frac{N_{i-1} - N_i}{N_{i-1}} \tag{6}$$

The downtime rate in processing step i, q_S, is represented in equation 7, where t_s is the downtime per part and t_p is the total cycle time, including downtime, i.e. t_0 plus t_s.

$$q_{S_i} = \frac{t_{s_i}}{t_{p_i}} = \frac{t_{p_i} - t_{0_i}}{t_{p_i}} \tag{7}$$

Production-rate loss, q_P, denotes speed losses due to such factors as machine instabilities. Equation 8 represents q_P where t_{0v} is the nominal cycle time in processing step i plus any extra time caused by speed losses.

$$q_{P_i} = \frac{t_{0v_i} - t_{0_i}}{t_{0v_i}} \tag{8}$$

Machine utilization, U_{RP}, can be dealt with in various ways, although the authors maintain that long-term free capacity should be considered a cost. Equation 9 represents the expression for U_{RP} where T_{plan} is the planned production time in step i and T_{prod} is the actual production time in step i.

$$U_{RP_i} = \frac{T_{prod_i}}{T_{plan_i}} \tag{9}$$

In the part cost equation, the cost of free capacity is distributed over the parts produced in relation to the production time for the batch, T_{pb}. T_{pb} is described in equation 10.

$$T_{pb_i} = T_{su_i} + \frac{N_{i-1} \cdot t_{0_i}}{(1 - q_{S_i}) \cdot (1 - q_{P_i})} \tag{10}$$

The value-added cost per part is represented in equation 11. The value-added cost of a part is its ideal cost, i.e. the cost of doing things right without any non-value-added costs such as downtimes or scrapped parts.

$$k_{VA_i} = \frac{\left(k_{CP_i} + k_{D_i}\right)}{60} \cdot t_{0_i} \tag{11}$$

The scrap cost per part is defined in equation 12.

$$k_{Q_i} = \left(k_{i-1} + \frac{k_{CP_i} \cdot t_{0_i}}{60} + \frac{k_{D_i} \cdot t_{0_i}}{60} \right) \cdot \frac{q_{Q_i}}{(1 - q_{Q_i})} \tag{12}$$

The downtime cost per part is defined in equation 13.

$$k_{S_i} = \left(\frac{k_{CS_i}}{60} + \frac{k_{D_i}}{60} \right) \cdot \frac{t_{0_i} \cdot q_{S_i}}{(1 - q_{Q_i}) \cdot (1 - q_{S_i}) \cdot (1 - q_{P_i})} \tag{13}$$

Equation 14 describes the production-rate loss cost per part.

$$k_{P_i} = \left(\frac{k_{CP_i}}{60} + \frac{k_{D_i}}{60} \right) \cdot \frac{t_{0_i} \cdot q_{P_i}}{(1 - q_{Q_i}) \cdot (1 - q_{P_i})} \tag{14}$$

Equation 15 describes the setup cost per part.

$$k_{Tsu_i} = \left(\frac{k_{CS_i}}{60} + \frac{k_{D_i}}{60} \right) \cdot \frac{T_{su_i}}{N_{i-1} \cdot (1 - q_{Q_i})} \tag{15}$$

4.2. Additional cost expressions

The cost software described in section 7 also takes account of cost expressions based on equation 5 but not described in Jönsson *et al.* (2008a,b). Except for equation 16, these cost expressions was developed for the process cost sheet in the software application, see section 7.4.

The machine utilization cost per part is represented in equation 16.

$$k_{U_i} = \frac{K_{CS_i}}{60} \cdot \frac{1 - U_{RP_i}}{U_{RP_i}} \cdot \frac{T_{pb_i}}{N_{i-1} \cdot (1 - q_{Q_i})} \tag{16}$$

Equations 17 to 22 describe similar cost expressions as do equations 11 to 16, the difference being that these equations describe the manufacturing costs linked to the machines involved instead of to the products. These cost expressions are divided by the batch time, T_{pb}, and consequently describe the cost per hour. The value-added cost per hour linked to a machine is represented in equation 17.

$$K_{VA_i} = \frac{\dfrac{k_{CP_i} + k_{D_i}}{60} \cdot \left(t_{0_i} \cdot N_i\right)}{T_{pb_i} \cdot \dfrac{1}{60}} \tag{17}$$

The scrap cost per hour linked to a machine is represented in equation 18.

$$K_{Q_i} = \frac{k_{i-1} \cdot \left(N_{i-1} \cdot q_{Q_i}\right) + \frac{k_{CP_i}}{60} \cdot \left(t_{0_i} \cdot N_{i-1} \cdot q_{Q_i}\right) + \frac{k_{D_i}}{60} \cdot \left(t_{0_i} \cdot N_{i-1} \cdot q_{Q_i}\right)}{T_{pb_i} \cdot \frac{1}{60}} \tag{18}$$

The downtime cost per hour linked to a machine is represented in equation 19.

$$K_{S_i} = \frac{\frac{k_{CS_i}}{60} \cdot \left(\frac{t_{0_i} \cdot N_{i-1} \cdot q_{S_i}}{(1-q_{P_i}) \cdot (1-q_{S_i})} \right) + \frac{k_{D_i}}{60} \cdot \left(\frac{t_{0_i} \cdot N_{i-1} \cdot q_{S_i}}{(1-q_{P_i}) \cdot (1-q_{S_i})} \right)}{T_{pb_i} \cdot \frac{1}{60}} \tag{19}$$

The production-rate loss per hour linked to a machine is not used in the cost software, but can be defined according to equation 20.

$$K_{P_i} = \frac{\frac{k_{CP_i} \cdot t_{0_i} \cdot N_{i-1} \cdot q_{P_i}}{60 \cdot (1-q_{P_i})} + \frac{k_{D_i} \cdot t_{0_i} \cdot N_{i-1} \cdot q_{P_i}}{60 \cdot (1-q_{P_i})}}{T_{pb_i} \cdot \frac{1}{60}} \tag{20}$$

The setup cost per hour linked to a machine is represented in equation 21.

$$K_{Tsu_i} = \frac{\frac{k_{CS_i} + k_{D_i}}{60} \cdot T_{su_i}}{T_{pb_i} \cdot \frac{1}{60}} \tag{21}$$

The utilization cost per hour linked to a machine is represented in equation 22.

$$K_{U_i} = \frac{\frac{k_{CS_i}}{60} \cdot \left(\frac{1-U_{RP_i}}{U_{RP_i}} \cdot \left(T_{su_i} + \frac{t_{0_i} \cdot N_{i-1}}{(1-q_{P_i}) \cdot (1-q_{S_i})} \right) \right)}{T_{pb_i} \cdot \frac{1}{60}} \tag{22}$$

Although OEE is an equipment performance ratio with a value of between 0 and 1 and the cost model describes the manufacturing costs per part, similarities between the two make more precise comparison of them relevant. Both OEE and the cost model describe the performance of the equipment using similar parameters. The definitions of quality rate, Q, availability rate, A, and performance efficiency, P, in OEE bear obvious similarities to those of scrap rate, q_Q, downtime rate, q_S, and production-rate loss, q_P, respectively. Q is identical to $1\text{-}q_Q$ and P is identical to $1\text{-}q_P$, except for the inclusion of minor stops in P. A is close to being identical to $1\text{-}q_S$, the difference between the two being the inclusion of setup times in A. Availability, A, includes setup time as a non-planned downtime, which is the separate parameter T_{su} in the cost model and is thus not included in q_S.

If White’s criteria for PMS are applied, the cost model provides the same results as OEE does, except that the cost model also measures to some extent the cost component in terms of the part cost, k. It measures quality by q_Q, flexibility by T_{su} and speed by q_P. The cost model describes various important performance aspects of the manufacturing processes involved, yet the model presented here does not aim to encompass the entire range of parameters contained in a full PMS. It needs to be complemented with additional measures, reflecting other matters pertaining to the company, to provide a complete PMS in accordance with White's criteria.

5. A study of systems for collecting manufacturing data

Two pre-studies were carried out before the cost software was developed to investigate the conditions for an industrial implementation of the cost model. In the first of them, four commercial software products for data collection were reviewed to determine the extent to which these support the collection of the required data. The data required for the cost model can be divided into manufacturing and economic data. The review considers only the manufacturing data, which are related to the performance of the manufacturing system and must constantly be collected. The economic data are not considered equally critical, because they are more fixed and hence constitute a small amount of the required data. The manufacturing-related data are commonly collected either by a manufacturing data collection module in an enterprise resource planning (ERP) system or by a stand-alone software product for manufacturing data collection (or in some cases only with pen and paper). These types of data collection systems will from now on be referred to as manufacturing data collection systems (MDCS). The following section will describe the manufacturing data required for the cost model. These requirements were used in reviewing the MDCS.

5.1. Required manufacturing data input

The manufacturing data needed to calculate the manufacturing part costs using the developed cost model will be described in this section.

Data are needed regarding the various *types* (result parameters) and *causes* (factors) of losses due to scrapped parts, downtimes, and production-rate losses. The system should include both result parameters and the factors that cause them, to yield a detailed account of production results.

Scrap rate, q_Q: It should be possible to register scrapped parts and to calculate the scrap rates connected to the machines, product and order numbers involved for a specific time range.

Downtime rate, q_S: It should be possible to register all the downtimes occurring during production. A division between planned and unplanned downtimes should be possible. The data should be connected with a specific machine, order number, product number, and date in each case. A system for automatic registration of downtimes is desirable, since this obviates the necessity of the operator to recall the lengths of the downtimes and makes the data more accurate.

Production-rate loss, q_P: This includes the registering of speed losses and of the reworking of units already processed. The data should be connected to a specific machine, order number, product number and date in each case.

Batch size, N: It should be possible to retrieve from the system the batch size for a specific order number and product number from a specific processing step.

Cycle time, t_0: The nominal cycle time in each processing step for a given product should be available.

Setup time, T_{su}: It should be possible to register each setup time connected to a specific order number and product number in a specific processing step.

Machine utilization, U_{RP}: The system should contain a function for registering the idle capacity of each machine, cell, or production line.

Since the costs calculated using the economic model are based on data for a specific product or part, using a selected time horizon, it is important that the manufacturing data are connected to a specific product number and order number.

5.2. Software review

The investigation included three stand-alone MDCS software products, Axxos, bePAS, and MUR, and one ERP system containing an MDCS module, M3. Three of the systems were chosen based on the commercial systems found in companies participating in the research project of which this study is part. The fourth system, bePAS, was found via an Internet search for MDCS. All the software products except MUR offered essentially the same standard features, including monitoring of scrapped parts, downtimes, speed losses, setup times, and machine utilization. These standard solutions fulfill the requirements presented in section 5.1, except that they fail to divide the three types of result parameters into separate sub-parameters. These software products only allow the disturbance data to be sorted based on type of disturbance (e.g. scrap, downtime, or speed losses) and its cause. The products examined used an open database structure, in that the data stored on them were accessible by other software systems. The programs differ in basic ways regarding the interface employed and how the data are presented to the user by the various reports available. The programs also differ in their support for automatic data registration. The software packages that support automatic data registration use signals from the control systems of the machines in automatically calculating downtimes and speed losses, for example. All examined products except MUR provide flexible, customer-specific solutions, implying that required parameters can be added if the customer so desires. MUR provides no support for scrap registration, and thus no support for calculating the batch sizes of various processing steps. Instead, it provides an easy way for operators to register downtime causes by simply selecting the code representing the cause on a special device, whereupon the downtimes are automatically registered in MUR. All the other products incorporated a monitor-based system for registering disturbances.

Since our review-type study of available MDCS products considered only four such products, we can make no comprehensive statement regarding support for the collection of data of the sort needed in MDCS products generally. However, the results did indicate that commercial software is available supporting such data collection, and that a suitable solution for the proposed cost software would be to use, as input, existing data collected by the company’s ERP and manufacturing monitoring systems. This would mean the use of a software application comprising a user interface and algorithms for collecting the data needed from the databases of other programs and for calculating the desired costs.

6. A study of systems for collecting manufacturing data used in practice

Although the above results indicated that production performance software companies provide the possibility to collect the manufacturing data needed for the cost model, this does not mean that manufacturing companies necessarily use this option in their MDCS. Accordingly, we also studied five manufacturing companies to investigate the extent to which they collected such data. Two of the companies had developed their own MDCS, while the other three used one of the MDCS reviewed in section 5.2 (i.e. bePAS, Axxos, or M3). It was found that these companies could collect, to a certain degree at least, data for all the required parameters, but that the companies tended to focus on the parameters they considered most important for their own manufacturing processes. A company having no major problems with downtimes tended not to have as well developed a system for registering downtimes as did a company with greater downtime problems. Due to such differences, none of the five studied companies could provide all of the input data needed by the planned cost software.

Four of the five studied companies had one or more separate MDCS, together with an ERP system, although in one case the MDCS served only as an interface with the ERP system in which all the collected data were stored. Two companies collected the manufacturing data using both an MDSC and an ERP system, some of the input data were registered in the MDCS and some in the ERP system.

Downtimes: Downtimes were relatively well documented by the five companies. All of them registered downtimes and their causes, using lists of causes from which the operators could choose when a stop occurred, although the companies differed in the number of alternate causes listed. All but one company connected the downtimes with the product number involved when a stop occurred.

Scrap: The companies differed in their procedures for registering scrapped parts. Unlike downtimes and speed losses, scrap handling appeared to be directly connected with the company's quality management. In one company, scrapped parts were not registered in the monitoring system by the operators as the downtimes were. Instead, these data were registered by a quality manager. In the other companies, data on scrapped parts were registered by the operators, but in varying degrees of detail. One company failed to connect scrap occurrences with the machines involved, only assigning the scrap to the production unit to which the machine belonged.

Speed losses: Speed losses were the least documented of the three disturbance parameters, possibly because the operators lacked the authority to alter a machine's speed during a production run or because the process characteristics meant that processing speed was not a variable parameter.

Batch size: All the companies registered the ingoing batch size in the first processing step, data regarding scrapped parts (to some extent), and the order and product numbers involved. All studied companies could apparently determine the ingoing and outgoing batch sizes.

Cycle time: All the companies stored, mainly in the ERP system, the nominal cycle times for the products produced.

Setup time: All the companies registered real setup times, and two documented nominal setup times as well.

Idle capacity: All studied companies could calculate the idle capacity of a specific machine or line.

The results of this study of the five manufacturing companies are summarized in Table 3. The companies are denoted by letters A to E, where B1 and B2 represent different departments of one company. The numbers in the table are interpreted as follows: 1) fulfills all the requirements presented in section 5.1; 2) available to a certain extent at the company in question; and 3) unavailable at the company.

Table 3. A summary of the study of manufacturing companies.

	Company					
Parameters	**A**	**B 1**	**B2**	**C**	**D**	**E**
Downtimes	1	2	1	1	2	2
Scrap	1	2	2	2	1	1
Speed losses	2	2	2	2	2	3
Batch size	1	1	1	1	1	1
Cycle time	1	1	1	1	1	1
Set-up times	1	1	1	1	1	1
Idle capacity	1	1	1	1	1	1

7. The developed manufacturing cost software

7.1. Software requirements

An appropriate software implementation is essential for making the described cost model usable in a genuine manufacturing environment. The first software implementations of the cost model were stand-alone solutions, in both Excel and Mathcad. Excel has the advantage that manufacturing companies already use it extensively, meaning that Excel-based cost software would be easily implemented at most manufacturing companies. However, the software design functions of Excel represent one of its limitations. Excel is a powerful tool for spreadsheet calculations, but has limitations in terms of not readily enabling construction of a flexible and user-friendly interface for carrying out simulations and other analyses of large amounts of data. Mathcad, in turn, is powerful in terms of allowing users to create and solve equations. This makes the software useful in implementing the model and testing various applications and representations of it, but the program lacks characteristics enabling it to serve as a basis for developing a flexible and user-friendly software application. In the two initial implementations, one in Excel and the other in Mathcad, the input data were manually registered in the program, which is sufficient for tests performed in limited case studies but fails to meet a manufacturer’s demands for flexibility and ease of use.

A solution would be to design a program that automatically uses existing data stored by the company’s ERP system and its MDCS. In such a situation, the cost software would be connected to the databases of other software. The advantage of this solution is that the required data would not have to be inserted into the software manually, though it does require that the input data of the company’s software systems are accessible. The studies presented in the two previous sections indicate that it would be appropriate for the manufacturing input data to be based on existing data stored in the company’s systems for collecting and storing manufacturing data (see Figure 2). The software consequently would not require a data collection module. Data on the manufacturing parameters of the cost model would be retrieved from the MDCS and data on the economic parameters from the accounting system. Accounting data are generally stored in an ERP system and the system for collecting manufacturing data is part of either the ERP system or a separate system.

The manufacturing cost software was developed in accordance with the schematic plan shown in Figure 2. It was developed together with company D in the study reported in section 6. Company D was chosen because of its good results, as identified in the study, and its great interest in a cost calculation software. The company manufactures tools for metal cutting and the study was conducted at one of their manufacturing plants where approximately 7000 different product variants are produced. The plant has a functional layout with batch volumes ranging from 10 units to several thousand units. This collaboration meant that the software could be developed based on genuine conditions and guided by valuable input from company personnel regarding software design. The decision to develop a demonstration program rather than one more broadly applicable, was made mainly due to the complexity of developing software of the latter type.

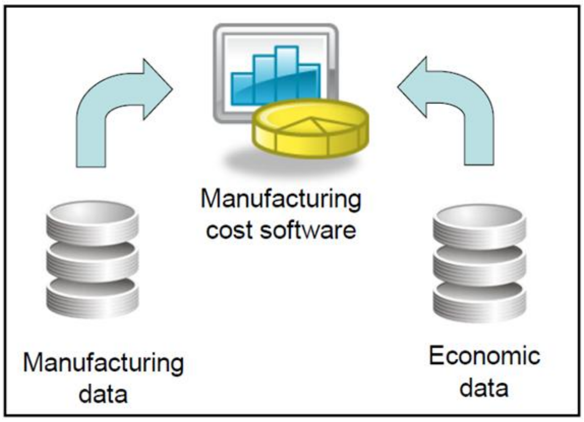


Figure 2. The input data for the cost software are based on data stored by the company's system for collecting data on manufacturing performance and/or by an ERP system.

The software was designed in a business intelligence (BI) software. BI systems allow data stored in various databases to be presented and analyzed in ways not possible using the system or systems in which the data were originally stored. The software was developed within the Qlikview BI system. Qlikview was chosen because it was already employed by the studied company, so personnel were experienced and competent in its use and could help in developing the software.

As described in section 6, company D collects data on all the required parameters except for speed losses, q_P. One parameter the company monitored was downtime rate, but these data were not linked to the specific product produced, such linking being one of the requirements listed above. In addition, only fairly long stops were recorded in the data collection system, the recording being done manually. The downtimes were calculated in the cost software by comparing the nominal batch time in each case with the actual batch time. This meant that the recorded causes of the downtimes were not accessible in the cost software, although now all the downtimes were included, including short stops.

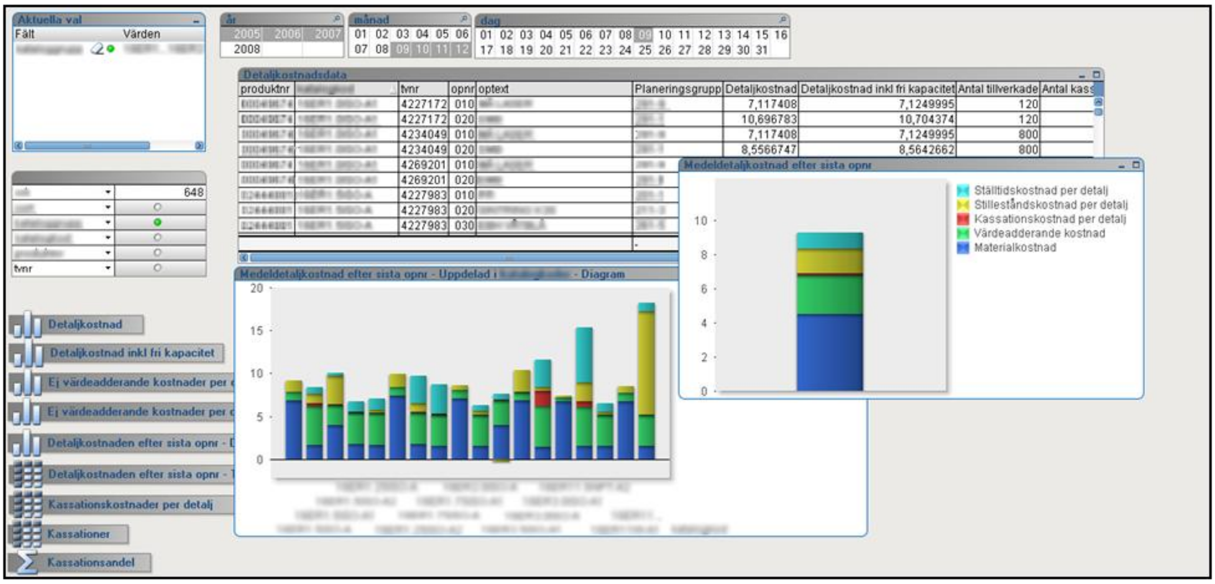
All the required data were loaded into the BI application, the manufacturing data being loaded from the company's MRP II system and the economic data from its ERP system. The downloaded data were then configured in a Qlikview script in accordance with the parameter definitions presented in section 4.

Before the application was developed, a list of criteria was established that the application had to fulfil, as follows:

- to show the cost of every completed order number in cost per part
- to show the cost distribution between material, value-added, non-value-added, and support activities
- to show the cost distribution between various non-value-added activities
- to visualize the results in an accessible way
- to have a user-friendly interface
- to be able to conduct 'what-if' analyses

Based on these criteria, we decided to divide the application into two sheets: *Part cost* and *What-if*, but the final version of the application contained two more sheets: *Batch cost* and

Process cost. Each sheet contains various tables and charts and a menu in which the user can select the products analyzed and the applicable time horizon. Figure 3 shows a screen shot of the part cost sheet.



Detaljkostnadsdata

produktnr	[redacted]	tvnr	opnr	optext	Planeringsgrupp	Detaljkostnad	Detaljkostnad inkl fri kapacitet	Antal tillverkade	Antal kass
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[redacted]	[redacted]	4227172	020	[redacted]	[redacted]	10,696783	10,704374	120	
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Figure 3. Screen shot of the part cost sheet in the cost software.

7.2. Part cost sheet

The purpose of the part cost sheet is to display various calculations linked to the cost per part, by the use of the equations 5 to 16. The sheet includes tables and charts showing how the part cost develops based on the processing steps involved. Information is also available regarding the values of the underlying parameters on which the part costs are based. Part costs can be calculated both for individual order numbers and as the mean part cost based on several order numbers. The calculated costs on this sheet are divided, as on the other three sheets, into six cost types: cumulative cost, value-added cost, scrap cost, downtime cost, setup cost, and utilization cost. The cumulative cost is the value of the part when it enters a particular processing step, and comprises the costs of the previous processing steps together with the material cost. The sheet also contains bar charts with which one can readily determine the distribution of these costs at each processing step or as the sum of all processing steps. Figure 4 shows one of the bar charts available, where the various colours represent the six costs described above.

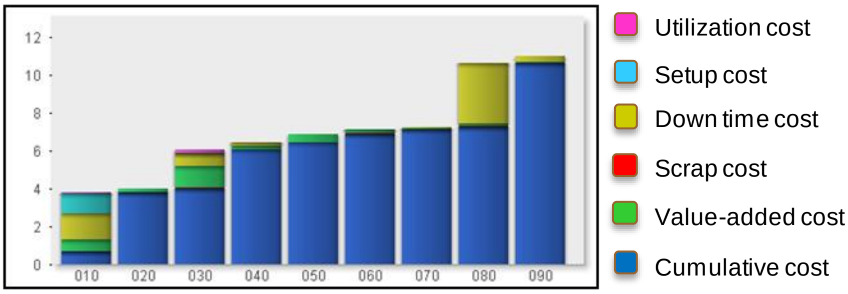

Figure 4. The cumulative costs at each processing step, divided into value-added costs and various non-value-added costs.

Figure 5 presents a bar chart showing the mean part cost based on several order numbers for a given product number. The chart provides a quick overview of the relative sizes of the non-value-added costs and of the relative contributions of the various cost items to the total manufacturing cost.

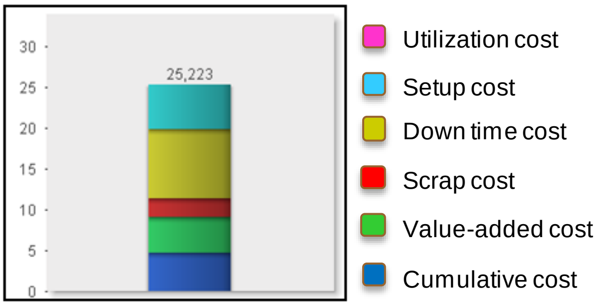

Figure 5. Mean part costs of several series of a given product.

7.3. *Batch cost sheet*

The batch cost sheet contains the total manufacturing costs of a batch, i.e. the part cost multiplied by the batch size. It contains many of the charts and tables found in the part cost sheet, but here as cost per batch.

7.4. *Process cost sheet*

During the development process, we decided to include the process and batch sheets in the application. The case study company made several hundred different products, which could make it difficult to gain an overview of the performance based on the cost per part. Therefore, the process cost sheet was developed, so that instead of costs being linked to the products, as they are in the process and batch sheets, they are linked to their related machines and machine groups. Instead of analyzing the costs of the parts produced, this sheet indicates where in the plant the costs occur and the size of the costs. This analysis is conducted by choosing one or more products from the menu, and a timeframe on which the analysis is to be based. The results presented in the tables and charts indicate the total process costs or the process costs per hour for the machines and machine groups involved in producing the chosen products. These costs are divided into value-added costs, downtime costs, scrap costs, setup costs, and utilization costs. Figure 6 presents an example of a bar chart from this sheet showing the manufacturing costs per hour for selected machine groups. The process cost calculations are based on the equations 17 to 22.

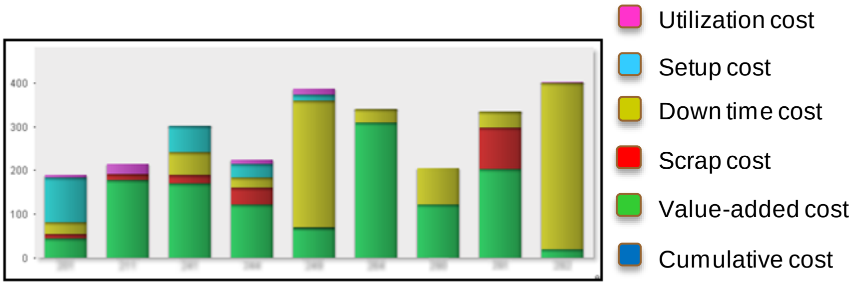

Figure 6. Process cost per hour for various machine groups; each bar represents a machine group.

7.5. *What-if cost sheet*

The purpose of the what-if sheet is to be able to make simple simulations that show how the cost is affected by changes in the ingoing parameter values. The sheet shows the actual part costs and the values of the parameters on which these costs are based, just as in the part cost sheet. The difference is that this sheet also contains input fields in which one can enter new values for the parameters contained in the cost model and examine how the new values alter the part costs. This allows one to conduct what-if analyses to investigate how a given improvement, such as reducing the downtime rate for a given processing step, would affect the final part cost of the analyzed product. The software can thus be used to support strategic decisions regarding production development by making it possible to analyze the effects of various scenarios on the part cost.

8. Discussion

Because of the popularity of using OEE to monitor manufacturing processes in industry, many companies already collect data on all or nearly all of the input parameters needed for the manufacturing cost software presented here. Although companies differ greatly in the level of detail and accuracy of the data they collect, an important difference between the data collected for OEE and the data required for the cost model is that OEE measures the equipment performance and does not need the specific product and order number data required by the cost model.

The Qlikview application was developed specifically for the company in which the case study was carried out, and may not be directly applicable in another company. The main difference between companies that needs to be taken into account concerns the configuration of company parameters into the cost model parameters. Another issue is that the definitions of the parameters in cost model is not completely applicable to all companies, but need in some cases be adjusted.

9. Conclusions

This paper explores the conditions for making a developed part cost model industrially available (RQ1). Two pre-studies were conducted to investigate the conditions for collecting the needed data. The first study demonstrated that some commercial software products support the collection of the needed data, while the second study demonstrated that the studied manufacturing companies were already to some extent collecting the needed data, though the level of data detail varied between them.

Based on these results, a software application was developed together with a company in order to find out how such a software application should be designed (RQ2). The software enables the relationship between equipment performance and manufacturing costs to be analyzed in an easy and informative way. The software shows the extent to which equipment performance at each processing step contributes to the total manufacturing cost as divided into the following cost categories: cumulative cost, value-added cost, scrap cost, downtime cost, setup cost, and utilization cost.

Unlike OEE, the developed cost model and software not only describe equipment performance, as OEE does, but also show how it affects the manufacturing costs of the products produced by the equipment. As indicated in section 3, Muchiri and Pintelon (2008) argue that one shortcoming of OEE is the absence of a cost dimension. The developed cost software addresses this lack, partly because the cost model uses performance measures that are largely the same as those used in OEE. Such software could also usefully complement the OEE monitoring that many companies already perform. The cost software adds to the OEE measure a cost perspective that can be useful in a more strategic context, enabling the analysis of matters such as how setup time affects part cost for a particular batch size. The software also makes it possible to analyze manufactured products individually and identify possible differences between them in non-value-added terms.

The software deals not only with the realized past, since the ‘What-if’ tool also allows the analysis of hypothetical future development activities from a cost perspective, making it possible, for example, to communicate future improvement activities to stakeholders in a comprehensible way.

A shortcoming of OEE referred to in section 3 is that it involves the assessment of separate pieces of equipment, failing to take account of linkages between equipment and material flows. In contrast, the developed cost model and software take into account where disturbances occur in a product’s manufacturing chain. A part scrapped near the end of the process chain is more costly than one scrapped earlier in the chain. This is clearly demonstrated in the software by means of various graphs, such as the one shown in Figure 4. The depicted bar chart shows the impact on total costs of the equipment used to process the material. The software takes account of the linkage between the processing steps, although waiting times between the processing steps and the costs connected with these are not included in the cost model or in the software.

Since manufacturing performance is here visualized in terms of costs, it is also easy to convey the information this represents, not only to people within the manufacturing unit in question, but also to people in other parts of the organization, such as company management. Everyone can relate to costs and costs are always of direct concern to management.

Acknowledgements

This work was supported by the Sustainable Production Initiative (SPI), Chalmers University of Technology, and Lund University, and was financed by VINNOVA.

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Paper 6

M. Jönsson, C. Andersson, and M. Svensson, “Availability improvement by structured data collection: a study at a sawmill,” Submitted to *International Journal of Production Research*.

Availability improvement by structured data collection: a study at a sawmill

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Abstract

The availability rate is often a critical performance parameter in a manufacturing system. This paper addresses the role of availability monitoring as a means of learning about availability losses. More specifically, it considers the level of data detail used when registering the causes of availability losses. Two questions are raised and answered. The first is whether companies gain any specific benefits from gathering more detailed data, while the second concerns whether collecting highly detailed data is difficult due to increased complexity for the operators responsible for registering the availability losses. To answer these questions, changes were made in a company's availability monitoring system, resulting in more detailed monitoring. The results indicate that having more detailed data is more advantageous than disadvantageous: the company's production manager believed that increased detail fostered better knowledge of performance losses, while operators perceived no particular difficulty in handling increased detail.

Keywords: availability; downtime causes; downtime monitoring

1 Introduction

Performance measurements are necessary for any industry or business striving to increase its efficiency and effectiveness. There are numerous views and definitions of performance measurement. Neely *et al*. (2005), for example, distinguishes between an individual measure and a set of measures, the latter being referred to as a performance measurement system (PMS). Manufacturing companies commonly use both individual performance measures and PMSs to monitor manufacturing process performance, and they usually constitute part of the company's improvement or change management program. Performance measures used by manufacturing companies vary greatly, but Neely *et al*. (2005) claim they can all be categorized according to the dimensions of quality, time, flexibility, and cost. One time aspect that many companies measure is equipment availability. Availability describes the proportion of planned production time that equipment is actually available for operation. Availability, definable in various ways depending on the time parameters included in the measure, is basically affected by downtime duration and the length of time between downtimes.

A widely used performance measure for companies in discrete manufacturing is overall equipment efficiency (OEE). OEE was developed by Nakajima (1988) as a performance measure to support the total productive maintenance (TPM) concept and it measures losses relating to manufacturing equipment. The original publication on OEE divided these losses into “six big losses”, i.e., equipment failure, setup time, idling and minor stoppages, reduced speed, quality defects, and reduced yield. Two of these losses, equipment failure and setup time, are often considered availability losses, but these two categories alone do not provide sufficiently detailed information to serve as a basis for decisions regarding improvement activities. One method, often mentioned in the literature, to find the root cause of a failure is the cause–effect (or Ishikawa) diagram (Slack, Chambers, Johnston, & Betts, 2009). A deficiency of this method is that it does not provide information about what root cause has the greatest impact on availability. Hence the Ishikawa diagram is not suitable for prioritizing between improvement activities. To improve availability, one must know what factors or causes underlie the availability losses; it is also advantageous to know the relative importance of these factors, to be able to prioritize the most critical one or ones.

Equipment can fail for various reasons, which vary between pieces of equipment in the factory workshop. Many companies have some kind of downtime registration system to monitor equipment availability. In some cases, data are collected using pen and paper, but Andersson and Bellgran (2011) claim it is preferable to register such data using some kind of data collection software. Besides logging the downtime, the data collected may also capture what caused the downtime. The downtime is often described, especially when using data collection software, by choosing an appropriate description from a list of various downtime causes.

The OEE measure is the product of three parameters: availability, performance, and quality. Looking at the performance of automated manufacturing and assembly equipment, the availability parameter usually represents most of the total loss in OEE performance. Availability is a critical performance measure for many companies, and according to a survey conducted by Muchiri *et al*. (2010), 83% of Belgian manufacturing companies were measuring availability. Even so, issues regarding downtime registration and its role as a decision basis are rarely treated in the literature.

2 Literature review

An extensive literature treats performance measurement, describing present trends, how to choose the right measures, what measures are commonly used, etc. The focus of the present paper and of the literature review is on how to increase the knowledge gained from performance measurement, specifically regarding manufacturing system availability, by documenting the reasons for any deviations. This specific topic is less explored in the measurement literature, which is fairly general in focus.

Some studies of the collection of downtime data and their use in improvement decisions are found among those with an OEE focus. After Nakajima presented the OEE measure, several papers examined the subject, some proposing improvements to the original OEE definition. For example, Jeong and Phillips (2001) extended Nakajima’s six losses to 10 losses, a schema they believe is more suitable in capital-intensive companies. The losses defined by Jeong and Phillips are: nonscheduled time, scheduled maintenance, unscheduled maintenance, R&D time, engineering usage time, setup and adjustment, WIP starvation time, idle time without operator, speed loss, and quality loss. Jeong and Phillips claim that a deficiency of the original OEE definition is that planned downtime, such as planned maintenance, is not considered a downtime loss. They believe that as planned downtimes are crucial to capital-intensive companies, these must be included in OEE. They acknowledge that the accuracy of the OEE measure depends on the quality of the collected input data. The available downtime causes to choose from in a computerized collection system must be well defined, which calls for careful collection system design. Jeong and Phillips describe a proprietary software application for OEE calculation and result presentation. They acknowledge that, once the OEE has been calculated and analyzed, improvement work must be carried out and that the 10 losses have different characteristics that must be considered. Their paper includes no data on the actual implementation of their application; only data from other papers are used in the presented examples.

Bamber *et al*. (2003) advocate the use of cross-functional teams to improve OEE figures, because they believe that several competences, for example, maintenance, production, and quality, are needed for successful improvement work. Using OEE calculations, their case study demonstrated that the company suffered from low availability. A cross-functional team drafted a cause–effect diagram to analyze the situation. The diagram led to insights into what actions had to be taken. The diagram also identified a need for cross-functional groups, because addressing the causes of the identified disturbances called for competences from several company functions. One factor facilitating work in the cross-functional team was that it included members of management, which led to quick decisions. In this case, the OEE monitoring apparently consisted solely of time data without any data describing the downtimes or their causes. This means that the OEE figures were only used to measure the performance; the causes underlying the losses had to be found when developing the cause–effect diagram.

Dal *et al*. (2000) describe OEE implementation by an airbag manufacturer. Operators documented the downtime losses by recording the durations and descriptions of the downtimes on a record sheet. The results were unsatisfactory because of imprecise definitions of downtime and availability. A workshop to analyze the collected data resulted in the identification of two major causes of the availability losses. Subsequent workshops concluded that the company needed standards for operator behavior during downtimes. The authors conclude that OEE is most beneficial when it is used not only to monitor losses but also to support improvement activities. They also discuss the importance of accurate data: data must be convincing for production management, otherwise they will not be used effectively. Jonsson and Lesshammar (1999), in contrast, argue that it is more important to apply a simple measure than an accurate one.

Ljungberg (1998) also discusses the importance of data collection, claiming that data collection problems have been insufficiently treated in the literature. Such problems include poor data collection systems—which must be fast but still accurate—and resistance on the part of operators and foremen to collecting the data. This resistance can be decreased, according to Ljungberg, by designing the data collection system together with the users, an approach also mentioned by Gibbons and Burgess (2010). Resistance can also be decreased if users are helped to understand how the data are actually compiled and used, according to Ljungberg. Ljungberg (1998) also discusses the pros and cons of registering the losses using pen-and-paper versus computerized systems. Pen-and-paper solutions are simpler than computerized systems, but the recorded lengths of downtimes will not be completely accurate. A computerized system can register correct downtime lengths, and some systems even force the operator to register a downtime cause before the equipment can be restarted, meaning that all losses will be registered. However, such software systems can be expensive and difficult to use. A computerized system in which the operator registers failure number and type while the computer keeps track of the downtime and the actual cycle time is recommended. Ljungberg's OEE measurements used five independent variables to categorize the cause of every recorded loss; these variables were production process, process knowledge, maintenance activities, external factors, and production conditions.

Wang and Pan (2011) recommend computerized data collection in which the operator chooses a specific downtime cause to describe the failure. They present an example from the semiconductor industry in which seven downtime causes are available. They also demonstrate how a cause–effect diagram can be used to determine more detailed downtime causes. How the collected data are or should be used is not considered. Andersson and Bellgran (2011) have compared manual and automatic downtime registration in a company having both systems. They too declare the advantages of an automatic system, its only disadvantages being investment and licensing costs and the set-up time.

Some non-OEE-related literature also considers downtime registration. For example, De Smet *et al*. (1997) describe various case studies of disturbance registration. In one case, the downtime causes from which the operator could choose when registering a failure were too general and vague. Operators could also supply additional explanation in a comment line, but did not use this feature satisfactorily. Consequently, a more relevant and detailed list of causes was developed for each machine, and feedback was given to the people who registered the failures to motivate them to better describe the failures.

The literature review indicates a lack of research into data collection, specifically regarding the level of detail on downtime causes, and into how such data can be used to support improvement work.

3 Research questions and method design

The research project on which this paper is based aims to improve the decision basis for improvement efforts addressing equipment performance. Equipment availability is, in this respect, a critical parameter and hence the focus of the paper. Introducing a work procedure for collecting performance and availability data entails various challenges. According to the reviewed literature, both the duration and cause of each downtime must be accurately registered to be able to prioritize improvement actions. Furthermore, the importance of operator ability and motivation to register data has been discussed. Reviewing the relevant literature on availability measurement and improvement indicated a lack of research into how information obtained from availability monitoring can be used to support improvement efforts aimed at improving availability. This paper explores the role of availability monitoring as a tool for gaining knowledge of availability losses and, more specifically, explores how the precision of the collected data affects their usability. The following research questions were formulated and addressed:

RQ1: Does an increased level of detail in the collected data on the causes of availability losses improve knowledge of performance losses?

RQ2: How do the personnel responsible for reporting availability losses perceive an increased level of data detail?

This project uses a case study-oriented approach incorporating some interactive elements. This approach was chosen because case studies enable phenomena to be studied in their real-world contexts and are appropriate when studying change processes (Yin, 2003). The studied company wanted to improve its knowledge of performance losses and as a first step decided to improve its availability monitoring. The interactive elements of the study consist of researcher involvement in the changes made in the studied company. The researcher attended meetings at which availability issues were discussed and actively participated in developing the new downtime cause structure in the availability monitoring system and in formulating the individual stoppage causes constituting the structure. The researcher took an interactive role so that the effects of a more detailed list of availability loss causes could be tested. Furthermore, this interactive role fostered insight into problematic issues regarding the design of an availability monitoring system, insight that could not be gained otherwise.

The data for the study were collected from observations, semi-structured interviews, and participation in meetings dealing with performance measurement. A few months after the changes described below were implemented, six operators and the production manager were interviewed. The operators were interviewed to obtain their opinions on the specific changes made to the system for collecting downtime data in general. The production manager was interviewed to learn how the company uses the downtime data and to obtain his reflections on the changes to the data collection system.

4 Initial conditions at the studied company

4.1 Production system

The study was conducted at a medium-sized Swedish sawmill company. A sawmill generally consists of three major processing steps: sawing, drying, and planing. The study presented here treats performance monitoring in the sawing department, where processing starts at the log deck and ends at the stackers. This limited area will from now on be referred to as the saw line, and is shown in Figure 1. The squares in the figure represent the main pieces of equipment and the two rectangles represent the control booths, i.e., the saw booth where the logs are adjusted before the first saw group and the edger booth where the boards are handled before the edger machines. The saw line is continuous with a few buffers, represented by the triangles in the figure. The products are boards and planks of various dimensions, the boards being made from the outer part of the log and the planks from the inner part. In saw groups 1 and 2, boards are sawed from the logs and fall to another conveyor belt that then distributes them to the edgers. The remaining parts of the logs continue on to the third saw group where the planks are made. After the edgers, the boards come to the buffer, where they can go to either stacker 1 or 2, which means that the operators can choose whether stacker 1 should stack boards or planks. The capacity of stacker 1 is generally sufficient to handle both boards and planks. Besides the equipment displayed in the figure, the line also includes various material-handling devices before and after each piece of processing equipment.

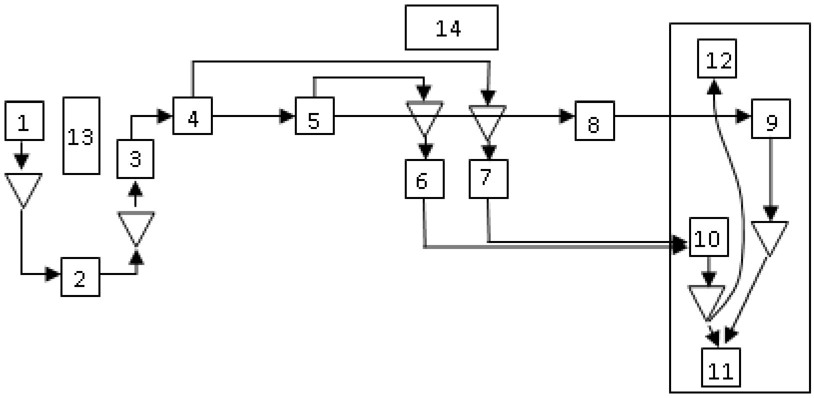

Figure 1. (1) Log deck, (2) debarking machine, (3) root reducer, (4) saw group 1 including reducer, (5) saw group 2 including reducer, (6) edger 1, (7) edger 2, (8) saw group 3, (9) trim saw, (10) drop sorter, (11) stacker 1, (12) stacker 2, (13) saw booth, (14) and edger booth.

4.2 Availability measurement

The company has an electronic data collection system for downtime registration. The downtimes are automatically registered by a sensor placed between the root reducer and saw group 1. If no logs have passed the sensor for 30 seconds, the data collection software registers a downtime. The operator must then specify from a list where the downtime occurred and its cause from a list of downtime causes. All downtimes are registered on one computer placed in the saw booth (see Figure 1) and their causes are documented by the operators working in this booth. If the cause of the downtime is located outside the working area of the operators in the saw booth, the needed information is reported to the operator in the booth by the operators responsible for taking the corrective action.

As mentioned above, all downtimes are measured by one sensor, which means that all downtimes, regardless of where in the saw line they occur, are measured from this position. For this reason, some downtimes, especially those occurring in the stackers after the large buffer, do not affect the flow at the measuring point and consequently are not captured by the data collection system. These hidden stoppages do not affect the flow in the saw line as a whole, but contribute to increased workload for personnel and keep them from more value-added activities. Though examining this system shortcoming is beyond the scope of this paper, it was something the company was aware of (in fact, the company had plans to install another sensor near stacker 1). The OEE measure is primarily a performance measure for individual machines, but here the availability rate describes the availability of the whole saw line. OEE measurement systems for entire lines were later proposed, for example, by Braglia *et al.* (2009). When measuring production line performance, it is important to identify the cycle time at the theoretical bottleneck station to obtain a correct availability value. According to Braglia *et al*. (2009), the correct availability rate of a line can be calculated from the availability at the last station multiplied by the ratio between the nominal cycle time in the theoretical bottleneck and the nominal cycle time at the last station. In this case, the last station can be either stacker 1 or both stackers 1 and 2, which means that the relationship presented in Braglia *et al*. is not directly applicable. The studied company has instead chosen to measure downtimes near one of the bottleneck stations. The saw line has two bottleneck stations, the root reducer and the edgers, depending on the product characteristics. As described above, the present data collection point is placed between the root reducer and saw group 1, which results in an accurate availability value only if the root reducer is the bottleneck station. To collect downtime data at the ideal bottleneck for every product type, two additional measuring sensors have been installed, but not yet activated.

The list of causes available for categorizing downtimes covered essentially all equipment, but only a few downtime causes were listed for each piece of equipment. The production manager believed that some downtime causes were missing from the list. There was also some dissatisfaction with the structure of the list of downtime causes; for example, setup time and unplanned tool exchange were included in the same group of downtime causes. The main deficiencies of the original data collection system were consequently:

- missing downtime causes
- structural shortcomings
- only one measuring point

The company was not completely satisfied with their original data collection procedure, which meant that it was in the interests of both researchers and the company to revise it.

4.3 Structure and downtime causes

In the original tree structure, the downtime causes were divided into eleven groups. The division was based mainly on the various pieces of equipment constituting the saw line, such as saw groups 1, 2, and 3 and the edgers, as shown in Figure 2. The downtime causes pertaining to all conveyor belts for the logs and sawn timber and to the equipment for the intake to the saw groups were put into one downtime group, while the downtime causes pertaining to the chip conveyor belts were put into another. Another group consisted of setup time, tool changes, and dimension control. Each piece of machinery and material-handling equipment had an individual group of downtime causes. Each of these groups contained two or more kinds of causes, containing at least the *Electrical* and *Mechanical* downtime causes. Figure 3 shows examples of the tree structure for four of the groups, i.e., *Log intake*, *Saw group 1*, *Edgers*, and *Green sorting*. The tree structure comprises the individual downtime causes or root causes, similar to a fishbone diagram. The original list consisted of a total of 128 downtime causes divided into 11 groups.

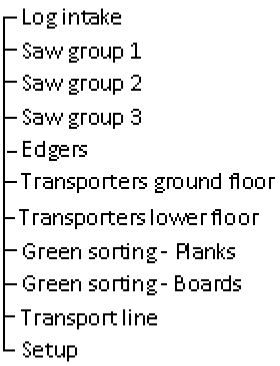

Figure 2. The division of downtime causes in the original structure.

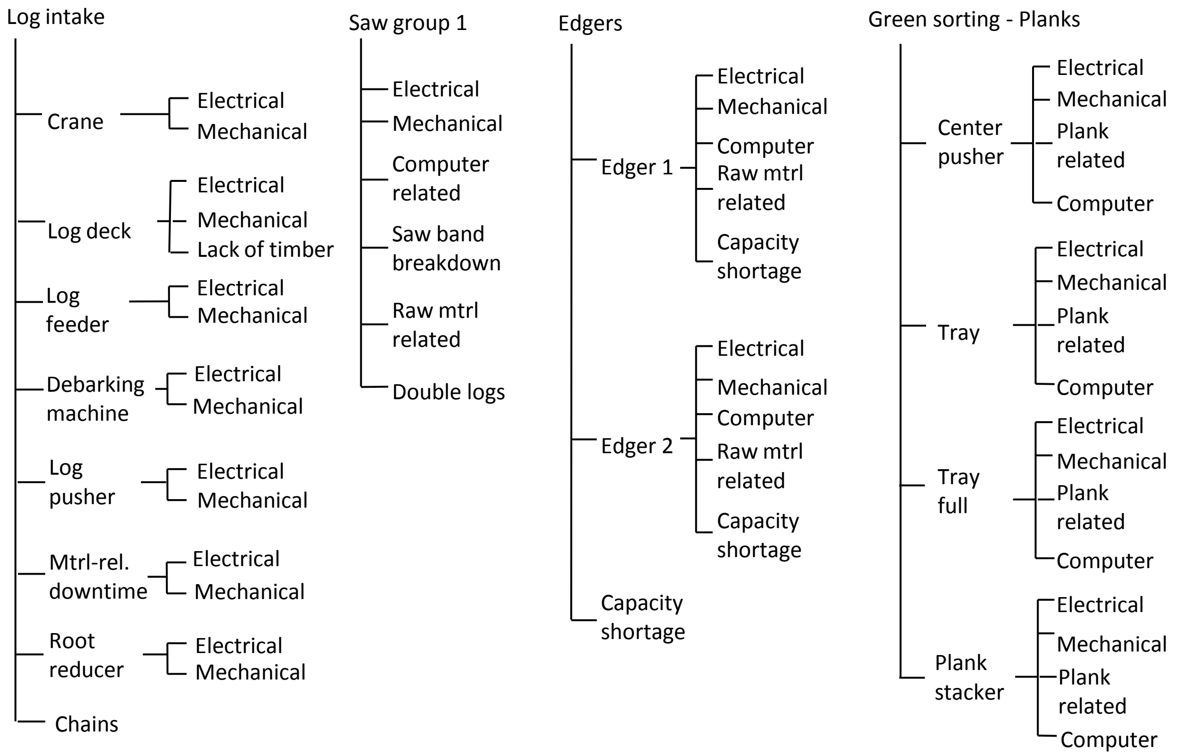

Figure 3. The downtime causes to choose from in four of the groups in the original structure.

5 The use of the collected data

A few months before the changes in the data collection system were implemented, a continuous improvement program was initiated in the sawmill, inspired by total productive maintenance (TPM) and lean manufacturing. Not all these activities had yet been implemented in the organization when this study was carried out. The company started the program by implementing 5s, which had just been finished before the start of this study. The production manager deliberately moved slowly when introducing the program, since the operators were not used to being involved in improvement work or in discussions of performance and of improvement activities. The production manager had also made some changes in the maintenance organization. The maintenance department had previously handled only corrective maintenance, but now was also responsible for performing preventive maintenance. The suggested changes in the downtime data collection were part of the initiated improvement program.

The collected downtime data are processed and compiled by the production manager once a week. This is done in the data collection software and results in a list of downtime causes and their durations sorted based on their position in the process flow. The data are then analyzed further in MS Excel; the data are divided according to the main equipment groups (see Figure 2) and the downtime rate for each main group is calculated. At this point, the downtime distribution for each piece of equipment is visualized, showing which group exhibits the highest amount of downtime. The data are also added to a time graph that shows the results for every week and thus how they change over time. These compiled data are included in a result report distributed to management every week. The detailed result list compiled in the data collection software is also used in meetings with maintenance personnel every second week. In these meetings, data for the last two weeks are used to investigate whether any major problems have arisen and, if so, in which equipment group and comprising what kinds of stoppages. The maintenance activities are then prioritized based on this list.

The same list of downtimes is also the basis of discussion in the weekly meetings with operators. In these meetings, the production manager normally addresses the three main downtime causes encountered over the previous week. These discussions, based on the collected downtime data, lead to a mutual understanding of what happened. As well as serving as a basis for improvement work, the downtime data are also used when making investment decisions and other changes in the production line. The company does not use Ishikawa diagrams or other methods besides the collected downtime data when analyzing availability.

6 Performed changes

6.1 Structure

The changes in the downtime monitoring system started with how the downtime causes were structured. We assumed that increased detail regarding the registration of causes would make more demands of the structure, which must still be simple to orient in and locate the right downtime cause. Meetings were held with the production manager and the maintenance worker with the deepest knowledge of the saw line, to discuss and determine how the tree structure should be designed. It was decided that the tree structure should be based on one developed by Ståhl (2010) (see Figure 4). This structure was originally developed for analyzing tool breakdowns in metal cutting, but has since been used to analyze entire manufacturing systems. The performance parameters Q, S, and P represent the OEE parameters quality, availability, and performance efficiency, respectively, while groups A to H in the figure represent the causes of the disturbances involved. One benefit of this model is the tree structure, the division of the causes into various groups, which can facilitate both downtime registration and result analysis.

		Performance parameters			
Groups of causes	Description	Q_1,..,Q_n (units)	S_1,...,S_n (min)	P_1,...,P_n (min)	Σ
A_1,...,A_n	Tool-related failures				
B_1,...,B_n	Material-related failures				
C_1,...,C_n	Machine-related failures				
D_1,...,D_n	Failures related to personnel and organization				
E_1,...,E_n	Maintenance-related factors				
F_1,...,F_n	Specific process-related factors				
G_1,...,G_n	Factors related to peripherals such as material handling equipment				
H	Unknown factors				
Σ					

Figure 4. Structure for the systematic analysis of manufacturing processes.

The idea is that this structure should be used for every machine, resulting in a more uniform tree structure than that already applied and one that takes into account downtime related to personnel and organization, which, in the experience of the present authors, can constitute a significant part of all manufacturing system failures. However, those downtimes are difficult to follow up on, because of general resistance to registering failures related to employee competence.

In these meetings, it was decided that some changes should made to the tree structure shown in Figure 4 to make it more consistent. Material-handling equipment (Group G) was removed from the structure, and was instead given the same downtime structure as the processing equipment. However, the material-handling equipment was assigned fewer downtime causes, as this equipment is less technologically advanced than the processing equipment. Factor groups D, E, and H were incorporated into groups A, B, and C instead of being treated as individual groups. This was done because it was concluded that most downtime related to groups D, E, and H results in failures related to groups A, B, and C; for example, machine-related downtime can occur for personnel-related reasons.

The aim of the new tree structure was to increase the level of detail by introducing more downtime causes without making it more difficult for the operators to navigate the structure.

The first level of the original downtime tree structure was largely retained. The groups *Transporters ground floor* and *Transport line* were removed from the list, and the equipment in these groups was instead put in the same groups as the processing equipment served. For example, *Transporters ground floor* contained four subgroups: *Intake saw groups 1*, *2*, *3* and *Board transporters*; the intake groups were placed in the groups *Saw groups 1*, *2*, and *3*, respectively. This meant that the processing equipment and the related material-handling devices were now found in the same main group. Figure 5 shows the tree structure for *Saw group 1* and its material-handling equipment.

The new tree structure consists of four levels, as shown in Figure 5. To obtain a uniform structure that facilitates the registering procedure for the operators and also the data analysis, the main processing and material-handling equipment were given essentially the same structure. The major difference is that only the tree structure for the main processing equipment has four levels. Level 1 includes the main process steps, Miscellaneous and Setup. For example, if you click on *Saw group 1*, you come to the second level consisting of the main processing equipment (*Saw group 1* in this example) and its material-handling equipment. The third level is identical for each piece of material-handling equipment and also constitutes the final level for this category. The processing equipment also has identical categories in the third level, except for the *Tools* group, which is found only in machines equipped with cutting or sawing tools.

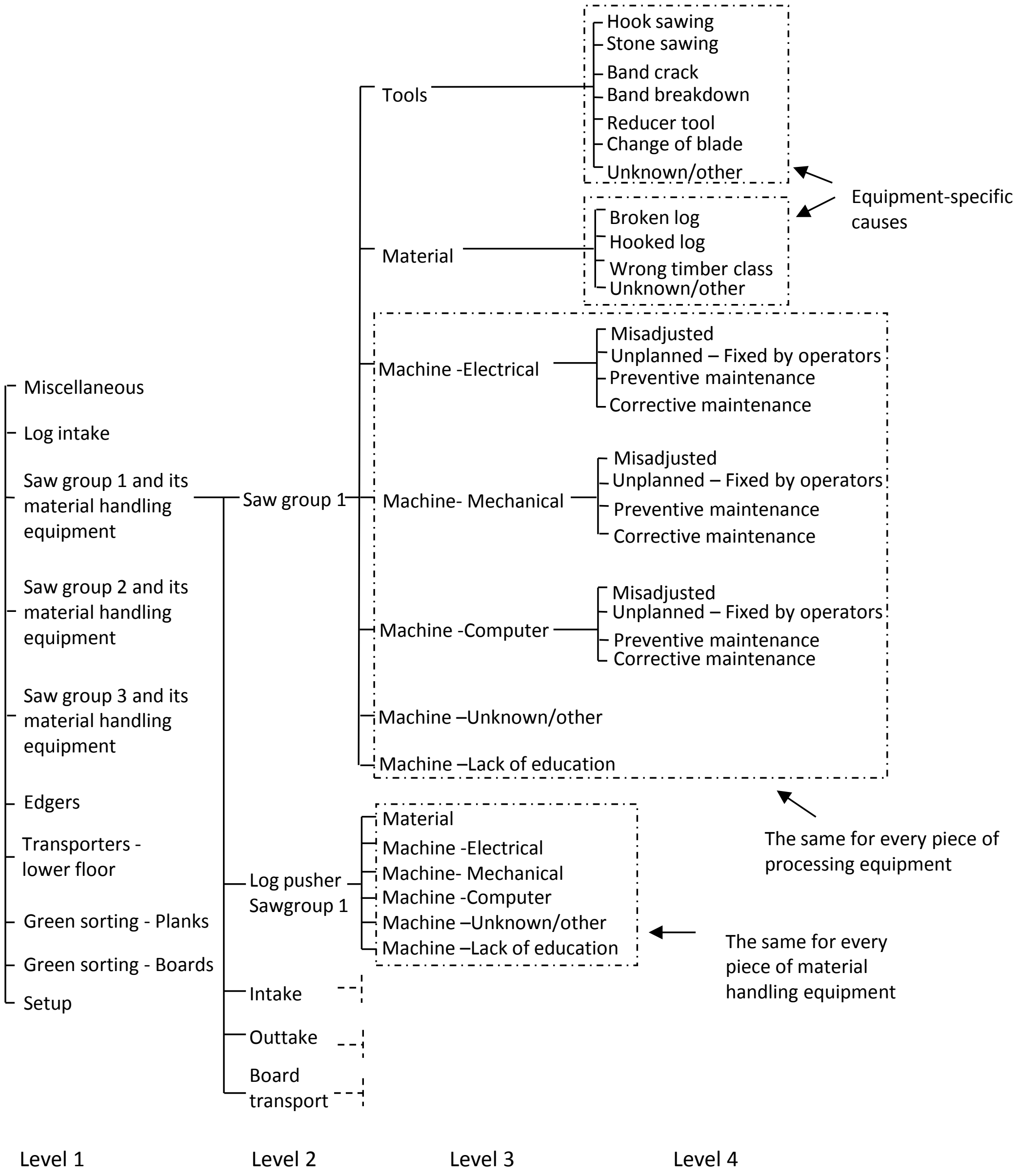

Figure 5. Example of the new tree structure and downtime causes.

6.2 Downtime causes

As mentioned above, the processing equipment has a more detailed downtime cause structure than do the material-handling devices. The tree structure for the latter offer only six downtime causes to choose from, as shown in the lower box in Figure 5, and they are the same for every piece of material-handling equipment. For the processing equipment, the *Tools* and *Material* subgroups include specific downtime items for every machine; the other downtime causes (indicated by the large rectangle in Figure 5) reappear for all processing equipment. There are three categories of machine- or equipment-related downtime, i.e., electrical, mechanical, and computer, and they have the same causes to choose from in the fourth level: *Misadjusted machine*, *Unplanned – Fixed by operators*, *Preventive maintenance*, and *Corrective maintenance*. Equipment-specific causes, as in the *Tools* and *Material* subgroups, were not included because making such a list was considered too complex, possibly making it too difficult and time consuming for operators to locate the appropriate causes.

One aim of the changes in the maintenance organization described earlier is to reduce the total time spent on maintenance by increasing the amount of preventive maintenance. In accordance with this, it was decided that *Preventive* and *Corrective maintenance* should be separated in the new tree structure. Maintenance-related downtimes consume maintenance resources, so it is of interest to highlight and separate them from the other downtimes. One can then obtain documentation of the distribution between maintenance and non-maintenance-related downtimes and how this distribution develops over time. The final two items, *Machine – Unknown/other* and *Machine – Lack of training*, are endpoints, i.e., they do not contain any individual downtime causes.

The item *Unknown/other* serves two purposes. First, it hinders downtimes from being incorrectly registered when operators choose a cause not corresponding to the actual cause of the downtime. Second, this category can indicate whether there are too few downtime items to choose from or whether operators are experiencing difficulties classifying the downtimes.

The new tree structure is divided into a maximum of four levels of detail and has a total of 292 individual downtime causes, compared with three levels of detail and 128 downtime causes in the original structure.

7 Results of implementing the described changes

One question addressed here (RQ1) was whether more detailed data regarding specific downtime causes could improve a company’s knowledge of its availability losses. According to the production manager, the changes in the downtime system have improved the usability of the collected data. He now knows more precisely what has happened in a downtime and thereby also what needs to be done to improve the situation. Because of the more detailed list of available downtime causes, he now finds it easier to steer discussions with operators towards specific problems. Before the changes, such discussions mainly concerned various production line areas, not specific root causes. He believes that the new level of detail provides him with enough information to choose the appropriate corrective and preventive actions needed to improve availability. Greater detail could, however, jeopardize the operators’ motivation and ability to register the correct downtime causes.

The other question raised here (RQ2) concerned how the personnel responsible for reporting the availability losses perceive the increased detail. The interviews with operators indicated that they generally favored the new list of downtime causes. They found that the new list enabled them to choose a downtime cause that actually described the occurred stoppage, making the monitoring more precise; this opinion was shared by all respondents. The main reason for the more precise description was the increased number of downtime causes to choose from in the system after the changes. With more downtime causes to choose from, operators might feel that data collection has become too complicated and time-consuming. However, the interviewed operators did not feel that the new system included too many downtime causes; as one operator put it, “You must have many downtime causes to choose from to obtain good follow-up.” One respondent said that the system could be even more detailed in some places, while other respondents suggested downtime causes that they felt were missing. Though one respondent believed that the new system would improve the monitoring results, he felt that data collection had become more difficult due to the great number of available downtime causes—there were almost too many to choose from.

All respondents were satisfied with the structure of the list of causes, and most operators said that the new structure was better than the previous one. The new structure has a deeper tree structure, which entails more mouse clicks to reach the right cause description, but this was generally not considered a problem. When operators were asked to estimate how much longer it takes to use the new list, the answers ranged from two to a few seconds. Some operators said that they found the new list and structure difficult to handle at first, but that after a few weeks they became more familiar with it and now had no more difficulties. The somewhat longer registration time when using the new list was mainly due to the deeper tree structure and increased number of downtime causes from which to choose.

More detailed monitoring makes more demands of those responsible for registering the downtime causes—according to Dal *et al*. (2000), the downtime data must be perceived as credible by production management for them to be used effectively. The operators are responsible for registering the downtime causes in the studied company, which means that operator competence greatly influences the correctness of the collected data. All interviewed operators said that it was occasionally difficult to know the cause of a stoppage, especially if it occurred in the raw sorting area. This is because the raw sorting area is far from the saw booth where the downtimes are registered. The operators in the raw sorting area must call the person in the saw booth and describe the cause of the downtime, and sometimes this communication is deficient, according to some respondents. Some respondents also said that even in situations in which one is involved in correcting a failure, it can be difficult to know its exact cause: several causes may be likely, and which of those are correct can be difficult to determine. Most respondents believed that it was easier to find an appropriate cause description after the described changes, because of the increased number of available causes to choose from and because of the consistent tree structure.

According to Ljungberg (1998), operators may not be sufficiently motivated to collect data, and motivation can be increased if operators believe the data are actually being used. All interviewed operators favored registering downtime and its causes, and several of them believed that the collected data constituted an important decision basis when production investments are made. However, three of the six respondents were somewhat critical of how the data were used in the company. They believed that the collected data were not used to the desired extent, and that no or too few investments were being made despite recurrence of the same downtime problems every week. The other three were satisfied with how the data are used.

8 Conclusions and discussion

This paper addresses the generation of knowledge of availability losses by documenting loss times and causes. Downtime monitoring is crucial for the studied company. It is used by the production manager as the basis of discussion in recurrent meetings with operators and maintenance personnel and in investment decisions. One purpose of the study was to investigate whether using a highly detailed list of cause descriptions was beneficial, or whether it was equally informative to use a simpler system that functioned more as an indicator of where in the system improvement resources should be spent, as mentioned by Jonsson and Lesshammar (1999). This was investigated by making changes to the existing downtime collection system by introducing more cause descriptions and developing a more consistent structure to make it easier to find the right cause and analyze the collected data. According to the production manager, the changes improved the company's knowledge of the causes of downtime occurrences. An increased number of available downtime causes in combination with a consistent structure has in this case been beneficial.

The study also aimed to investigate how the operators perceived an increased number of downtime causes. The results indicated that interviewees favored the changes, believing that the increased number of downtime causes has resulted in more precise documentation of the causes of the availability losses without making the documentation appreciably more difficult. However, some operators believed that the results of downtime registration were not used sufficiently or effectively in making improvements, highlighting that management must demonstrate the benefits of such data registration.

The results indicate that a downtime data collection system can be used not only to monitor the downtime rate but also as an analytical tool for establishing downtime causes, similar to an Ishikawa diagram. An advantage of the former is that it also establishes which downtime causes are most frequent and time consuming, enabling it to be used in prioritizing between improvement activities. In the studied case, the company had a computerized downtime data collection system including automatic downtime measurement—preferable for both practicality and data accuracy. The data handling is more efficient in such systems than in pen-and-paper solutions, and automatic downtime measurement increases the credibility of the obtained results because no false estimates or unreported downtime will occur.

To increase equipment availability, it is insufficient merely to understand the causes of the losses; methods and procedures for reducing the losses must also be in place. Issues regarding how to use the collected data are outside the scope of this paper, but whether or not more detailed and structured follow-up on availability would be beneficial depends largely on how the company uses the collected data. In the studied company, the results of the downtime data collection were the only tool for decision support regarding availability losses, which made the company an appropriate case for study. However, at the time of the study, the company had not yet fully developed a work procedure for reducing the losses. A continuous improvement program has been initiated. When it is fully implemented, the results of the downtime collection can be used more actively, making the operators even more motivated to collect the data because the information will be applied more actively in improvement work.

The study is based on only one company, which means that its results cannot be directly generalized to other companies. However, the results strengthen the hypothesis that increased knowledge of availability losses can be obtained using a detailed monitoring system and that increased detail will not necessarily be perceived unfavorably by the operators collecting the data.

Acknowledgements

This research was conducted within the Lean Wood Engineering program, financed by VINNOVA and within the Sustainable Production Initiative (SPI).

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