THESIS FOR THE DEGREE OF LICENTIATE OF TECHNOLOGY

Manufacturing Resource Modelling for Productivity Management

Towards a better understanding of the productivity improvement potential at shop floors

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ABSTRACT

The role of manufacturing has been vital for the creation of welfare in advanced economies ever since the industrial revolution. During the last decades several new markets have emerged and actors in manufacturing are competing on, what is now so often referred to as, globalised markets. There exists no single solution for manufactures to achieve economic efficiency. It is, however, evident that no manufacturing company can stay competitive without a sustainable and efficient use of available resources. The aim of this Licentiate thesis is to contribute to a better understanding of the productivity improvement potential at shop floors. Previous research has shown that manufacturing companies, in general, can improve the utilization of existing manufacturing resources by 30 to 50 per cent. To harvest this potential, owners must invest in their organisations. Therefore, the improvement potential needs to be visualised and quantified in order to motivate decision makers to prioritize shop floor improvement initiatives. A model and a modelling approach are proposed that provide insight into the link between the utilization of manufacturing resources and the real capacity of manufacturing processes. Quantification and visualisation of the improvement potential is accomplished by combining, and further developing, established industrial engineering techniques together with the international standard for manufacturing data management, incorporated in the model and the modelling approach. The model is not designed to give a complete description of a production system but to provide a bottom-up approach to analyse the improvement potential of selected processes and subsystems. Future work includes a software implementation of the model, towards the development of a decision support tool.

Keywords: Production improvement, productivity measurement, capacity, work study.

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I would never dream of ending an acknowledgement with a philosophical quote, instead I will state an obvious fact:

"Optimist: The glass is half full.
Pessimist: The glass is half empty.
Industrial Engineer: The glass is twice as large as it needs to be"

Richard Hedman

Gothenburg, November 2013

LIST OF APPENDED PAPERS

Paper A **Improvement potentials in Swedish electronics manufacturing industry – Analysis of five case studies.**
Sundkvist, R., Hedman, R., Almström, P., Kinnander, A., (2012).
Procedia CIRP - The 45th CIRP Conference on Manufacturing Systems, 2012, Athens, Greece, 3 pp.121-131.

Contribution: Sundkvist initiated the paper and wrote it with Almström and Kinnander as reviewers. Hedman co-authored the paper and participated in the gathering and analysis of the empirical data in three of the five case studies.

Paper B **A model for linking shop floor improvements to manufacturing cost and profitability.**
Sundkvist, R., Hedman, R., and Almström, P., (2012).
International Journal of Computer Integrated Manufacturing, 25 (4-5) pp. 315-325.

Contribution: Sundkvist, Hedman and Almström initiated and wrote the paper. Hedman developed and implemented the model architecture.

Paper C **Object-oriented Modelling of Manufacturing Resources Using Work Study Inputs.**
Hedman, R., Sundkvist, R., Almström, P., Kinnander, A., (2013).
Procedia CIRP – The 46th CIRP Conference on Manufacturing Systems, May 29-31, Setúbal, Portugal. 7 pp. 443-448.

Contribution: Hedman initiated and wrote the paper with Sundkvist and Almström as co-authors and Kinnander as reviewer. Hedman developed the model and the modelling approach, was the corresponding author, and presented the paper at the conference.

Paper D **Reference Model of Manufacturing Resources.**
Hedman, R., Sundkvist, R., Almström, P., Kinnander, A., (2013).
Proceedings of the International Conference on Advanced Manufacturing Engineering and Technologies, October 27-30, Stockholm, Sweden, 2 pp. 221-230.

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LIST OF ADDITIONAL PAPERS

The effect of factory floor productivity improvements on operational performance metrics.
Sundkvist, R., Almström, P., Hedman, R., Kinnander, A., (2013).

Published at the 20th European Operations Management Association (EurOMA) Conference, Dublin, Ireland.

Evaluating manufacturing information models for productivity and profitability assessment of manufacturing facilities.
Hedman, R., Sundkvist, R., Almström, P., Kinnander, A., (2012).

Proceedings of the 5th International Swedish Production Symposium, Linköping, Sweden.

Understanding cash conversion principles to facilitate and motivate manufacturing development initiatives.
Sundkvist, R., Hedman, R., Almström, P., Kinnander, A., (2012).

Proceedings of the 5th International Swedish Production Symposium, Linköping, Sweden.

How to realize the productivity potentials in the manufacturing industry.
Almström, P., Kinnander, A., Sundkvist, R., Hedman, R., (2012).

Proceedings of the 5th International Swedish Production Symposium, Linköping, Sweden.

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1 INTRODUCTION

This chapter introduces the research which is presented in this thesis, concerning manufacturing resource modelling for Productivity management. The background to the research is presented by describing the challenges in the manufacturing domain followed by a historical and current description of the targeted research field. Thereafter, the aim, objectives, and research questions are stated.

1.1 Challenges in manufacturing

In globalized markets the demands on employees and managers are growing and manufacturing's share of employment will continue to be under pressure in advanced economies (Manyika 2012). Manufacturing's share of the global trade is 70 per cent and in 2010 manufacturing employed approximately 45 million people in advanced economies (Manyika 2012). The European ManuFuture Strategic Research Agenda (Westkämper 2008) states that the main criterion for competition in manufacturing is economic efficiency which is measured by the relation of the cost of resources to the value of products. The increasing cost of resources in terms of material and energy is a direct result of world market conditions. This together with the costs of local labour and inefficiency of processes contribute to reduce the profitability of capital in the European manufacturing (Westkämper 2008). On a national level the Swedish production research agenda set by Teknikföretagen (2013) has defined a project topic for resource efficient production. It shall contribute in developing high-efficiency production systems that meets the requirements for flexibility and sustainable use of human and material resources in manufacturing. Consequently there are several challenges posed in the leadership in manufacturing to ensure economic efficiency and labour productivity.

The term productivity can however be interpreted in different ways. A common definition of productivity is the relationship between the products being produced and the amount of resources used in the transformation process (Bernolak 1997). There is a wide variation among the most and least productive actors in manufacturing globally (Manyika 2012). Productivity as an economic measure on a national level, as well as on an enterprise level, is calculated based on financial measures, such as the cost of resources and the value of sales. Nevertheless, that says very little about the actual productivity on the shop floors of manufacturing facilities. More importantly, the economic measure of productivity says nothing about the improvement potential at a shop floor level (Almström and Kinnander 2011). Overall in Europe there is uncertainness about the potential and the effects in manufacturing (Westkämper 2008). This is further confirmed by extensive shop floor productivity studies in Swedish manufacturing companies that have revealed a 30-50 per cent improvement potential in the utilization of manufacturing resources (Almström and Kinnander 2011).

1.2 Industrial engineering and work studies

It is almost unavoidable to talk about industrial engineering and work studies without mentioning the early days of mass production and the so called Taylorism. In the book The Principles of Scientific Management Frederick W. Taylor advocated to making production more efficient by creating a specialized class of managers who regulate different aspects of work, focusing primarily on manual work. It was condensed in four principles (Taylor 1914):

1) The development of a true science
2) The scientific selection of workers
3) His scientific education and development
4) Intimate friendly corporation between management and men

This resulted in a large debate in manufacturing known as the “efficiency craze” (Haber 1964). The actual degree of science in The Principles of Scientific Management has been questioned during the years. There is no confirmation that Taylor used any scientific criteria to select workers or managers (Stewart 2006; Hopp and Spearman 2008). It is however evident that Taylor defined the basic paradigm for manufacturing management (Westkämper 2008). The definition of industrial engineering, adopted by the Institute of Industrial Engineers state that industrial engineering is concerned with the design, improvement and installation of integrated systems of men, materials, equipment and energy (Zandin 2001). According to (Bailey and Barley 2005) the tools and techniques for work studies were the only parts of Scientific Management and Taylorism that industrial engineering departments adopted. Work studies can be categorized into shop practices and factory methods, motion and time studies and work measurement, ergonomics and job design (Bailey and Barley 2005).

Today, the European ManuFuture Strategic Research Agenda (Westkämper 2008) states that there is a need for a new type of Taylorism. It should consider specific human skills and take into account the constant changes and dynamics of the manufacturing domain. The efficiency trend started by Taylor during the 1920’s was again heightened with the introduction of just-in-time (JIT) in Japan during the 1970’s and 1980’s (Hopp and Spearman 2008). The efficiency trend boost of the western world was introduced after the MIT study of the Japanese automobile industry, presented in the book “The Machine That Changed the World” (Womack et al. 2007), that later contributed in outlining the so called Lean “philosophy”. According to Kuhlang and colleagues (2013) many of the methods and techniques used in lean initiatives today are based on already established methods and principles and from Taylor’s times. A period of downsizing industrial engineering departments around the world has, however, led to a loss of competencies in work study techniques among industrial engineers (Bailey and Barley 2005; Almström and Kinnander 2011; Kuhlang et al. 2013). Bailey and Barley (2005) describes how the role of industrial engineers has changed within the American industry during the past 50 years. They argue that it is time for industrial engineers to restore the interest in the nature of work and the particulars of the workplace. Kuhlang and colleagues (Kuhlang et al. 2013) refers to "the renaissance of the industrial engineer" when describing the revitalized need of competencies in work studies and time data management among industrial engineers in Germany. The full potential of work study tools and techniques was never reached during Taylor’s years but they remain vital elements for the manufacturing industry’s continued development (Niebel et al. 2003; Hopp and Spearman 2008) and for the understanding of the improvement potential at shop floors of manufacturing facilities around the world (Almström and Kinnander 2011).

1.3 Field of research

The management of resources and activities is incorporated in the definition of operations which refers to the application of resources to the production and delivery of products and services (Slack et al. 2010). Resources can in this sense be humans, material, and equipment as well as capital and energy. Operations are studied in the field of Operations management which besides manufacturing also includes areas such as service, healthcare, retail and transportation (Slack et al. 2010). Operations management research aims to contribute both to the knowledge of academics as well as to the knowledge of practitioners and development of skills in managing operations (Slack et al. 2010). Strategy and design are the two main perspectives of Operations management research (Karlsson 2008). The strategy perspective focuses on the roles and objectives for the operation while the design perspective involves planning information and material flow, and also physical layouts, and choice of process technologies for the transformation processes (Karlsson 2008; Slack et al. 2010).

Modelling and simulation is one research area within Operations management. It started in conjunction with the Scientific management era and has a strong quantitative focus (Karlsson 2008). It has contributed to knowledge in areas such as inventory control, forecasting, mathematical optimization and queuing theory etc. (Hopp and Spearman 2008). The produced models are often representation of idealized problems which, according to Karlsson (2008), can provide valuable input concerning basic trade-offs at a managerial level. They are, however, at the same time often insufficient as explanatory models of real operational processes. Another shortcoming of the idealized models is that the effect of the human factor on the performance of the operational processes is largely neglected (Karlsson 2008).

Operations management is, however, broader than the scope of this thesis. The Manufacturing technology research group have defined the field of research as Productivity management. It is an emerging field of research positioned as a branch of Operations management, based on shop floor activities. Productivity management is to:

- Set requirements and develop standards for process planning and design.
- Define, develop and apply measures for planning, follow-up, and control.
- Assess, revise, and improve activities using industrial engineering techniques.

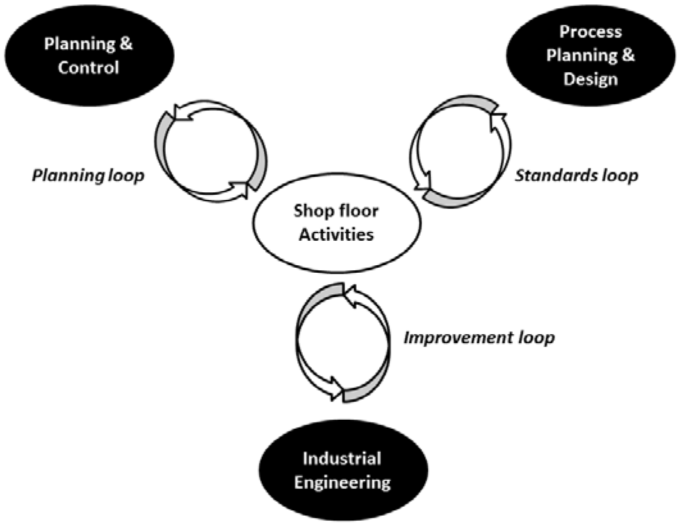

Figure 1 The scope of Productivity management

Productivity management is more than only measuring and improving productivity. Managing productivity is to continuously develop and improve the means necessary to achieve and sustain high productivity in the ever changing context of manufacturing. Productivity management is thus an objective-oriented discipline which requires prescriptive models to help guide decision making, and good descriptive models are the foundation for good prescriptive models.

1.4 Aim, objective and research questions

Productivity management research aims to contribute to the field of Operations management in providing bottom-up understanding of real operational manufacturing processes and their improvement potential. This is accomplished by applying and further developing the heritage of industrial engineering in general, and work studies in particular. In addition, Productivity management research aims to contribute in developing tools and aids for the practical side of operations management.

The objective of this Licentiate thesis is to present a model of manufacturing resources, and a modelling approach, that can describe and quantify the improvement potential of real operational manufacturing processes. The model should provide insight into the link between the utilization of manufacturing resources and the capacity of manufacturing processes, thereby supporting the analysis and prioritization of shop floor improvement initiatives.

Based on the objective, following research questions are stated in the context of Productivity management:

RQ 1: What are the key constructs needed to describe manufacturing resources and manufacturing processes?

The links between the key constructs of manufacturing resources and manufacturing processes can be expressed in a model. Thus, the second research question is stated as:

RQ 2: How can a model be designed taking into consideration the most important relations between manufacturing resources and manufacturing processes that influences a production system's improvement potential?

1.5 Delimitations

The developed model is intended to be applied for analysis and improvement of existing manufacturing systems. The incorporated definition of manufacturing resources is limited to humans and equipment. The model therefore does not consider resources in terms of energy, material or capital.

1.6 Structure of the thesis

In *Chapter 1* is the background presented together with a description of the research field of Productivity Management and the stated aim, objective and research questions. *Chapter 2* gives an overview of the theoretical framework and the state of the art that has been the foundation for the performed research. It includes topics such as modelling of manufacturing resources, modelling of productivity and a selection of industrial engineering techniques. The approach taken to answer the research question is described in *Chapter 3* which also presents the adopted view on science and the research process. *Chapter 4* summarizes the most important findings from the appended papers and in *Chapter 5* it is discussed how those findings relate to the research questions. *Chapter 6* concludes the thesis and the conducted research by answering the research questions.

2 THEORETICAL FRAMEWORK

This chapter gives an overview of the theoretical framework related to manufacturing resource modelling for productivity management. Related topics which have been taken into account during the research are presented and discussed.

2.1 Modelling of manufacturing resources

Models of manufacturing resources provide information about the people and equipment that perform activities on the shop floor and they can be modelled for a variety of purposes. Typically, manufacturing resource information is used for resource selection and process capability evaluations during the product development stage (Molina et al. 1995; Giachetti 1998; Zhang et al. 1999; Chengying et al. 2003; Feng and Song 2003; Young et al. 2005). Manufacturing resource modelling is also of importance within information system, such as computer integrated manufacturing (CIM), for planning and scheduling, and control and execution of production (Steele et al. 2001; Feng and Song 2003; Nielsen 2003; Guerra-Zubiaga and Young 2008). The models of manufacturing resource often include comprehensive definitions of activities performed by equipment resources, i.e. machine tools etc. Human resources and manual activities are, however, defined to a very limited extent and sometimes even neglected.

2.1.1 Modelling approaches

During the last decades numerous modelling approaches have been developed (Siau 2004). Modelling approaches differ in how they cognize the real world and three basic approaches can be found within the domain of manufacturing information systems (Lee 1999).

Entity-relationship approach is based on the graphical notion technique and consists of three basic building blocks: entities, relations and attributes (Chen 1976). The approach is commonly used within data-base design (Siau and Wang 2007).

Functional modelling approach focuses on processes and the transformation of data flow, often expressed as data flow diagrams (Lee 1999). It has objects and functions as basic constructs and provides static representations of systems.

Object-oriented (O-O) approach replaces entities with objects and classes. It considers both data and functions that enable a picture of the whole process and which actors or processes that is associated with it. An object is a representation of real, or intended, things and a class defines the objects properties and behaviours (Lee 1999).

2.1.2 Modelling methods and languages

Modelling methods and languages are based on one, or several, modelling approaches. Some of the most frequently used for modelling of manufacturing systems are presented below.

Integrated Computer-Aided Manufacturing (ICAM) DEFinition – IDEF constitutes of a large family of methods that are widespread in the industrial context. The original IDEFs were developed to enhance communication among people who needed to decide how their existing systems were to be integrated.

IDEF0 is built on the Structured Analysis and Design Technique (SADT) and is a functional modelling method. It describes a system's functions by the process of function decomposition and categorization of relations between functions by using the classifications Input, Output, Control and Mechanism. IDEF0 diagrams are static and have no representation of time. (NIST 1993)

IDEF3 is termed as a process description capture method and was developed to overcome some of the shortcomings and limitations of IDEF0 models. It is a structured method of expressing the domain experts' knowledge about how a particular system works. IDEF3 contains two modelling approaches: functional and object-oriented. (Dorador and Young 2000)

IDEF1X is originated from the IDEF1 (Information modelling) method and it is a data modelling method developed to support the design and analysis of semantic data models. It has an enhanced graphical representation compared to earlier IDEF methods and is based on the Entity-relationship approach. (Kusiak et al. 1997).

Unified Modelling Language (UML) provides several graphical modelling diagrams targeted mostly to systems modelling. It has become an industry standard for modelling software-intensive systems (OMG 2011). The languages notations and rules are designed to represent data requirements in terms of O-O models. Use case diagrams can be created to capture a system's functionality and class diagrams to capture its vocabulary. There are also several diagrams to describe system behaviour and to represent implementation, interaction and deployment activities. (Siau et al. 2005; OMG 2011)

EXPRESS modelling language is a part of the Standard for the Exchange of Product model data (STEP) and defined in ISO 10303-11. It consists of language elements that allow an unambiguous data definition and specification of constraints on the data defined and is based on the O-O approach. It uses a textual representation with graphical subsets available; this graphical representation is called EXPRESS-G. (ISO 1994).

2.1.3 Standardised representations of manufacturing resources

In general, standardised information models of manufacturing systems exist to improve the management of information. The representations of manufacturing resources are essential in those models. There are well-established standards for manufacturing resource data acquisition and information exchange. Two of them are the Core Manufacturing Simulation Data (CMSD) and ISO 15531 Manufacturing Management Data Exchange (MANDATE), compared in Table 1.

Table 1 Specifications comparison between CMSD and ISO 15531.

	Scope	Domain coverage	Application supported
CMSD	"Simulation of manufacturing operations in job shop environment"	Core set manufacturing data	Discrete event simulation of manufacturing and 2D layout
ISO 15531	"Computer-interpretable representation and exchange of industrial manufacturing management data"	Manufacturing resource usage management data Manufacturing flow management data	Manufacturing resource planning (MRPII)

The CMSD, developed by Simulation Interoperability Standards Organisation (SISO), provides data specifications that shall enable efficient exchange of manufacturing life-cycle data in a simulation environment (Lee et al. 2011). Resources are defined as equipment or employees that are used to carry out manufacturing processes. The standard has a resource information package, expressed as UML diagrams, which contains a resource class with 11 defined attributes and association roles, including for instance; type of resource, shift assignment, associated resources, hourly rate, skill, and resource group definition (SISO 2010).

The ISO 15531 MANDATE (ISO 2005) has status as an International Standard (IS) and is associated with ISO 10303 which, as stated previously, is for product data representations, and IEC 62264-1 the standard for enterprise-control system integration. The conceptual information model for resources usage management data in ISO 15531 -32 is structured, using EXPRESS, into six modules:

1. Resource hierarchy
2. Structure of resource characteristics
3. Resource status
4. Definition of resource views
5. Definition of resource characteristics
6. Resource configuration

While the ISO 10303 is targeted on product representation is the focus of ISO 15531 put on defining the processes of the whole enterprise. It has been implemented in a manufacturing resource planning environment to address both operational and financial planning with simulation capabilities to evaluate "what-if" scenarios (Cutting-Decelle et al. 2012).

2.2 Shop floor productivity and capacity

There are numerous scientific publications concerning different approaches to measure and improve productivity at manufacturing facilities. Muthiah and Huang (2006) reviewed and categorised methods for productivity improvement of manufacturing systems into:

- Operations research-based methods

- System analysis based methods
- Continuous improvement methods
- Performance metrics-based methods

Operations research methods, as stated in section 1.3, typically have a strong quantitative focus and are thus based on mathematical or analytical models. The purpose of the methods is oriented towards decision making based on understanding the behaviour of manufacturing systems. They can include methods such as linear programming, stochastic programming, queuing theory, and different optimization approaches etc. Curry and Feldman (2011) presents practical applications of queuing theory for analysis of manufacturing systems. In addition, Li and Meerkov (2009) provides a comprehensive compilation of methods for mathematical modelling of manufacturing systems. The mathematical approach can also be used to create calculation models of productivity and capacity to, for instance, support diagnosis, benchmarking, and the design of plant performance systems, such as in the cases presented by Grando and Cigolini (2005; 2007).

The system analysis based methods, as categorized by Muthiah and Huang (2006), have their foundation in information systems. Manufacturing systems are broken down into smaller entities and modelled in a hierarchal structure. That includes the creation of conceptual reference models using, for instance, SADT, IDEF and similar (Al-Ahmari and Ridgway 1999; Huang et al. 2002).

When referring to continues improvement methodologies Muthiah and Huang (2006) lists well know concepts such as Lean, Six Sigma, and Theory of Constraints etc. They can, however, not be separated from the other categories of methods since several integrated approaches exits as well. For example, Hernandez-Matias et al. (2008) applies system analysis based method in a continuous improvement context. Furthermore, performance metrics-based methods such as Little's law (Little 1961) and Overall Equipment Efficiency (OEE) (Dal et al. 2000) are incorporated in both operations research-based methods and continues improvement methodologies and vice versa. The combination of methods and approaches is not uncommon since it is generally agreed that no single method or model can capture all aspects of a manufacturing system.

2.2.1 Industrial engineering techniques

Acquisition of shop floor data is naturally a prerequisite for modelling and analysis of productivity and capacity. Shop floor data can be acquired automatically through real time follow up- and control systems, such as manufacturing execution systems (MES). It can also be historical data stored in companies' planning systems. Nevertheless, it is not uncommon that there exists a substantial difference between the operation times in reality and the operation times stored in the companies' systems. Two of the main causes for this is that often are the operation times not set correctly to begin with, and they are seldom, or never, updated once they are logged in the system (Almström and Winroth 2010).

There exist several well established industrial engineering techniques that can be used for direct measurements in order to acquire shop floor data.

Predetermined time systems originate from the Scientific Management era where Frederick W. Taylor was one of the first to assign standard times to basic elements of work. Today it exists over 50 systems of predetermined time (Niebel et al. 2003). Some of the most commonly used predetermined time systems are the family of Methods-Time Measurement (MTM) (Maynard et al. 1948) and Maynard Operation Sequence Technique (MOST). Many Swedish companies use the MTM-based system Sequence Based Activity and Method Analysis (SAM) (IMD 2004). Method analysis is the name of the established technique, using predetermined time systems, were manual activities are improved, or developed, by for instance reducing or eliminating unnecessary movements, reach distances etc. (Niebel et al. 2003).

Performance rating is defined by Niebel, Freivalds et al. (2003) as "the assignment of a percentage to the operator's average observed time, based on the actual performance of the operator as compared to the observer's conception of standard performance". It can, simplified be described as an assessment of the speed of work in relation to the defined standard time for that work task.

Work sampling is a statistical method for determining the amount of time a resource spends on performing defined activities. Compared to traditional time studies is work sampling considered as a faster and less costly procedure providing equal or even better data. It is based on the law of probability where analyzes of work is done by taking a large number of observation at random times (Niebel et al. 2003) A smaller number of likelihood occurrences tend to follow the same distribution pattern that a larger number produces (Brisley 2001). Niebel, Freivalds et al. (2003) lists following advantages of a sampling approach compared to time studies:

- It does not require continuous observation by an analyst over a long time.
- Clerical time is diminished.
- The total work hours expended by the analyst are usually much fewer.
- The operator is not subjected to long-period stopwatch observations.
- Crew operations can be readily studied by a single analyst.

2.2.2 The dimensions of shop floor productivity

Productivity can be improved by increasing output or decreasing input. Saito (2001) and Helmrich (2003) have defined the three dimensions of productivity to better understand what factors to focus on when improving productivity.

The method factor (M) is defined as the ideal or intended productivity rate. It is the inverse of the ideal cycle time for the specific work task.

The performance factor (P) corresponds to the speed the work is carried out at in relation to the ideal cycle time.

The utilization factor (U) represents the time that is spent on performing the intended work in relation the total planned time. Utilization can never go beyond 100%.

The three factors are multiplied together to show the actual productivity rate when performance and utilization losses are considered. The concept has been used in several publications (Saito 2001; Almström and Kinnander 2008; Kuhlang et al. 2011).

3 RESEARCH METHOD

This section presents how the research has been conducted by describing the research process in relation to different views of science. The main research methods and techniques used are also presented followed by the selected approach to validate the research.

3.1 Views on science

Research can be defined as an activity that contributes to the understanding of a phenomenon (Kuhn 1996). Selecting a research approach will indirectly decide which view of science that is adopted and it involves the role of theory and its relation to research. There are two fundamental relations between research and theory and it concerns weather data is collected to test theories or to build theories (Chalmers 1999; Popper 2002) . By following a deductive strategy the researcher uses existing theory to formulate hypothesizes and thereafter collects data attempting to falsify the theory (Popper 2002). Reversely, by following the inductive strategy the researcher uses observations and findings to build theories (Popper 2002). Quantitative research methods are typically related to a deductive strategy while qualitative research methods relates to an inductive strategy. However, in practice the two strategies and their related methods are not as clear cut as they are defined (Bryman and Bell 2007). A selected research approach might include both inductive and deductive components in different parts during the research process. The strategies therefore should be seen more as tendencies rather than hard distinctions (Bryman and Bell 2007). As stated, the research presented in this thesis concerns the identification and description of key constructs, to identify the linkages between these constructs, and present those relationships in a descriptive model. Therefore, the research process is closely aligned with the inductive strategy. van Aken (2004) have distinguished three categories of scientific disciplines:

1) The formal sciences, e.g. philosophy and mathematics.
2) The explanatory sciences, e.g. the natural sciences and major sections of the social sciences.
3) The design sciences, e.g. the engineering sciences and medical science.

The research presented in this thesis is a developmental and engineering type of research, which then falls under the category of design science.

3.2 Design science research

Design science is described as the recognition of laws of design and its activities, and also the development of rules (Hubka and Eder 1988; Blessing and Chakrabarti 2009). Design is both a process (set of activities) and a product (artefact) (Hevner et al. 2004). According to Blessing and Chakrabarti (2009) the objectives of design science research are the formulation and validation of models and theories (or better theories) about the phenomenon of design with all its facets, e.g. people, product, knowledge/methods/tools, organization. These models and theories then serve as the basis for development and validation of support to improve design practice and its outcomes.

Research in design science combines description-driven and prescription-driven research. Van Aken (2004) states that the outcome of the research should be tested and grounded technological rules. A technological rule is general knowledge, i.e. that it is valid for classes of cases, linking an artefact with a desired outcome or performance in a certain field of application (Aken 2004). In explanatory research the anticipated outcome is often the causal model (Bryman and Bell 2007). In comparison with technological rules, the causal models are often partial and explain only certain aspects of the studied phenomenon. Technological rules, on the other hand, are holistic. Therefore, general knowledge must be translated to the unique and specific case at hand in order to be used by professional in the studied field (Aken 2004). In Table 2, Vaishanavi and Kuechler (2004) categorize and summarize the outputs of design science using a broad perspective.

Table 2 The outputs of design science research, adapted from (Vaishnavi and Kuechler 2004).

	Output	Description
1	Constructs	The conceptual vocabulary of a domain
2	Models	A set of propositions or statements expressing relationships between constructs
3	Methods	A set of steps used to perform a task
4	Instantiations	The operationalization of constructs, models and methods
5	Better theories	Artefact construction as analogous to experimental natural science, coupled with reflection and abstraction

The artefacts can thus be constructs, models, methods and instantiations. The constructs represent the language in which the structure, problem and solution is defined. The models use the constructs to represent a real world solution and also aid in understanding and communicating the developed solutions (March and Smith 1995).

3.3 Research process

The research presented has been conducted from 2011 to mid-2013 (Figure 2). In order to provide transparency, this section will describe the research process in relation to a framework for design science research. It is followed by a presentation of the main research methods used. A more detailed method description is found in relation to each appended paper.

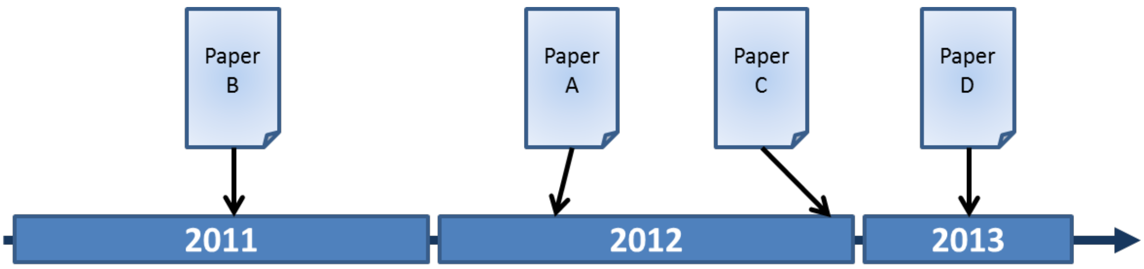

Figure 2 Research timeline.

3.3.1 Design science framework for research

Research in design science is based on the conception that the reality needs to be modelled in different stages in order to be understandable for the researcher, i.e. an analytical perspective (Duffy and O'donnell 1998; Aken 2004; Blessing and Chakrabarti 2009) (Vaishnavi and Kuechler 2004). Observations and analyses of the reality results in descriptive phenomena models (Duffy and O'donnell 1998). It is essentially a creative step and can be criticized for introducing non-repeatability into the design science research method (Vaishnavi and Kuechler 2004). Nevertheless, Vaishanavi and Kuechler (2004) states that analogues can be found in all research methods. They use an example from positivistic research where creativity is inherent in the leap from curiosity about an organizational phenomenon to the development of appropriate constructs that operationalize the phenomena, and selection of a suitable research design for the measurements.

As illustrated in Figure 3, the actual research work can focus and start on any element of the framework, and iteratively switch focus between the elements. Models are in general tested by moving from right to left in the framework.

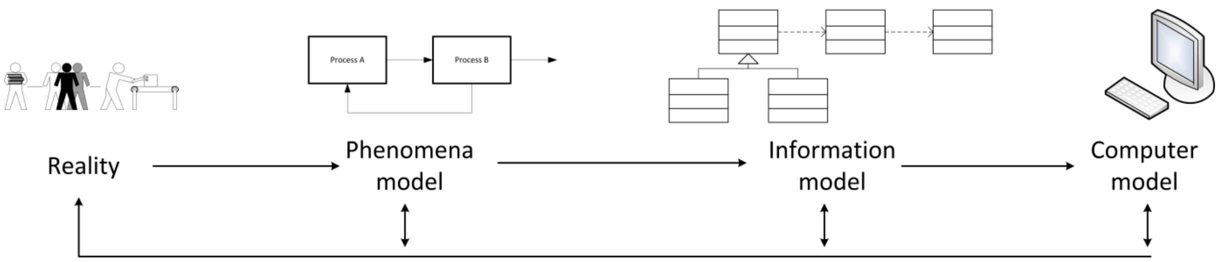

Figure 3 Research framework, adapted from (Duffy and O'donnell 1998).

Selected phenomena models are developed into more detail as information models which in turn constitute the foundation for the development of computer models. The presumption of the framework is that computer systems can provide active support for human limitations without interfere with the fundamental strengths of human activities (Duffy and O'donnell 1998).

3.3.2 Research process iterations

The approach taken to answer the research questions is described as two research process iterations that are put in relation to the framework for design science research (Figure 4). Iteration 1 is associated with the appended papers A and B, while iteration 2 is associated with appended papers A, C and D. In both iterations, case studies and literature surveys represented the observation and analysis of reality, i.e. the first element of the framework.

The first iteration resulted in a computer model and a modelling approach. Its purpose was to show a link between profitability effects caused by productivity improvements and thereby supporting the analysis and prioritization of shop floor improvement initiatives. The output from iteration 1 was evaluated and a need for a more detailed and through information architecture in order to meet the research objective was then identified. It resulted in iteration 2 where a reference model and a related modelling approach were developed.

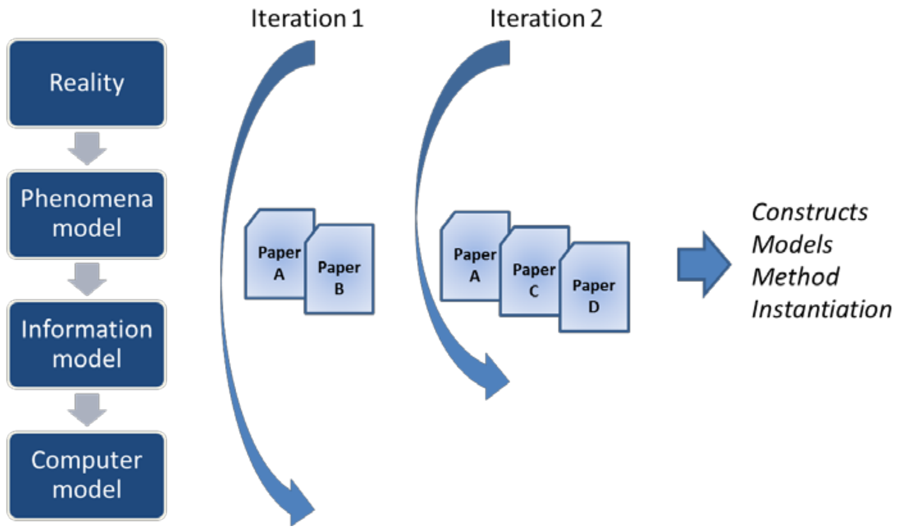

Figure 4 Research process.

3.3.3 Research methods and techniques

Following sections provide a general description of case study design, literature surveys, and systems development which constitute the main research methods used.

Case study

A large proportion of the empirical framework for the developed phenomena and information models is derived from the results and experiences of the five case studies in appended paper A. The case study design is preferable if the study wants to explore contextual conditions of real life events (Yin 2009). It allows the usage of many different data sources. The studies were conducted according to the methodology developed by Sundkvist (2011). It included data collection techniques such as structured interviews, access to company data, and direct measurements using industrial engineering techniques such as work sampling and method studies. The two initial case companies were selected based on their participation in the ProViking 2 research project ChEPro and remaining companies since they were electronic manufacturers with similar type of production.

Literature review

Literature reviews have been conducted for each of the appended papers using search strategies such as building blocks, fractionalizing and most specific fact. The most frequently used databases were Scopus, Google Scholar, ProQuest, Emerald, and Summon which is the Chalmers University of Technology's library discovery search service. In addition, table of content alerts for relevant scientific journals have been used in order to monitor the current research front.

Systems development

Systems development as a research method has been used during the development of information models and computer models. It can consist of following stages (Nunamaker Jr and Chen 1990):

1) Construct a conceptual framework
2) Develop the system architecture
3) Analyse and design the system
4) Build the system
5) Observe and evaluate the system

Williamson and Bow (2002) differ between systems development as a research method and systems development for commercial purposes. In research, the major emphasis is put on the actual concept illustrated by the system, and less thought is taken considering the quality of the actual system implementation. In addition, the evaluation of the physical artefacts, i.e. the information model or computer model, also differs from testing of a commercial system. It is performed from based on the research questions, and the functionality of the system is a secondary issue (Williamson and Bow 2002). The information models and their constructs are expressed using the Unified Modelling Language (UML) (OMG 2011).

3.4 Quality of research

This section present the different criteria from which the quality of the conducted research is further discussed upon later in section 5.

3.4.1 Reliability

Reliability is connected to if whether the results of the research are repeatable. That also includes to demonstrate that the results did not occur by chance (Williamson and Bow 2002). The empirical data is collected, compiled and structured using established techniques, presented in the theoretical framework. The model development follows the systems development method and the resulting model is built on established standards and theory.

3.4.2 Validity

Validation of models is the process of determining to what degree the models corresponds to the real world from a user perspective (Oberkampf et al. 2004). The **construct validity**, which also can be referred to as measurement validity, concerns whether or not a construct that is developed of a phenomena really does reflect the phenomena that it is supposed to be denoting (Williamson and Bow 2002; Bryman and Bell 2007). An assessment of construct validity assumes that the construct, or measure, is reliable (Bryman and Bell 2007). The **internal validity** concerns the relationships and the internal consistency of the constructs when they are put together in the model (Pedersen et al. 2000; Bryman and Bell 2007). The degree of **external validity** determines whether the results of the performed research can be generalised outside the specific research context (Bryman and Bell 2007). This is ensured by generating representative example problems where the model and method can be evaluated with respect to its purpose.

4 SUMMARY OF APPENDED PAPERS

This section presents a summary of the appended papers highlighting the aim, methods and conclusions. A background for each paper is given to provide motivation for why the paper was initiated and to put the individual papers in context with the research process.

4.1 Paper A - Improvement potentials in Swedish electronics manufacturing industry – Analysis of five case studies

Background

The five case studies were initiated as a part of the research project ChEPro funded by Swedish Foundation for Strategic Research (SSF) and the ProViking 2 research program. The overall purpose was strengthening the Swedish electronics industry by introducing novel design solutions as well as improving the existing production systems. Five companies from the Swedish electronics manufacturing industry were analysed. Four out of five companies are classed as Small and Medium-sized Enterprises (SMEs), with a number of employees ranging from 50-250 and one is classed as a large company.

Aim and method

The aim of the studies was to develop and test a methodology for profitability analysis of a manufacturing facility during a very limited amount of time. In this context profitability analysis refers to analysis of the effects on profitability generated from doing shop floor productivity improvements.

The methodology for each case, which is more elaborately defined in (Sundkvist 2011), consists of data collection, analysis, and finally presentation during a period of five days, or one work week.

Day 1

A complete PPA study (Almström and Kinnander 2011) is performed at a selected subsystem of the manufacturing facility. As stated, this includes measuring the utilization of manufacturing resources combined with an overall analysis of the manufacturing system.

Day 2 & 3

The activities of the studied subsystem are mapped and analysed using the Sequence Based Activity and Method analysis (SAM) (IMD 2004). This, together with the results from the PPA study, defines the current state of the subsystem. A future state is thereafter developed and is presented as a collection of potential scenarios for different productivity improvements.

Day 4

Day four is devoted to financial data collection. Historical data in terms of the annual report is used together with data from the company's accounting system and with help from the accounting personnel, i.e. a controller. The financial data is intended to be used to calculate

Return on Investments (ROA) using Du Pont schematics (White et al. 2003) linked to the proposed productivity improvements.

Day 5
During the final day all collected data is compiled and presented for the company.

Results and conclusions
The results from the five case studies can be looked upon from two perspectives. Either focusing on the improvement potential in Swedish electronics industry or the application of the developed methodology and its capability to capture and evaluate profitability effects of shop floor productivity improvements. The application of the methodology is the most relevant perspective for the research presented in this thesis.

The cases confirmed that a detailed current state description of a subsystem could be created during the limited time span where current status and potential changes in productivity are expressed using the M, P and U dimensions. The productivity increase for future scenarios was estimated in a systematically and re-tractable way by using SAM analysis to calculate new productivity ratios (M-values). Due to the long-time consumption required to conduct SAM analysis any performance rating (the P dimension) was, however, often neglected. It was shown that the largest productivity potential unquestionable is in improving the method. Therefore, method analysis was prioritized rather than to analyse and evaluate the performance of the individual resources. No follow up study was made to see if suggested improvements actually were implemented, and therefore it is not possible to determine the potential improvement in resource utilization (the U dimension). Consequently, it cannot be excluded that a method improvement might result in lower resource utilization if the utilization is not measured after the method improvements have been implemented.

It was found that the work sampling results, i.e. the utilization, for machine operators were harder to interpret than for the utilization of assemblers. Machine operators influence costs directly but output indirectly since the output is created by the machines. The machine operator’s utilization can however affect the machines utilization, which was measured with OEE. It was therefore concluded that the applied methodology works well for manual activities, such as assembly, but needs to be further investigated on how the synergies and the interrelations between operator utilization and machine utilization should be analysed.

Concerning the profitability analysis of the manufacturing facilities it was concluded that when using ROA in a short term analysis, such as the proposed methodology, there were difficulties of analysing the effects from historical events that formed the balance sheet to its current state. In addition, it was also difficult to normalize the effects of surrounding events occurring during a full business cycle. Therefore alternative measures of profitability or other financial measures were stated as another area that needed more investigation.

4.2 Paper B - A model for linking shop floor improvements to manufacturing cost and profitability

Background

The underlying rationale for the article is that many companies do not know how their production system contributes to the organization's profitability. A need for a tool that could ease the communication between production engineers or shop floor personnel, in general, and the management or the owners of the company had been identified. In addition, the measurements and surveys during each of the cases (Paper A) generated vast amounts of data. It resulted in a complex, and consequently, time consuming data compilation and analysis. The development of a supporting computer model was therefore initiated parallel with the case studies (Paper A).

Aim and method

The aim was to partly automate the compilation of data to facilitate the development of descriptive current state models of the assessed manufacturing systems. The intended application of the computer model included three steps: (i) Build descriptive current state models of manufacturing systems, (ii) Perform simulations of possible profitability effects of productivity improvements, and (iii) Display the results.

The data recording and compilation had primarily been done using Microsoft Excel spread sheets. It was therefore decided that the computer model should use Excel spread sheets as a platform. Phenomena models based on observations and analyses from the first three case studies were created. They were in turn further developed into more detailed data flow diagrams, which constituted the conceptual framework for the system building. A literature study focusing on linking operation effects to financial effects was also conducted.

Results and conclusions

The models of the assessed systems are structured according to the production system definition in Table 3. The computer model is written in Visual Basic for Applications (VBA). Each task is built by VBA modules incorporating Excel's standard functions and analysis tools. For example, simulation of profitability effects of productivity improvements is accomplished by creating "What if"-scenarios.

Table 3 Production system definition.

Level:	Name:	Description:
1	System	The manufacturing facility.
2	Subsystem	A defined area of the production facility (level 1), e.g. the storage area, the painting area or the assembly area etc.
3	Activity	A specific activity performed in the subsystem (level 2), e.g. assembly, inspection or testing etc.
4	Sub-activity	A specific part of an operation (level 3) containing a sequence of elements (level 5). For example count components, put components in box, deliver box to position A to B.
5	Element	An individual activity performed in the sub-operation, e.g. get, put or use etc.

The developed computer model incorporated industrial engineering techniques together with accounting and financial analysis in an attempt to link shop floor improvements to manufacturing cost and profitability. The modelling approach follows similar steps as the data collection procedure in the cases (Paper A).

There are, however, several difficulties in both the data collection and building the relationships in the computer model. A method analysis of one product might not be valid for other products even though they are arranged as the same type of manufacturing process. The literature survey revealed that to make the method analyses and activity definitions more accurate it was proposed that time equations for product families, derived from Time-Driven Activity Based Costing (Kaplan and Anderson 2004), should be formulated.

4.3 Paper C - Object-oriented Modelling of Manufacturing Resources Using Work Study Inputs

Background

The computer model and the modelling approach (Paper B) was tested and evaluated during the two final case studies of the ChEPro project. It was then found that more detailed information model was needed in order to meet the research objective. Iteration 2 of the research process was therefore initiated.

A literature survey of manufacturing information models related to productivity assessment was conducted (Hedman et al. 2012) prior to Paper C. Most of the published manufacturing information models are subject to manufacturing systems integration for modelling areas such as process planning, performance measurement, manufacturing resource capability modelling or selection, business modelling, and modelling for manufacturing system design.

Aim and method

During the survey it was revealed that there are well established standards and systems for data acquisition and information exchange concerning manufacturing equipment. Human manufacturing resources were, however, often defined to a very limited extent, or even neglected. There is a great uncertainty in what to measure, how to measure, and further in in how to use those measures to improve planning and control of production. The solution can be found in conventional work study techniques. The aim of Paper C is to show how work study data can be applied as input to detailed modelling of human manufacturing resources and manual work tasks. The application of work study techniques is essential in Productivity management, and it can indeed be of interest for any model or system application that strives for valid representations of manual work tasks.

Phenomena models from the two final cases were developed, focusing on the application of output data from work study techniques. To provide a platform for more detailed information models was a survey of information standards conducted. The standards reviewed were: SISO-STD-008-2010 - Standard for Core Manufacturing Simulation Data, and ISO 15531 MANDATE – Manufacturing Management Data Exchange.

Results and conclusions

The ISO 15531 MANDATE was considered most sutiable to be used as a basis. Relevant definitions and the structure of manufacturing resource characteristics was adopted from the standard. The adopted definition of a manufacturing resource is thus: “any device, tool, and means, excepted raw material and final product components, at the disposal of the enterprise to produce goods or services”. The production system defintion, which defines the context for manufacturing resources, was further developed from Table 3 into a production system model expressed as a UML class diagram (Figure 5).

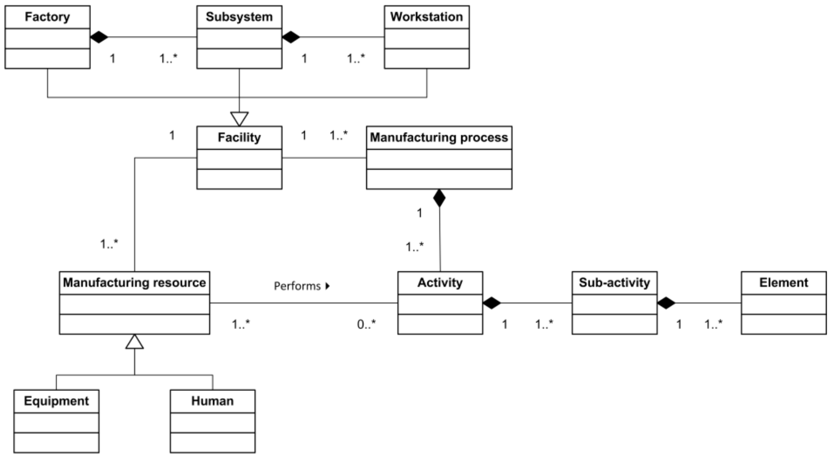

Figure 5 Production system model.

Facility

A Factory represents the actual manufacturing facility and is the top system level of the model. It can be broken down into subsystems which correspond to defined areas of the manufacturing facility. A subsystem consists of one or several workstations which are defined areas within the subsystem.

Manufacturing processes

In a Facility one or several Manufacturing processes are executed. A Manufacturing process can be described from the views Factory, Subsystem, or Workstation. Hence, a Manufacturing process can be seen as the entire process of converting raw material in to finished products (Factory view) or as a delimited set of activities performed in a Subsystem or at a Workstation.

Activities

An activity consists of sub-activities that constitute a specific part of an activity, expressed as a sequence of elements. The elements are standard movements which are defined in a pre-determined time system such as MTM (Maynard et al. 1948). The activities are formulated as time equations, derived from Kaplan and Anderson (2004). In Figure 6 are time drives (X_1, X_2, and X_3) assigned to sub-activities. Dependent on the desired level of detail they can, however, be assigned to elements or to complete activities. Selected time equation components can thus be eliminated if their time driver value is set to 0. The TDABC approach was chosen in order to handle product variations.

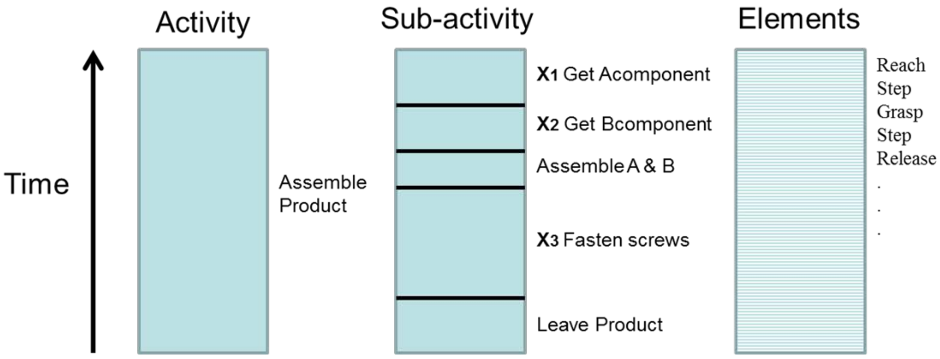

Figure 6 Activity composition.

As an example, the time equation for the activity in Figure 6 is expressed as:

Assemble product =X_1×Get Acomponent + X_2×Get Bcomponent +Assemble A&B + X_3×Fasten scews + Leave product

The norm time for the activity is given by quantifying the time driver values, i.e. number of A- or B components, number of screws to fasten etc. Norm time is referred to as ideal cycle time of the activity. Ideal shall, however, not be confused with optimal. As seen during the case studies (Paper A) there is a large improvement potential on an activity level. The ideal cycle time only refers to the ideal time duration related to the current standard, i.e. activity design. Consequently, improving the activity design will result in a new ideal cycle time.

The performance factor (P) corresponds to the speed the work is carried out at in relation to the ideal cycle time. For manual work the performance factor can be both below and above 100%. The normal speed in MTM is set to be valid for a “normal” person working at this speed for 8h a day and for the whole working life without getting exhausted or injured. The performance rate is lower for not fully trained workers and for people with disabilities.

Table 4 Definition of performance rates.

	Variable	Definition
P	Personal performance rate (P_P)	The personal performance rate is affected by the individual’s physical ability and his or her motivation to work at a high speed (relative the MTM norm), independent of work task.
	Skill based performance rate (P_S)	The skill based performance rate is the individual’s speed at performing a specific work task depending on the training and the experience the individual has for the task.

Measurements of manufacturing resource utilization (U) can be done by work sampling studies when the resources perform activities. As seen in Figure 7 measurements can be done on a Workstation level as well as on a Subsystem or Factory level.

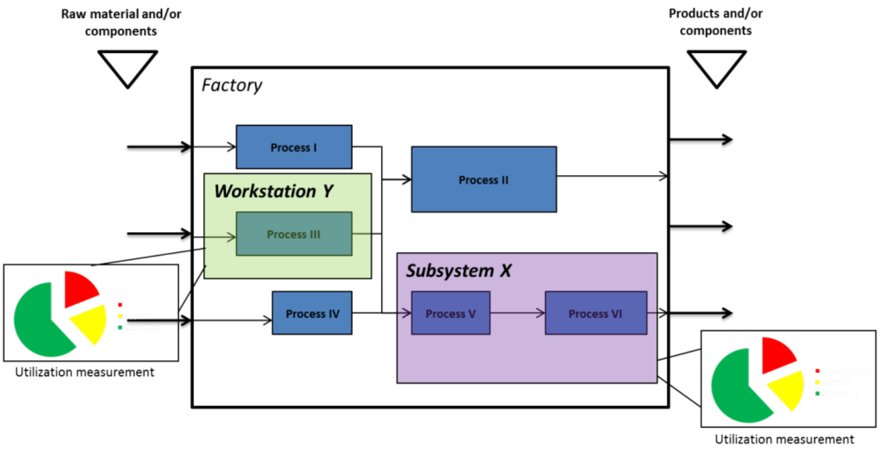

Figure 7 Utilization measurement.

The work sampling study is designed according to the definitions in Table 5. The utilization ratios U_N, U_S, and U_D symbolises utilization losses. Consequently, U= 100% would imply that the resource is spending 100% of the planned time on performing the defined activity with zero losses. Utilization above 100% is not possible, and utilization equal to 100% in a real life setting is highly unlikely since there will always be losses. Naturally, improvement initiatives should strive to minimize the identified losses.

Table 5 Definition of utilization rates.

	Variable	Definition
U	Need based utilization rate (U_N)	The need based utilization rate depends on the need for relaxation and personal time. It is often regulated by agreements at the work place. It includes paid breaks and losses before and after a break.
	System designed utilization rate (U_S)	The system designed utilization rate is defined as the balance losses designed into the system. It can be balance losses on an assembly line as well as losses in a semi-automated work station.
	Disturbance affected utilization rate (U_D)	Disturbance affected utilization rate corresponds to the losses caused by different random disturbances. It includes the lost time from discovery of the disturbance until the work is performed at full speed again.

The ideal productivity rate (M) for a manufacturing process is given by inversing the ideal cycle time of its constraining activity if there were no losses the ideal productivity rate would correspond to the processes ideal capacity. However, the real capacity (CAP_R), or practical capacity considering performance (P) and utilization (U) losses, for a manufacturing process is defined as: M × P × U.

4.4 Paper D - Reference Model of Manufacturing Resources

Background

This paper was initiated as the natural next step in research process iteration 2, to apply the findings of Paper C in a broader context.

Aim and method

The aim was to present a reference model that could be incorporated to cost efficiently explain and quantify a manufacturing firm's hidden improvement potential in currently used manufacturing resources. It is intended to be implemented in software to provide decision support for assessing the improvement potential, for instance during rapid scenario analyses or to provide input data to more advanced simulation tools.

Results and conclusions

As adapted from ISO 15531 are the manufacturing resource characteristics organized as Figure 8. The entity resource_administration specifies the resource's cost per time unit, i.e. salary for humans, depreciation for equipment etc. The entity resource_capability has a list, or a reference to a list, to what activities the resource can perform. The capability of a resource can be further specified using performance related attributes (P_P or P_S) for each activity. The capacity of a manufacturing resource, defined in the entity resource_capacity compromises information about its potential workload. It is expressed as planned capacity (CAP_{PL}) which corresponds to the resource's working schedule, i.e. its planned availability. For equipment it corresponds to the planned production time.

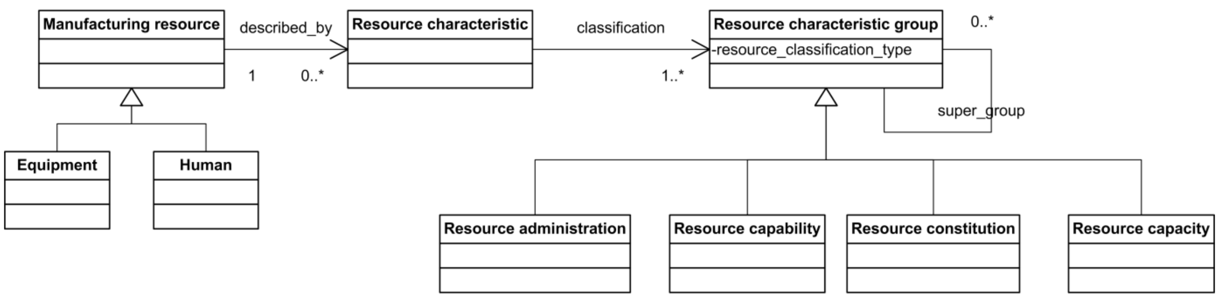

Figure 8 Organisation of manufacturing resource characteristics, adapted from ISO 15531 (2005).

The modelling approach is the foundation for creating AS IS models of the assessed manufacturing systems. The system boundary is a firm's factory walls. In a Facility, for a selected range of product families:

1. Map activities and develop time equations based on methods analysis and pre-determined time systems.
2. Re-integrate activities into the general system by arranging them into manufacturing processes according to product routings.
3. Assign resources according to manufacturing order, production planning etc. Define performance related attributes for each resource.
4. On the selected system view (Factory, Subsystem, Workstation), measure manufacturing resource utilization through work sampling and/or data from manufacturing execution systems (MES).
5. Following a constraint based approach to calculate the real capacity (CAP_R) for the manufacturing process.

Utilization losses are, as stated, identified and categorised as disturbance-, system-, or need related. The time equations display the work content of the current standard. The improvement potentials are, thereby, in terms of resource utilization and work design visualised and quantified all the way down to the individual movements of a manual work task.

The fundamental objective of a manufacturing system is to transform inputs to outputs. Improvement initiatives are typically focused towards maximizing throughput while at the same time minimizing inventory and operating expenses. Selecting the best approach to improve a manufacturing system is, however, context dependent. Two performance measurement areas can, however, be distinguished: internal efficiency, i.e. actual resource usage connected to the resource function, and flow efficiency, i.e. the actual resource usage in relation to the throughput time. Two resource roles have been defined for analysis purpose, to be able to evaluate possible improvement scenarios with respect to flow efficiency and internal efficiency (Figure 9). A manufacturing resource is assigned to a role which in turn is required by one or several activities.

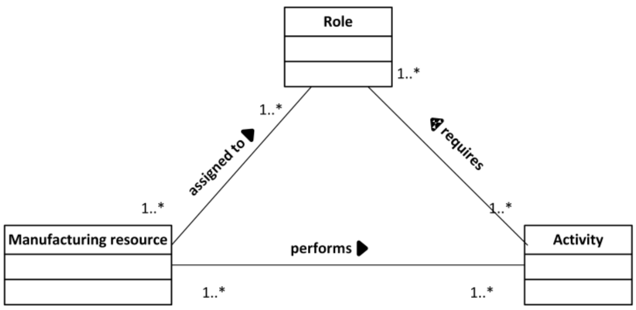

Figure 9 Resource role associations.

A resource has a direct role if it is assigned to perform an activity that is positioned direct in the product flow and thereby has a direct effect on the throughput time. That includes, for instance, activities where material:

- undergoes transformation (i.e. machining or joining)
- is being transported downstream
- undergoes inspection activities (i.e. quality control or testing)

A resource has an indirect role if it is assigned to perform an activity that is decoupled from the direct product flow and thereby only has an indirect effect on the throughput time. Activities can be identical, independent of if the resource is assigned to a direct role or an indirect role. The distinguishing of direct and indirect roles is done after step 5 in the modeling approach and consequently depends on the design of the assessed manufacturing system and the planning of its operations. The model can thereafter be put in relation to the established laws of manufacturing system behavior.

5 DISCUSSION

This chapter discusses how the main results relate to the research questions and the objective of the thesis. The research approach is also discussed based on methodological considerations and the reliability and validity of the results. Finally, suggestions for future work are proposed.

The findings presented in this thesis concerns modelling of manufacturing resources for productivity management. As stated, the objective of this Licentiate thesis is:

> "… to present a model of manufacturing resources, and a modelling approach, that can describe and quantify the improvement potential of real operational manufacturing processes. The model should provide insight into the link between the utilization of manufacturing resources and the capacity of manufacturing processes, thereby supporting the analysis and prioritization of shop floor improvement initiatives."

5.1 The key constructs needed to describe manufacturing resources and manufacturing processes

Manufacturing resources and manufacturing processes are examples of real-life objects. They are represented by information, which is structured in a conceptual model and expressed using a modelling language, as shown in Figure 10. Constructs, i.e. the conceptual vocabulary of the domain, refers to the formulation the objects. In other words, their definition and how that definition is described, or expressed, with a modelling language.

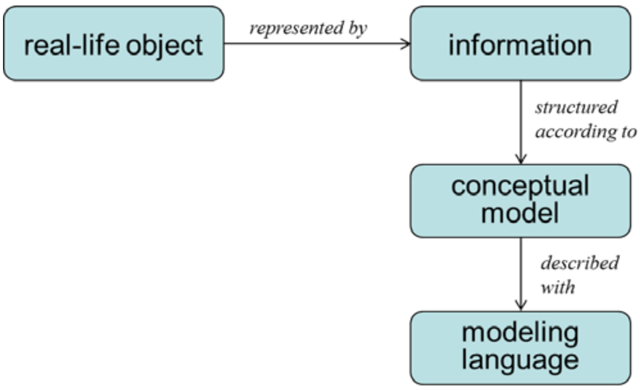

Figure 10 Formulation of constructs.

Answering the first research question consequently addresses how the key constructs of manufacturing resources and manufacturing processes were formulated in order to meet the stated objective. Three main criteria have been considered during the research process:

- The constructs shall, in order to support comprehensibility and communicability, be based on established vocabulary and description within the domain of Productivity management.

- The constructs shall enable a quantification and visualisation of the improvement potential of both resources and processes founded on the formulation of an actual state versus and ideal state.
- Construct data that constitute resource- and process information shall be acquired using available and generally accepted data collection methods and techniques, and not being dependent on unique system applications etc.

There is no official standard devoted solely for Productivity management that defines the constructs of resources and processes. The scope and purpose of the international standard for manufacturing data management (ISO 15531) was, however, found as most suitable to represent the basis for vocabulary and description of the constructs. Mostly due to its purpose which is to facilitate manufacturing data management to support decisions for efficient and sustainable resource usage. Consequently, its definition of manufacturing resources was adopted. The key constructs needed to describe the resources are accordingly three of the defined resource characteristics: resource administration, resource capability and resource capacity. The standard for core manufacturing simulation data (CMSD) would have been applicable as well. Nevertheless, the ISO 15531 was selected since it was considered to be more established, due to its status as an international standard (IS), and for having a more holistic view of production systems.

Previous research had shown that there is a great improvement potential in Swedish manufacturing industry, especially in manual activities (Almström and Kinnander 2008). During the literature review for Paper C it was, as stated, found that no other existing model of manufacturing resources could provide a good enough description of activities performed by humans. In this case, good enough description refers to the ability of quantifying and visualising the improvement potential. That ability is found among the different approaches for modelling of shop floor productivity and capacity. The concept of the productivity dimensions Method, Performance and Utilization had during the case studies (Paper A) and in previous research (Saito 2001; Helmrich 2003; Kuhlang et al. 2011) proven capable of representing manual work tasks and visualizing shop floor improvement potentials. The concept was therefore further developed (Paper C and D) and integrated with the ISO 15531 standard. As seen, the standard was not adopted to its full extent since its scope and broader than the context of the research presented in this thesis. The objective is not to develop a new manufacturing resource planning system. The integration was made by defining the attributes of the resource characteristics using primarily the developed performance (P) and utilization (U) rates.

Formulating key constructs for the description of manufacturing processes also followed the integrated approach between ISO 15531 and the productivity dimensions. In the standard a process is defined as “a structured set of activities involving various enterprise entities that is designed and organised for a given purpose”. The design of activities according to given standard, or norm, is the definition of a method (M) of the productivity dimensions. In order to capture costs for resource consumption etc. are activities formulated as time-equations derived from, as stated, time-driven activity based costing (TDABC) by Kaplan and Anderson (2004). The TDABC approach was evaluated with other accounting methods, such as the traditional activity based costing (ABC) and throughput accounting, in Paper B. In addition, the collection of construct data, for both resources and processes, can be accomplished using well-established industrial engineering techniques, as a result from the integration of the productivity dimensions.

The motivation for choosing UML as modelling language, describing the constructs, also deserves some attention. An evaluation of UML, EXPRESS and IDEF was made after the first iteration of the research process (Hedman et al. 2012). The IDEF family was found to be the oldest and most widespread modelling method with origins in manufacturing process modelling and computer integrated manufacturing. The EXPRESS language is, as stated, part of the ISO 10303 standard and is commonly used for integration between different manufacturing system applications, often with an orientation towards machining. UML has primarily been applied for systems development and is, compared with IDEF and EXPRESS, more common outside the manufacturing sphere. During the last decades the developments of the three modelling methods and languages have resulted in that they have individually become more and more comprehensive and overlapping in terms of where they can be applied. There is no ultimate language or method than can capture all dimensions of a manufacturing system. All three modelling languages and methods are, however, sufficient to meet the requirements for the models presented in this thesis. UML was chosen since the developed models are intended to be implemented in software, as a decision support tool for the practical side of operations management, and UML provides the best prerequisites for that. Though, the incorporated ISO 15531 standard is formulated using EXPRESS. Mapping selected parts if the standard from EXPRESS-G to UML was conducted using the guidelines provided by Arnold and Podehl (1999).

5.2 The relations between manufacturing resources and manufacturing processes

By definition is a model a set of proposition or statements expressing the relationships between constructs (Vaishnavi and Kuechler 2004). A reductionist viewpoint was taken when developing the model. That means that efforts were made to reduce the complexity of a production system to a manageable level by focusing attention to the specific relations between resources and processes that influences a production system’s improvement potential.

The first step of expressing the relationship between resources and processes was to put them in the context of a production system. The production system model was, as stated, developed from the defined production system hierarchy (Paper A and B) into a UML class diagram (Figure 5). There the most fundamental relationship is expressed; resources perform activities. It is important to note the multiplicity of the association between resources and processes in the production system model. It states that one, or more, resources can perform zero, or more activities. In other words, resources exist even when they do not perform activities. An activity does not, however, exist physically unless it is being performed by one or more resources. In the ISO 15531 this is referred to as resources exist a priori, without being assigned a specific task. The relations between manufacturing resources and manufacturing processes are further described using the M, P and U dimension incorporated in the model.

Method – The processes are, as stated, built up by activities, sub-activities and elements. The activity design, indirectly the process design, can therefore be expressed as a norm, or standard time. That enables the formulation of an ideal state, which does not include performance and utilization losses. The integration of predetermined time systems and the composition of processes and activities also allow a future ideal state be developed, by for instance using method analysis techniques. Of course, a production system will always have losses and in reality can an ideal state never be reached. Though, the ideal state is the foundation for setting the objectives and requirements for doing shop floor improvement initiatives. It can also be used when evaluating the results of conducted improvement initiatives.

Performance – Resources' capability is included in their relation to the activities that shall be performed. By incorporating the performance rates the model considers resource's skill and motivation. The skill based performance rate states what a resource can perform, meaning to specify which activities, and to what extent the activity can be performed, i.e. the speed of performing the activity in relation to its norm time. Reduced speed of performing an activity can be due to the skill level (such as a novice) or the physical ability (such as an injury). For equipment is speed losses reduced speed, referring to when the actual speed differs from the planned speed. It would be an overestimate to argue that the model, in its current state, is sufficient enough to be used to measure and assess the motivation of individual human resources. In order to accomplish that, factors such as physical and psycho-social work environment needs to be considered in more detail.

Utilization – Resource utilization which refers to the amount of time that a resource spends on performing planned activities can then, of course, only be measured when activities are being performed. Though, the utilization is not solely result of the direct relation between resource and activity. As defined in Paper C, the utilization losses are influenced by factors of the surrounding environment which prevents the resource from performing planned activities, i.e. disturbances, system design factors, and need based factors. The work sampling technique can also be used to determine the utilization of equipment resources (Niebel et al. 2003). Same type of data could be extracted from a well-designed manufacturing executions system. Distinguishing the different utilization factors' impact on a production system's performance will be dependent on what level in the production system hierarchy that they are measured and analysed. This was the motivation for defining the facility hierarchy of Factory – Subsystem – Workstation in the production system model. The higher up in the hierarchy, the more influences from surrounding environment can be captured. Though, the level of detail will be reduced. Which view that shall be adopted is a decision that a potential analyst will have to take, based on the current context and objective of the analysis.

The real capacity of a manufacturing process, which as defined is the result of multiplying the M, P and U dimensions, is used to evaluate a production system's improvement potential against an ideal state. Visualisation of this improvement potential is one of the main parts stated in the objective. The developed model visualises the improvement potential in following ways:

- The decomposition of manufacturing processes into activities, and then further into sub-activities and elements enables a visualisation of potentially unnecessary components all the way down to single movements.
- The performance rates show the performance improvement potential by visualising performance losses primarily due to resource's skill and physical ability. This can be used to identify the need for training, i.e. to increase the amount of activities that a resource is able to perform or to increase the skill of activities that the resource already can perform. In addition, by visualising skill and physical ability will the model aid in assuring that resources are not assigned to perform activities that exceed their capabilities. Thereby reducing the risk for personal injuries or product quality defects.
- Visualisation of the improvement potential concerning resource utilization is accomplished by presenting the results from utilization measurements next to the mapping of activity design. Thereby, the improvement potential in resource utilization is shown in relation to the current standard (activity design) and the surrounding system (disturbances, production system design, and need based criteria).

The last relation covered in the model is between resource, activity and role. It was developed to facilitate the selection of how improvement initiatives shall be directed by, as stated, distinguish between flow efficiency and internal efficiency. To evaluate the impact of the role associations, it needs to be empirically tested and validated further.

The developed modelling approach represents the method for building the relations in the model. Its steps were founded on the data collection procedure derived from the case studies in Paper A. The same modelling approach is intended to be followed regardless if a single work station or an entire factory is to be analysed.

5.3 Quality of research

The research questions stated to fulfil the formulated objective have been answered. The repeatability of the results is strengthening by the documentation from the case studies and the use of established data collection and analysis techniques. The repeatability of the case studies is further strengthened by the very similar type of production of the five studied companies that enabled a good basis for comparison. The development of phenomena models and information models followed the systems development method. Though, as stated does the actual model development include creative steps which have been criticised as introducing non-repeatability into design science research (Vaishnavi and Kuechler 2004). The decisions taken when creating the model are more detailed expressed in the appended papers, but the existence of some creative aspects is, however, judged as unavoidable.

Construct validity is ensured through the use of accepted standards and previous literature, as described in section 5.1. Internal validity can be discussed based on the relationships expressed in the developed model. Just as for internal validity, the relationships between constructs rest on previous research, standards and empirical tests through case studies. There is, however, a need to further validate the model from the second iteration in a real setting once it has been initiated as a computer model. External validity can be ensured based on the representative examples from case studies and also the models ability to handle typical manufacturing system behaviour, as expressed in Paper D.

5.4 Future work

The output from the second iteration of the research process is mainly of a theoretical character. The natural next step is therefore the instantiation of the model and modelling approach into a computer model, such as a software tool or similar. This will be the basis for to strengthen external validity, and also for extensions of the model and its intended application. The relations between manufacturing resources and manufacturing processes are in the model primarily expressed using the M, P and U dimensions. The interrelationships among the dimensions need more research in order to better understand the actual effects of different shop floor improvement initiatives. For instance, how an improved activity or process design will affect the overall resource utilization and performance, and vice versa.

6 CONCLUSION

This section concludes the findings of this thesis by answering the stated research questions.

The output of the research presented is a model and a modelling approach for manufacturing resources, developed in a context of productivity management. The results aim to contribute to a better understanding of real operational manufacturing processes and their improvement potential.

RQ 1: What are the key constructs needed to describe manufacturing resources and manufacturing processes?

The key constructs needed to describe manufacturing resources are the defined resource characteristics. They are divided into the categories administration, capability and capacity.

The key constructs needed to describe manufacturing processes are their composition of activities, sub-activities and elements, expressed as time-equations based on standard, or norm times, representing the current ideal state.

RQ 2: How can a model be designed taking into consideration the most important relations between manufacturing resources and manufacturing processes that influences a production system's improvement potential?

The model places the manufacturing resources and manufacturing processes in the context of a generic production system model. The model is not designed to give a complete description of a production system but to provide a bottom-up approach to analyse the improvement potential of selected processes and subsystems. The model is designed to establish an ideal current state of the analysed object, which improvement initiatives can be directed towards. The practical capacity of manufacturing processes are defined based on the relations between processes and resources where the improvement potential is visualised with a level of detail that can be adjusted dependent on the prerequisites of the analysis.

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