THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Financial benefits of shop floor productivity improvements

Robin Sundkvist

Department of Materials and Manufacturing Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2014

Financial benefits of shop floor productivity improvements

Robin Sundkvist

ISBN 978-91-7385-991-2

Doktorsavhandlingar vid Chalmers tekniska högskola

Ny serie nr 3672

ISSN 0346-718X

Department of Materials and Manufacturing Technology

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0) 31-772 1000

Printed by:

Chalmers Reproservice

Gothenburg, Sweden, 2014

Financial benefits of shop floor productivity improvements
Robin Sundkvist, Department of Materials and Manufacturing Technology,
Chalmers University of Technology

Abstract

The prevailing situation in the global economy calls for innovative productivity investment approaches aiming to prevent further labour force reductions and to restore manufacturers' competitiveness. The purpose of this research initiative has been to motivate production managers to invest in productivity improvements by establishing a framework that explains how shop floor productivity improvements provide financial benefits. The research initiative has employed an iterative research process that is based on case study research and interviews.

Productivity is, however, a broad term concerning materials, energy consumption, human skills and capabilities, production technology and capital. This thesis presents an explanatory framework that focuses on shop floor productivity, i.e. productivity concerning activities and resources used to refine, assemble and transform materials into finished goods. The explanatory framework bears upon a set of productivity analysis tools and techniques that are used to decompose shop floor work content into parts that can be analysed. The framework emphasizes the importance of efficient utilization of a firm's current resources before investing in new technology for solving capacity issues.

Several stakeholders can use the information provided by this framework. For instance, it can be used for increasing operators' awareness of the economic impact of quality losses, rework or idling production lines. Also, the framework can be used to increase production managers' and the treasury department's awareness of the production system's inherent capacity limitations and how the production system's current capacity is used to ensure and provide customer satisfaction. And finally to prevent unnecessary technology investments in situations in which utilization improvements with small investment means provide better economic payoff compared with capital-intensive technology investments.

Three improvement actions have been proposed based on the explanatory framework presented in this thesis. These are *real capacity improvements*, *production policy improvements* and *inventory policy improvements*. Each proposal refers to improvements of a production system's existing resources with small or non-monetary investments that in a direct fashion contribute to improved financial performance.

Keywords: Manufacturing, Productivity, Cash flow

Acknowledgements

The research presented in this thesis was carried out at the research group of Productivity Management at the department of Materials and Manufacturing Technology at Chalmers University of Technology, Sweden, in collaboration with several industrial partners. The research project has received support by the Swedish Foundation for Strategic Research (SSF), the ProViking 2 research program, and also the Sustainable Production Initiative and the Production Area of Advance at Chalmers University of Technology.

First I would like to acknowledge my research group, especially my supervisor Associate Professor Peter Almström, for putting both time and effort in the research project and for giving continuous feedback and insightful thoughts during the complete research project. Many thanks also go to Professor Anders Kinnander, who has given me the opportunity to work with inspiring tasks and challenging activities from the beginning to the end of the research project. I am also grateful to all the companies and their personnel that participated in various studies and thus provided valuable inputs this research project and, also to Christian Carlén at Condustria Industrial Management AB for being an excellent industrial mentor.

In addition I would like to thank Tech. Lic. Richard Hedman for providing valuable insights, some related to this thesis and others to topics stretching beyond the scope of this thesis. I would also like to acknowledge the members of the Manufacturing Operations Excellence Center (MOCE) for providing intangible experiences and knowledge of all kinds. Last, but not least, I would like to thank all my friends, family, with special regards to my beloved Matilda and Monken, for all motivation and happiness in everyday life.

Robin Sundkvist,

Gothenburg, March 2014

Publications

Some of this thesis findings and results have been presented in the following publications:

1. Sundkvist, R.; Almström, P. ; Kinnander, A. (2009). Manufacturing system analysis methods review, *In the proceedings of the international 3rd Swedish production symposium.*
2. Sundkvist, R.; Hedman, R.; Almström, P. (2012). A model for linking shop floor improvements to manufacturing cost and profitability. *International Journal of Computer Integrated Manufacturing*. 25 (4-5) s. 315-325.
3. Sundkvist, R.; Hedman, R.; Almström, P. et al. (2012). Improvement potentials in Swedish electronics manufacturing industry – Analysis of five case studies , *Procedia CIRP - The 45th CIRP Conference on Manufacturing Systems, May 16-18, Athens, Greece*. 3 s. 126-131.
4. Sundkvist, R.; Hedman, R.; Almström, P. (2012). Understanding cash conversion principles to facilitate and motivate manufacturing development initiatives, *Proceedings of the 5th International Swedish Production Symposium, Linköping*.
5. Sundkvist, R.; Almström, P. ; Hedman, R. et al. (2013). The effect of factory floor productivity improvements on operational performance measures, *Published at EurOMA 2013, 7th-12th June 2013, Dublin, Ireland*.
6. Sundkvist, R.; Almström, P. ; Kinnander, A. (2010). A profitability assessment method for the electronics manufacturing industry, *In the proceedings of the 10th manufacturing accounting research conference, Ghent.*
7. Hedman, R.; Sundkvist, R.; Almström, P. et al. (2012). Evaluating Manufacturing Information Models for Productivity and Profitability Assessment of Manufacturing Facilities, *Proceedings of the 5th International Swedish Production Symposium*.
8. Almström, P. ; Kinnander, A. ; Sundkvist, R. et al. (2012). How to realize the productivity potentials in the manufacturing industry, *Proceedings of the 5th International Swedish Production Symposium, Linköping*.
9. Hedman, R.; Sundkvist, R.; Almström, P. et al. (2013). Object-oriented Modelling of Manufacturing Resources Using Work Study Inputs, *Procedia CIRP*. 7 s. 443-448.

Table of contents

List of figures

List of abbreviations

C2C = Cash-to-cash cycle

CAP_A = Available capacity

CAP_I = Ideal capacity

CAP_{PL} = Planned capacity

CAP_R = Real capacity

CAP_{RQ} = Requested capacity

CAP_U = Utilized capacity

CFO = Cash Flow from Operations

COGS = Cost Of Goods Sold

CS = Current state

DES = Discrete event simulation

FS = Future state

IFG = In-house finished goods

JIT = Just-In-Time

LMT = Lean maturity model

MPU = Method, Performance, Utilization

MRP = Material Requirement Planning

MS = Manufacturing Strategy

MSE = Manufacturing System Engineering

MTM = Method-Time-Measurement

OM = Operations Management

OEE = Overall Equipment Efficiency

OEM = Original Equipment Manufacturer

OPF = Original Performance Frontier theory

P_P= Personal Performance rate

P_S = Skilled based Performance rate

PM/S = Performance Measurement / System

PPA = Productivity Potential Assessment

PPM = Parts per million

PSA = Production System Analysis

PSE = Production System Engineering

PTS = Predetermined Time System

RQ = Research question

RBV = Resource Based View

ROA = Return on assets

ROI = Return on investments

RPA = Rapid Plant Assessment

RPF = Revised Performance Frontier theory

SAM = Sequential Activity and Method analysis

SCA = Sustainable Competitive Advantages

SMA = Surface mount assembly

SPS = Scania Production System

T_R = Throughput rate

T_T =Throughput time

TDABC = Time-Driven Activity Based Costing

THM = Through-hole mounting

TQM = Total Quality Management

TPM = Total Productive Maintenance

U_D = Disturbance based utilization rate

U_N=Need based utilization rate

U_S = System design based utilization rate

UML = Unified Modelling Language

WIP = Work-In-Process

VSM = Value Stream Mapping

WACC = Weighted Average Cost of Capital

1. Introduction

This chapter describes the background for this research initiative and also positions the research context. A brief historical review and an outlook of today's challenges and opportunities are provided. The purpose, aims and objectives of the thesis are also presented, followed by a numbered list of the research questions. The chapter ends with a description of the research limitations and an outline of the thesis.

1.1 Background

The global economy is slowly recovering from the past financial crisis that forced manufacturers worldwide to rapidly cut costs. These actions resulted in significant unemployment increases and large budget deficits both at national levels and at enterprise levels (Reinhart and Rogoff, 2009). The resulting uncertainty and volatility in today's economic environment provides manufacturers with challenges such as sudden fluctuations in market demand and economic conditions. In order to cope with these challenges, manufacturing firms needs to establish flexible and cost-effective operations that react (and possibly pro-act) quickly but with maintained or improved capabilities to capture growth opportunities. Manufacturers in various countries are facing unique challenges. However, the overall challenge in both developing and advanced economies is to sustain and develop economic growth. And, one of the main sources of economic growth is *productivity* (Prokopenko, 1992).

Productivity is a well-known and established term that describes the relationship between the products or services produced and the quantity of resources used in the transformation process (Bernolak, 1997). The meaning of productivity differs depending on what context it is used in. For instance, at national levels it is used to guide policy makers in setting wage policies and at enterprise levels it is used to ascertain performance (Prokopenko, 1992). Productivity growth, especially contributions from the manufacturing sector, has helped drive economic growth and raise living standards for many centuries. Today, manufacturing is still the predominant sector contributing productivity growth in both developing and advanced economies (Mckinsey Global Institute, 2012). Manufacturing matters due its crucial role for productivity contributions. The manufacturing sector also significantly contributes to exports that subsequently contribute to GDP growth (Feder, 1983). This growth is the foundation of building and maintaining national wealth, for instance through enabling infrastructure investments, constructing modern housing and facilities and funding R&D projects to reduce CO_2 emissions, etc.

Figure 1 is depicting productivity increase in Swedish business sectors from 1994 to year-to-date, measured as value-added (production value less costs for materials and external services) per hour worked. The average productivity increase from 1993 and onwards is 2.5%. The manufacturing sector's contribution has been higher than average, with an increase of 3.8% per year, while the service sector in the same period of time presents an average increase of 1.6% per year

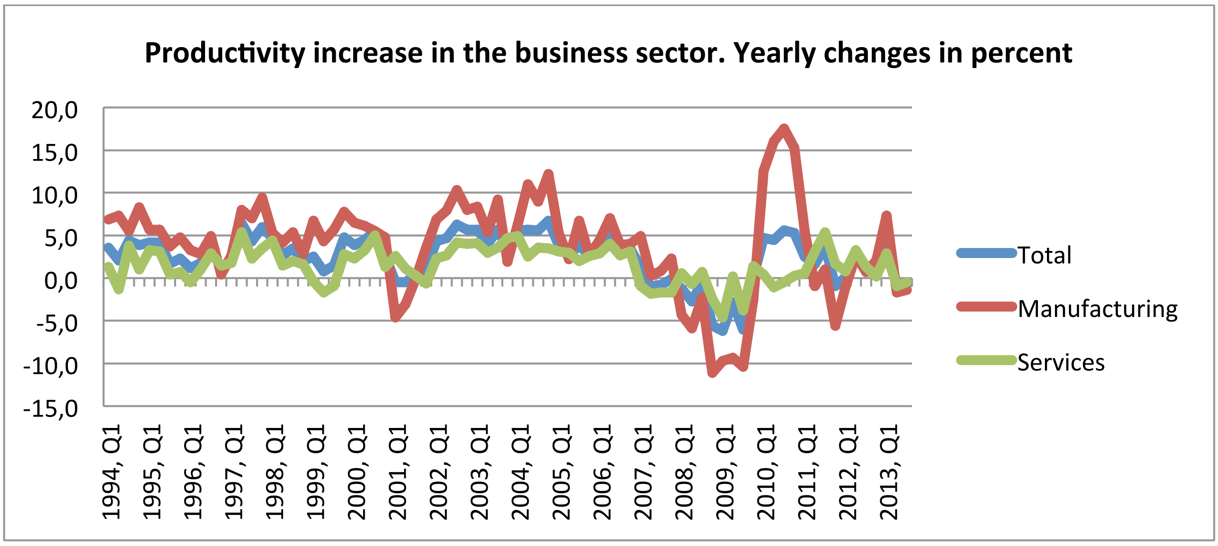

Figure 1: Productivity increase in Swedish business sectors. Source: Statistics Sweden.

According to the Mckinsey Global Institute (2012), manufacturers' contribution to economic growth is, however, expected to decrease in advanced economies such as Sweden due to several reasons, partly due to productivity improvements that entail that the manufacturing sector's employment share will be under pressure. Other reasons for this development are the service sector's growing share of the economy and the power of global competition. Nevertheless, manufacturers will continue to hire workers and play a key role in economic growth even though the share of employment is reduced.

The origin of firms' productivity increase is traditionally considered to be the result of innovative solutions and technological development of equipment and machines (Long and Summers, 1991). An example is the replacement of traditional manual labour tasks in favour for automatic solutions. Manufacturing firms have historically focused on technological development for reaching increased productivity rather than on the management aspects of firms' productivity development (Prokopenko, 1992). Today, as a result of the crisis, manufacturers are signalling that they will focus more on making their assets reliable and responsive than on acquiring new manufacturing assets (Accenture, 2013). These investments are typically referred to as productivity enhancement programmes. Productivity enhancement programmes include information technology investments such as implementing performance management systems and manufacturing execution systems. The rationale for these programmes is that firms believe that they can use their assets more efficiently and provide more value with existing or fewer resources.

According to Statistics Sweden, manufacturing firms' capacity utilization has been at constant levels of around 85-90% since the beginning of the 1990s, with dips evident only around times of economic downturns, for instance 2008-2009 (Fig. 2).

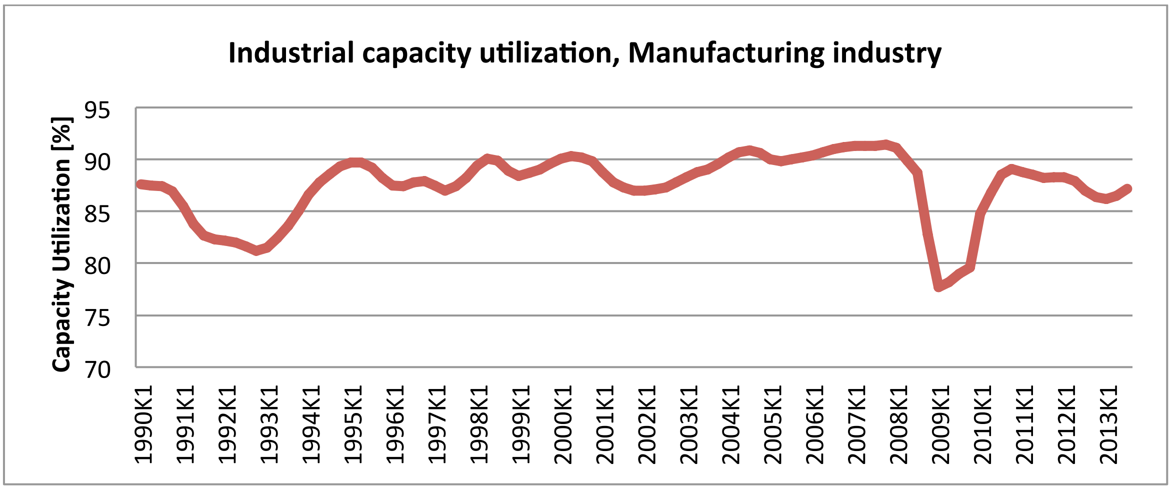

Figure 2: Industrial capacity utilization in Sweden. Source: Statistics Sweden.

In contrast to Accenture's study, Figure 2 explains that there is a little room for capacity-related improvements. In this context, productivity must be broken down between *demand* and *expenditures*. It is obviously difficult to increase sales volumes without capacity investments if current utilization figures are at rates corresponding to 85-90%. As a consequence, productivity enhancement programmes would have a minor impact on productivity that is demand-related.

These utilization figures are, however, based on subjective estimates of capacity and not measures of physical entities. The estimates are provided by a yearly survey made by Statistics Sweden. In contrast to this survey research, Almström and Kinnander (2008) examined manufacturing firms' shop floor utilization by objective means. For instance, work-sampling studies were conducted in combination with collection of real production data, including performance and quality losses. The objective of their study was to determine what manufacturing firms' resources actually were doing during planned production time. One conclusion was that the average capacity utilization figures were far less than the 85% to 90% presented by Statistics Sweden. In fact, the utilization figures for suppliers in the Swedish automotive industry averaged 60% based on a study of 60 companies (Almström and Kinnander, 2008). The highest utilization figures in this study were found to be almost 90%. This result indicates an improvement potential up to 50% simply by using existing resources more efficiently and can be attained without large fixed asset investments. However, utilization losses are often hard to achieve since they require management awareness, increased operator and management competencies and cultural change, which require organizational investments (Almström, 2013).

Almström and Kinnander (2008) research on shop floor productivity thus explains the imperative of productivity enhancement programmes. That is, the outcome of these programmes can affect firms' ability to meet increased demands with the same or lower expenditures. This is obviously an important issue for firms that are experiencing difficult economic conditions or fierce competition.

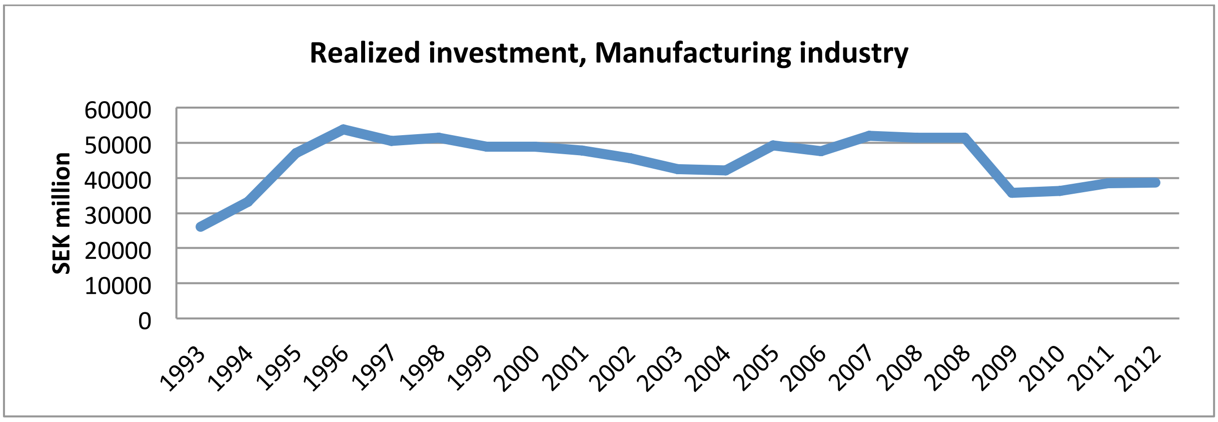

Figure 3: Realized investments in Swedish manufacturing industry. Source: Statistics Sweden.

Figure 3 presents realized investments in equipment and machinery in the Swedish manufacturing industry over the past few decades. This figure presents a clear drop during the crisis (2008-2009) and the fact that no immediate recovery has appeared even though the cost of capital is at low levels due to historically low interest rates. A possible explanation is that risk awareness among decision makers has increased in the post-crisis time frame. This is also an issue that adds to the productivity imperative. That is, if firms are investing less in machines and equipment, they must compensate by other means of contributing to productivity growth and thus to long-term economic growth.

The following list characterizes today's business environment in which manufacturers operate:

- Productivity is mainly increased by technological development and capacity utilization is at constant levels.
- Manufacturers' share of employment is decreasing in advanced economies. This is related to historical productivity increases and thus increased capital intensity. That is, the proportion of fixed assets in relation to current assets has increased due to automation investments.
- Unchanged or slightly declining investment levels.
- Increased global competition.

1.2 Challenges

The overall challenge of maintaining and improving productivity can be decomposed into smaller categories. A productivity growth aggregate refers to "*the change in aggregate final demand minus the change in the aggregate expenditures on labour and capital*" (Petrin and Levinsohn, 2012). Consequently, there is one *demand* category and one *expenditure* category that need to be addressed.

The demand category refers to the volume and value of sales. This category is related to firms' ability to establish and retain high levels of *innovation productivity*. The challenge is to create returns on R&D investments – for instance, the ability to understand and create future needs and consequently effectively employ resources to exploit these needs. The latter category is related to expenditures, i.e. firms' abilities to exploit these needs at appropriate expenditures levels and thus establish and retain high levels of *production productivity*. The challenge is to create returns on assets. The production productivity challenge can be further divided into subcategories:

- There is a challenge to continuously convince investors to invest in production productivity, i.e. in both fixed and current assets development.
- There is a challenge to exploit unused productive capacity.
- There is a challenge to adapt current and future manufacturing capacity to requested capacity.
- There is a challenge to improve manufacturing firms' abilities to compete and grow in a volatile economic environment, e.g. create agile and flexible production systems.

This thesis addresses the challenge of production productivity.

1.3 Field of research

In practice, production productivity is only a secondary concern for a firm's owners. It is more likely that their primary concern is related to financial objectives such as creating a certain return on investments or return on assets.

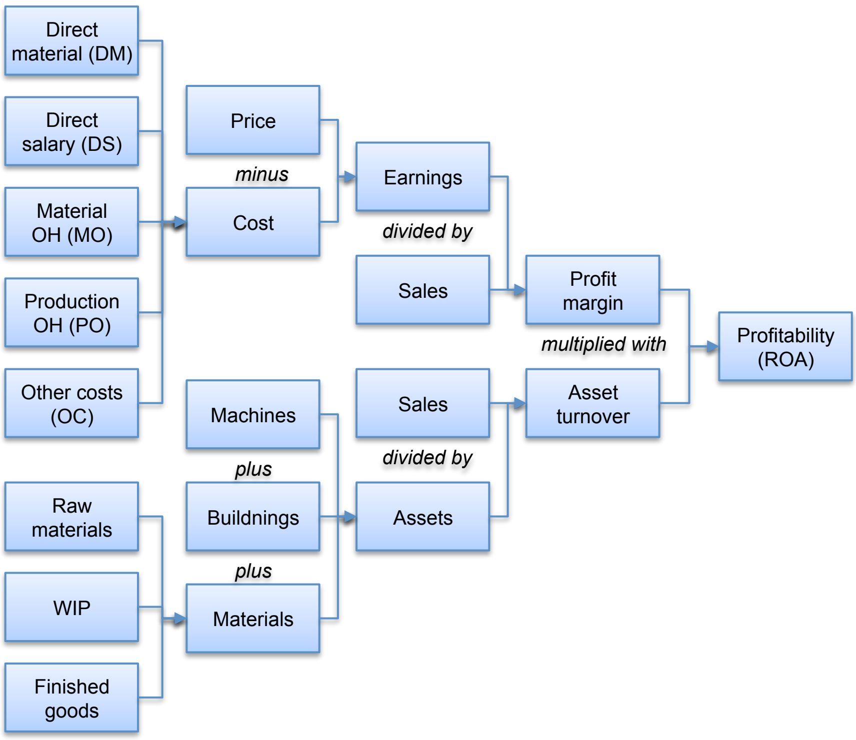

Figure 4: DuPont schematics of profitability (Friedlob and Plewa Jr, 1996)

Figure 4 depicts a DuPont schematics of profitability (return-on-assets) (Friedlob and Plewa Jr, 1996). The left boxes of Fig. 4 present income statement accounts (costs) and balance sheet accounts (assets) that can be affected by production productivity improvements. This field of research focuses on how shop floor productivity improvement affects these accounts. There is, however, a difficulty involved in interpreting financial performance measures such as profitability. The difficulty lies in the fact that profits may be sacrificed for emerging business opportunities that require excessive expenditures to be exploited (Tangen, 2003, White, 2006). Furthermore, profits may be overstated or understated depending on the accounting methods used, etc. Accordingly, there is a problem involved in understanding what actually causes profitability changes – external factors, internal factors, or a combination of the two.

Challenges past and present are mastered with the incentive to maintain a continuous cash flow to secure future business survival. The challenge can broadly be described as generating organizational performance that matters. Previous research has covered this area of interest, i.e. how to maintain and improve manufacturing operations that strive to improve financial results. The essence of this content is covered by operations management literature.

Measuring and developing productivity that strives for increased profitability are aligned with the creation of shareholder value, commonly considered as the paramount business goal (Hahn and Kuhn, 2011). Productivity is a performance measure, i.e. it belongs to the process of quantifying the efficiency and effectiveness of actions (Neely et al., 1995). Productivity involves several dimensions of organizational efficiency and effectiveness. It is evident that various types of productivity improvement actions lead to improved firm performance. The relationship between various types of improvements, for instance resource efficiency improvements and specific measures of performance such as costs, has been extensively discussed (Modi and Mishra, 2011, Adler et al., 2009)

In general, resource efficiency can be related to several research areas concerning labour, equipment, capital and materials. Eroglu and Hofer (2011) discuss inventory leanness' effect on firm performance and find it to be mostly positive but generally non-linear, which indicates the difficulty of identifying clear relationships between inventory management and firm performance. Capkun et al. (2009) conclude that their statistical analysis supports prior literature's hypothesis of a causal relationship between inventory performance and financial performance. Reducing inventory, that is reducing or freeing up capital will theoretically reduce financial costs (Primrose, 1992). However, as Eroglu and Hofer (2011) point out, economies of scale in inventory management will affect financial results, concluding that there is an "*optimal degree of inventory leanness beyond which the marginal effect of leanness on financial performance become negative*".

Quality in terms of material and labour is another area that can be translated into financial terms. Empirical operations management research within this area frequently provides findings that support a positive relationship between various management practices, for instance total quality management (TQM) and financial results. For example, see Hendricks and Singhal (2001) and Kaynak (2003).

Other areas that have an impact on shop floor productivity, is learning ability, labour flexibility and product variation, see Letmathe et al. (2012), Sawhney (2013) and Mccreery et al. (2004). Sawhney (2013) discusses evident trade-offs between technical and behavioural issues regarding flexible labour for managing temporary bottlenecks. These include time loss due to walking distances, training costs, learning and forgetting time and efficiency versus quality. One finding is that "*acquired and implemented labour flexibility has been identified as a significant contributor to plant performance measured by reduced WIP inventory and cost*" (Sawhney, 2013).

However, few attempts have actually been made to construct a theory that covers the aforementioned areas, that is explaining how improved economic performance is achieved through improvement actions that also are aligned with strategic concerns (Choong, 2013, Schmenner and Swink, 1998). One of the specific challenges is to raise the level of unit of analysis, from specific inputs such as material or labour to system levels and organizational changes that matter (Ahlstrom and Karlsson, 1996).

1.4 Productivity management

This research initiative is positioned within the field of *operations management*, i.e. "*about the way organizations produce goods and services*" (Slack et al., 2007). Typical operations management (OM) characteristics are an applied field of managerial character, issues and problems in the real world within cross-disciplinary research areas, e.g., economics, finance, organizational behaviour, mathematics, etc. (Karlsson, 2009). Current trends within the field of OM research are the servitization of manufacturing, e-operations, outsourcing, leanness and agility, and performance measurement and quality control (Clegg et al., 2013). This research initiative primarily addresses issues related to leanness and agility and performance measurement and quality control.

Prokopenko (1992) asserts that productivity should be managed by means drawn from quantitative analysis and the field of operations management. The following explanation of Productivity Management is borrowed from the Japan Management Association's explanation of *total productivity management* (Suito, 1998).

The term *total* refers to the involvement of an organization's stakeholders to align all improvement activities in a certain direction. A productivity programme cannot be considered total unless everyone is involved. The term productivity refers to "*the effective enhancement of an organization's productive capability*" (Suito, 1998). The third component refers to business administration expertise. Suito (1998) explains the purpose of the total productivity management concept with the following two points:

1. To integrate and intensively apply all of the various productivity improvements techniques and activities used for running a business
2. To construct a system that is able to respond accurately and flexibly to today's innovation-oriented and rapidly changing environment – and to achieve outstanding planned results through vigorous and forward-looking improvement activities

For these purposes specific aims can be identified – for instance to establish specific goals and benchmarks, adopt a top-down and priority-focused management approach, to ensure that business activities are directed towards efficient attainment of the goals, and to construct an efficient and highly motivated organisation that delivers the desired bottom-line results. There is, however, a clear distinction between this thesis' content and the description Suito (1998) offers regarding productivity management.

This thesis only considers particular parts of a firm's production system, i.e. the shop floor. As a consequence the term *total* may be neglected. Moreover, this thesis focuses particularly on a few, rather than all, of the various techniques and tools available for improvement purposes. The stance throughout the thesis is a pronounced bottom-up analysis approach with a strict focus on facts rather than assumptions. A bottom-up analysis approach in this context must not be confused with the management approach that Suito (1998) suggests should be top-down. Finally, a distinction must be made between working capital, i.e. the capital needed to run operations, and capital that is tied up in fixed assets (e.g. building, machinery and equipment). Productivity management involves the efficient use of both types of capital. However, working capital is addressed in this thesis, which is also aligned with today's challenge of using existing assets more efficiently rather than acquiring new assets.

This research contributes to the field of productivity management by addressing how production system productivity should be analysed by means of a bottom-up approach and by presenting the relationship between productivity improvements and corresponding economic effects.

1.5 Purpose and objectives

The purpose of this research initiative is to provide industry practitioners with means and knowledge that support the productivity improvement process. The aim is to strengthen manufacturing firms' competitiveness and thus their contribution to economic growth. This purpose and aim are aligned with the overall challenge of maintaining and developing manufacturing firms' competitiveness through continuous productivity improvements. This thesis also aims to provide knowledge that can be used for educational purposes through dissemination of productivity management.

The on-going research initiative within productivity management is currently divided into two related research areas. The first research area considers how shop floor resources and production data may be modelled and analysed (Hedman, 2013). The second research area considers relationships between productivity improvements and corresponding financial effects. This thesis' primary focus is the latter research area. The objectives of this thesis are:

- To promote the importance of shop floor productivity and its significance for manufacturing firms' economic performance development
- To analyse existing theories and analysis methods for shop floor analysis and improvements
- To present a framework for shop floor productivity analysis that can be used for academic research and for industry practitioners to build knowledge within the framework of productivity management

1.6 Research questions

Three research questions (RQs) have been formulated on the basis of previous productivity management research and the stated objectives of this thesis:

RQ1: How is shop floor productivity analysed and modelled?

RQ2: How can shop floor productivity be improved?

RQ3: What is the financial benefit of shop floor productivity improvements?

Research question one was formulated to increase the understanding and practice of production system analysis with a special interest in shop floor productivity. Understanding production systems is a prerequisite for applying tailored improvement solutions. The result of RQ1 is thus the foundation for RQ2 and RQ3. The expected contribution of answering RQ1 is to set production system definitions and examine current knowledge gaps within productivity management.

The overall challenge facing today's manufacturing firms is, as previously stated, to continuously maintain and develop productivity. The next question is how this development can be performed in line with the purpose of productivity management. In other words, how *can effective enhancement of an organization's productive capability* be accomplished?

The rationale for RQ3 and the justification for the thesis is that a firm's (in capitalized markets) paramount business objective is to create shareholder value by economic growth (Hahn and Kuhn, 2011). A firm's management must thus accordingly continuously invest and improve the firm's operations in accordance with this objective.

To promote the importance of productivity, it is thus a necessity to understand what the financial benefits of improving productivity are.

1.7 Delimitations

Figure 5 depicts that productivity can be broken down in *internal factors* (controllable) and *external factors* (non-controllable). From a manufacturing firm's perspective, it is evident that national and international economics, consumer behaviour and national infrastructural decisions are outside a manufacturing firm's control. However, to efficiently improve factors that are under their control (e.g. a firm's product portfolio), these external factors must be considered. Consequently, factors that are uncontrollable by one organization or institution may be controllable by another. Each productivity factor requires different approaches, methods and techniques to be improved.

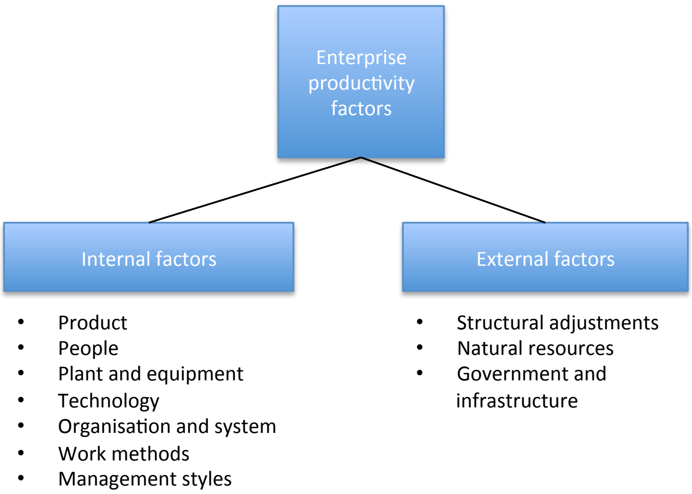

Figure 5: A model of enterprise productivity factors adapted from Prokopenko (1992).

This thesis is limited to examining how controllable and tangible production-related factors affect shop floor productivity and in turn economic performance. The research initiative has only considered existing production systems and is thus separated from issues regarding "green field" development of production systems.

1.8 Outline of the thesis

This thesis is arranged as a monograph, i.e. without appended papers. Chapter Two presents a body of knowledge that introduces the reader to notions, definitions and related topics that are used throughout the thesis. The content of Chapter Two is depicted in Fig. 6. The first section of Chapter Two gives the reader insights into what a *system* is, with special attention given to *production systems*. The next section describes what a *manufacturing strategy* is and the importance of knowing where to be (i.e. setting goals and objectives that are aligned with the firm's overall strategic vision). The following section introduces the notion of *performance measurement,* a topic of vital importance for both planning and control issues. The next section describes the content of *shop floor productivity analysis* with the primarily focus on different means (performance measures, assessment techniques and methods) of improving these systems. The strategic view points out the direction of these improvements and hence acts as a prerequisite for production system improvements.

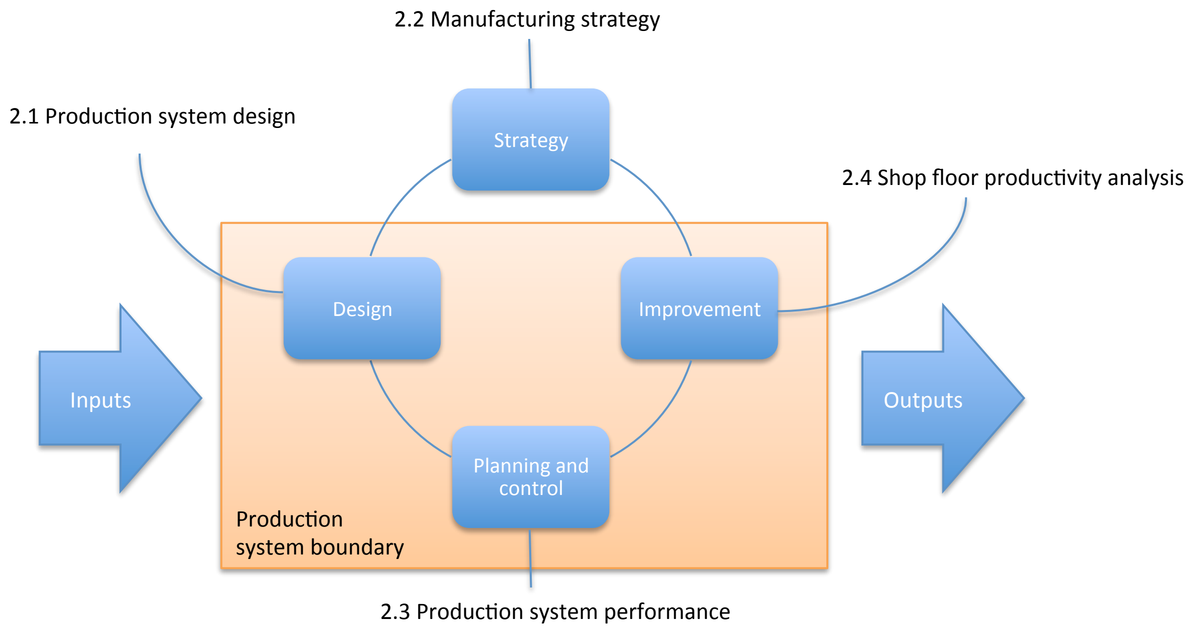

Figure 6: A model of productivity management

Figure 6 is adapted from the Slack et al. (2007) model of operations management and operations strategy. The difference between Slack's model and Figure 6 is the context it used in, i.e. this thesis gives special consideration to shop floor operations. Chapter Three presents the research methodology, i.e. how the research has been conducted. Chapter Four presents the empirical results of the case studies and interview studies. Chapter Five presents the resulting theoretical framework based on existing concepts and theories in combination with the empirical results. Chapter Five provides a production system model with corresponding definitions, such as resource definitions, activity definitions, production process definitions, etc. It also provides a concept of how shop floor productivity should be analysed. This analysis concept is furthermore incorporated into an existing manufacturing strategy theory that constitutes a framework for shop floor productivity analysis. Chapter Five ends with an introduction to an economic analysis framework that connects the dots between shop floor productivity and enterprise level economic performance. Chapter Six discusses the research questions, the research methodology and future research. Chapter Seven presents the conclusions.

2. Frame of reference

The frame of reference chapter first explains what a production system is. This explanation acts as a foundation for further understanding of how production system performance can be assessed and evaluated in order to improve it. An essential part of this chapter is to give the reader a good understanding of what a successful production system is in terms of various performance measures and to explain the importance of a clear manufacturing strategy that governs a firm's targets for economic growth. The final part of this chapter provides insights into productivity analysis techniques and measures that are frequently cited within the context of the thesis.

2.1 A system perspective

Historically, production-related problems have been solved from a functional problem solving perspective, meaning that prevailing complexity has been simplified through reduction. In practice, this means that business analysts reduce problems to a manageable size so they can be solved effectively. In contrast, the system problem solving perspective emphasizes the big picture by utilizing concepts such as objectives, relations and transformation (Wu, 1994). These two approaches are commonly referred to as *reductionism* and *holism*.

2.1.1 Systems theory

A system is a combination of parts forming a complex or unitary whole (Blanchard and Fabrycky, 1998). Different classifications of systems can be found in the environment, for instance natural systems, human-made systems, transportation systems, conceptual systems, technical systems etc. To qualify as a system, the items involved must have a functional interrelationship and useful purpose. Man-made systems are distinguished from natural systems with respect to their purpose. A man-made system has, in contrast to a natural system, an explicitly stated purpose (Wu, 1994).

According to Blanchard and Fabrycky (1998), systems are composed of components, attributes and relationships. Components are the operating part of the system, i.e. the system's inputs, processes and outputs. Each component of the system (a set of components) can be assigned a value describing the system state by a control action and one or more restrictions. All operating parts have certain properties that characterize the system, i.e. component *attributes*. These attributes can be described as colour, shape or volume, etc. Properties that are specific to systems theory are referred to as *emergent properties.* Emergent properties imply that the output of the system can be more than the sum of its parts.

A system is a set of interrelated components. Every component of the system is characterized by possessing a property that affects the whole system property. Also, each component property depends on at least one other component of the set. And each sub-set of components must have this characteristic, meaning that components cannot be divided into independent subsets (Blanchard and Fabrycky, 1998). A component of a system can be a system in itself, which implies that every system may be part of another larger system in a hierarchy.

Thus, it is important to position system components when using a system approach. If a component can be decomposed into smaller components, there is more than one hierarchal level, the lower level referred to as a *subsystem*. Also, it is important to define the system boundaries (limits). Outside of the system boundaries is referred to as the *environment*. Systems are not isolated from this environment. For instance, materials that pass from the environment through the system boundaries are called *input,* and materials that pass out from the system are called *output*. Components that arrive from the environment and leave the system in another form are called *throughput*.

Each human-made system by definition has a purpose, for instance producing products. Given specific inputs, system components can be selected to fulfil this purpose. The purpose of producing products is the *function* of the system. Performance measures can be established when the system function is defined. These measures are used to indicate how efficiently the system performs. Furthermore, the system components are categorized into structural components, operating components and flow components (Blanchard and Fabrycky, 1998). Structural components are static parts of the system, for instance buildings that may define a certain restriction on the system. Within this restriction, operating parts are found, for instance machines and equipment that process material to some desirable output. Flow components are the materials that are transformed or altered. These components have various attributes that affect the system. For instance, a specific input may have attributes that affect the operating components. A schematic representation of a system is depicted in Fig. 7.

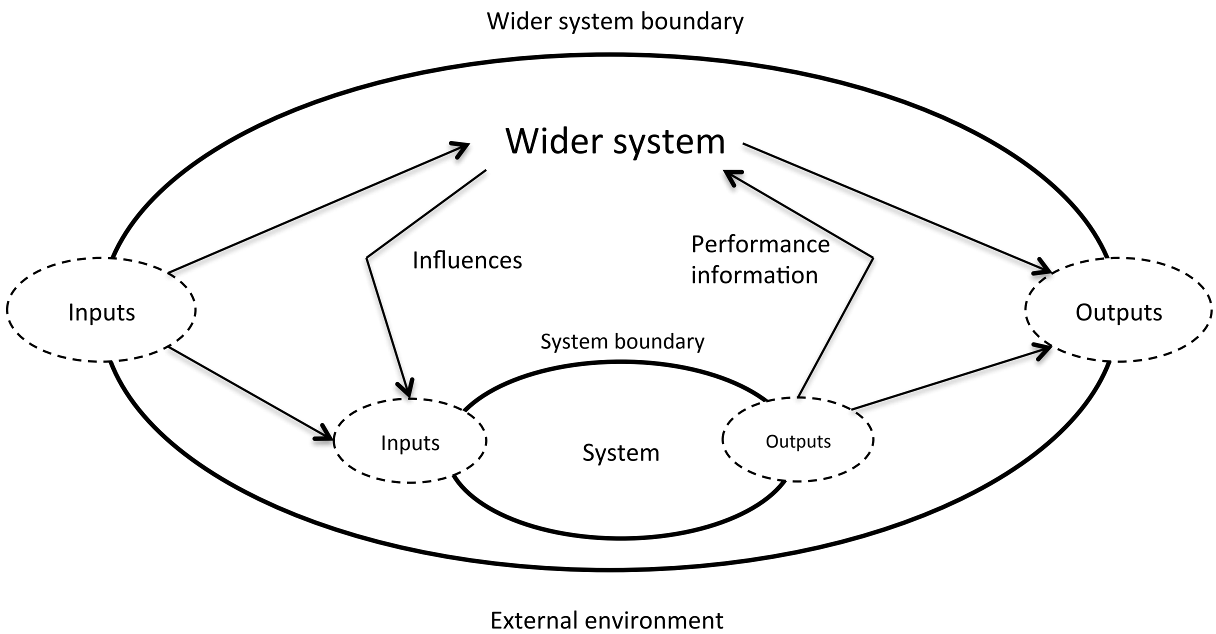

Figure 7: A schematic representation of a system, adapted from Wu (1994)

2.1.2 Production system theory

Production system theory is derived from systems theory and systems engineering. A production system is a system with the explicit purpose of transforming inputs to requested outputs. Production systems incorporate new manufacturing technologies and techniques into production processes such that production systems can be efficiently developed towards wider company objectives. This area of research is usually referred to as production systems engineering (PSE) or manufacturing systems engineering (MSE). One of the main reasons to continually develop production systems is to be able to fully realize the benefits that new technologies enable. Associated research areas are product design and development, human resource development, operations management, materials and manufacturing development, etc. Production engineering issues have traditionally been related to local parts of the system, for instance one machine, one area of assembly or one organizational issue. The interplay between humans, information systems, machines and equipment, environmental influence, control systems and computers was not considered from a system perspective until the introduction of information technology and systems (Wu, 1994). System design authors express this paradigm shift, or technological development, from the age of technology to the age of systems (Wu, 1994).

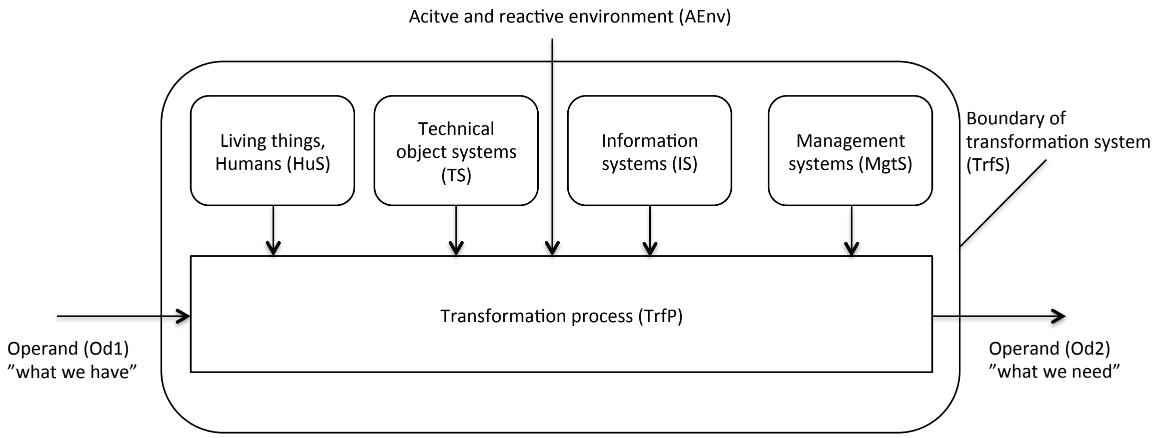

Figure 8: A general model of transformation systems (Ernst Eder, 2010)

Figure 8 depicts an example of a transforming system that comprises operators and operands. The operand refers to materials, energy, information, and living things (M, E, I, L). The operand will be transformed from state 1 (Od1) into state 2 (Od2) by using active and reactive effects created by the system's operators (human systems, technical systems, active and reactive environment, information systems and management systems) (Ernst Eder, 2010).

Analysing and designing production systems can be considered from two points of view. One point of view is to satisfy human needs and the other has to do with materials and forces of nature. During the last century's technological development, human impact on the environment has increased tremendously. From this perspective, often referred to as sustainability, systems need to be developed in order to utilize existing resources more efficiently. A typical example is consideration of new or more common materials for similar purposes that only special uncommon materials have traditionally been used for. The other point of view for sustaining and developing human needs calls for new technological development. Engineering decisions that lead to improvements within these two points of view are based on several areas of expertise, frequently trade-offs between economic factors, human factors, sustainability factors, etc. Doing this successfully demands a holistic approach to these complex relationships between components and attributes. Flood (1993) disassembled complexity into interconnected parts, such as people, systems, number of elements, number of relationships, values and beliefs, notions and perceptions, etc., and claimed that only an interdisciplinary study can deal with all aspects of complexity and that only system science is truly interdisciplinary. Production system models are thus designed and analysed with the purpose of reducing the complexity of various problems.

The word "*model*" implies representation when used as a noun (Blanchard and Fabrycky, 1998) – for instance, when a production engineer tries to represent a physical shop floor with a flow chart. Blanchard and Fabrycky (1998) classify various types of models as physical, analogue, mathematical and schematic. Authors may use different classifications, e.g. Wu (1994) mentions descriptive, physical, analytical and procedural models based on the method of prediction. Physical models look like what they represent, e.g. a prototype of a car body. Analogue models behave like the object or phenomenon represented. Mathematical models symbolically represent the phenomena being studied, e.g. physical laws like Newton and Ohm's law. Finally, schematic models graphically represent a situation, for instance a flowchart of a specific material flow. Within a production system, models may be used for different purposes. Mathematical models are typically used within process control, inventory control and production simulation, while schematic models are used for process flow optimization and for information and communication purposes.

2.1.3 Production system models

Whether human, conceptual or technical systems are involved, they can be described in different ways. Seliger et al. (1987) mentioned three theoretical aspects of a system: the *functional*, the *structural* and the *hierarchical*. Examples of each aspect are given below.

Bauer et al. (1994) discusses the hierarchal aspect by referring to the National Bureau of Standards (NBS) model of a manufacturing system, consisting of five hierarchical levels: facility, shop, cell, workstation and equipment (Fig. 9). In this example, the system is described as parts consisting of a supersystem (facility), which in turn consists of several systems (shop) and their subsystems (cell, etc.).

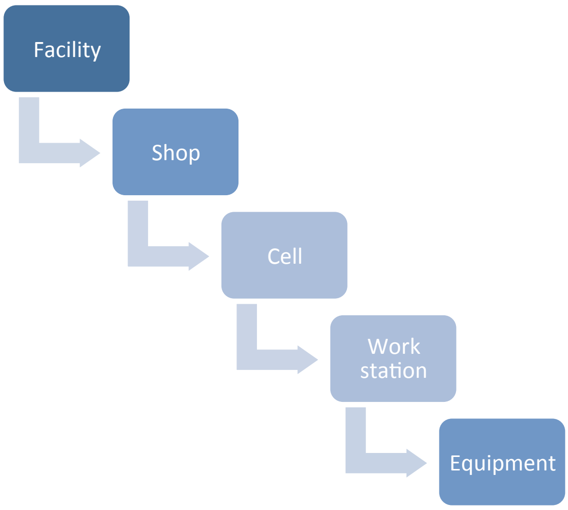

Figure 9: The hierarchal aspect is discussed by means of the NBS model of a manufacturing system.

The functional aspect typically describes the behaviour of a given system independent of its realization and is often regarded as black box transformation of inputs into outputs (Fig. 10). They consist of inputs such as technology, labour, energy, information, etc. are organized within a "black box" process to produce certain outputs, such as products or services (Bellgran and Säfsten, 2010, Ernst Eder, 2010).

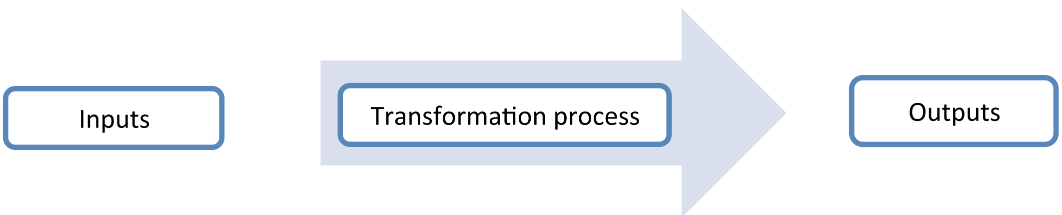

Figure 10: The functional aspect is discussed by means of a transformation process

Ernst Eder (2010) asserts that a transformation process contains human, technical, information and management systems. How these systems interact is not clarified, which makes it possible to set delimitations around the area of interest. A more detailed example of a functional system is given by Beer (1985). Beer's contribution to system models is called the Viable System Model (VSM), which can be used to diagnose and regulate production systems.

The structural aspect is often used when describing a system as a set of elements interlinked by relationships. Miltenburg (2005) describes a set of seven production systems that are regarded as structural system descriptions (table 1).

Table 1: Seven production systems as described by Miltenburg (2005)

Production system	Product/volume	Layout/Flow
Job shop	Very many products/one or few of each	Functional layout/flow extremely varied
Batch flow	Many products/low volumes	Cellular layout/flow varied with patterns
Operator-paced line flow	Several to many products/Medium volumes	Line layout/flow mostly regular, paced by operators
Equipment-paced line flow	Several products/high volumes	Line layout/flow regular, paces by the equipment
Continuous flow	One or few products/very high volumes	Line layout/flow rigid, continuous
Just-in-time (JIT)	Many products/low to medium, volumes	Line layout/flow mostly regular, paced by operators
Flexible manufacturing system (FMS)	Very many products/low volumes	Cellular or line layout/flow mostly regular, paced by the equipment

It is clear that an unambiguous production system definition does not exist. However, all three aspects that have been presented are relevant and useful, depending on the context in which they are used. The purpose of each system aspect varies. Some system descriptions are used to support, others to perform and some to manage and control. Beer (1985) advocated the control function of the production system as the most important and claimed that it must be governed by a strategy. While the production system can be looked at as the body, the control system is the mind, and the mind needs a strategy in order to coordinate actions to avoid operational sub-optimizations (Beer, 1985). Seliger et al. (1987) asserted that a complete production system description needs to consider each of the aspects described.

In this thesis, the term *production system* is used synonymously with the term *manufacturing system*. Some authors argue that the manufacturing system is superior to the production system (Bellgran and Säfsten, 2010). However both *production system* and *manufacturing system* are used to describe relationships at a factory, which includes activities needed to transform raw materials and components to finished products ready to be delivered to customers.

In general, models are used to simplify reality in order to reduce the complexity facing various decision-makers. Performance measures may serve as input to these models, but they may also serve as a stand-alone analysis for assessing performance of a production system. Production system analysis is thus a broad term involving several methodologies, tools and techniques. These aids are used for the common objective of addressing the context and related problems of production systems such that the production system efficiently supports the broader company objective (Wu, 1994). There are many available options for performing this analysis, e.g. modelling the system, measuring the performance of the system, and assessing and benchmarking the system and its external environment. The approach used depends for instance on the position in the life cycle within which the production system is located. For instance, a green field solution (i.e. building a brand new production system) calls for one analysis approach while an existing production system presents other challenges and should thus be analysed with other approaches.

As stated above, each system requires control and management to effectively reach goals and operate efficiently. These control actions are provided by the management system, more commonly known as the concept of strategy. The following section describes the field of manufacturing strategy and addresses related concepts and definitions that are used throughout the thesis.

2.2 Manufacturing strategy

Manufacturing strategy (MS) denotes pattern of actions intended for achievement of goals and objectives. Manufacturing strategy can be defined as "*the effective use of manufacturing strengths as a competitive weapon for the achievement of business and corporate goals*" (Swamidass and Newell, 1987). Research within MS is usually broken down between the *process* of strategy and the *content* of strategy (Leong et al., 1990). Strategy content is concerned with strategic decisions that shape and develop the long-term direction of specific actions and form the building blocks of a specific strategy (Slack and Lewis, 2002). The strategy process is concerned with the procedures that are, or can be, used to formulate those strategies that the organisation should adopt (Slack and Lewis, 2002). The strategy content thus determines a firm's performance objectives, i.e. what the firm should be good at, while the strategy process determines how operations attain reconciliation between the firm's resources and the firm's market requirements. A more detailed discussion of content and process within the context of MS is presented below.

Wickham Skinner, a pioneer within manufacturing strategy research, introduced manufacturing strategy's role in the corporate framework by suggesting a hierarchal model for strategy (Skinner, 1969). The paramount level in this model is the *corporate strategy* and includes two elements: selection of product markets or industries and allocation of resources among them. The first element, which defines the business in which a corporation will participate, is typically expressed in terms of dimensions such as materials, technologies and markets (Wheelwright, 1984). The second element, which relates to the allocation of resources, usually results in a function that is concerned with acquiring financial capital (Wheelwright, 1984). The process of identifying possible product markets that can be exploited by allocating a firm's resources can thus be seen as the traditional strategic perspective.

Within a multi-business corporation, each individual business unit has its own *business strategy* that aims to provide the business unit with distinct competencies as competitive weapons. The business strategy refers to two critical tasks. It specifies the limits of the business in such a way as to be linked to the corporate strategy. And it specifies the basis on which the business unit maintains and gains competitive advantages (Wheelwright, 1984).

The manufacturing strategy subsequently forms a cluster with other business-specific strategies such as marketing and sales strategies, financial strategy, environmental strategy that complements higher-level business and corporate strategies (Swamidass and Newell, 1987).

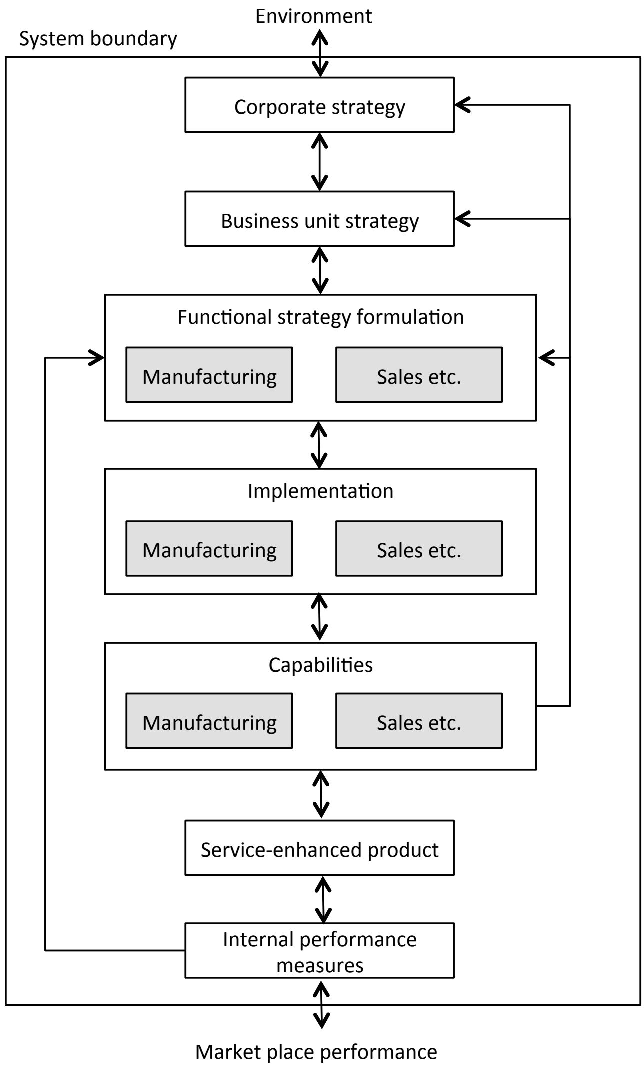

Figure 11: A process model of manufacturing strategy. Source: Leong et al. (1990).

Figure 11 depicts a hierarchical model of a strategy process occurring within an environment of customers, competitors and other stakeholders (e.g. government agencies, financial institutions, the public sector, etc.). The higher-level strategies (corporate and business unit levels) determine appropriate patterns of actions for the lower-level functional strategies, such as manufacturing (shaded boxes). Feedback is obtained from each functional area's capabilities. Each function's specific capabilities are the result of each functional strategy formulation if appropriately implemented and realized. Strategic advantages are achieved if a set of capabilities is attained that is unique in comparison with that provided by competing businesses. These unique capabilities serve to produce a *service-enhanced product,* which is referred to as a bundle of goods and services available for customers to purchase. The next step in this model is to measure the extent to which the service-enhanced product meets the organization's strategic objectives. In the end, the marketplace provides an external performance measure for the service-enhanced product and hence the strategy as well.

An important part of the strategy model is the process of formulating the functional strategy. Slack and Lewis (2002) divide the process of strategy formulation into three levels: *fit*, *sustainability* and *risk*. The most obvious consideration of a manufacturing strategy formulation process is to match manufacturing resources with market requirements. The difficulty is often in interpreting markets in such a way that unambiguous performance objectives are possible to establish. Related problems might be that various parts of the firm pursue different objectives that result in internal coordination problems. The subsequent level, sustainability, refers to a firm's capability of reacting to changes in market requirements and thus supporting the creation of sustainable competitive advantages. A firm must possess the skills required to develop new manufacturing capabilities that are aligned with these changing market requirements, as well as the skills required to create capabilities that are can be exploited in the marketplace. However, the task of maintaining and extending competitive advantages by following market changes and developing manufacturing capabilities is made difficult by uncertainties, i.e. risks.

The second distinction of manufacturing strategy, strategy content, describes the parts of a manufacturing strategy. This research area has developed over time and can be divided into several sub-categories (table 2).

Table 2: Strategy choices concerning a manufacturing strategy. Source: Wheelwright (1984)

1.	Capacity – Amount, timing, type
2.	Facilities – Size, location, focus
3.	Technology – Equipment, automation, connectedness
4.	Vertical integration – Direction, extent, balance
5.	Workforce – Skill level, pay, security
6.	Quality – Defect prevention, monitoring, intervention
7.	Production planning and materials control – Computerization, centralization, decision rules
8.	Organization – structure, reporting levels, support

The dominant research theme is and has been manufacturing capabilities and strategic choices (Dangayach and Deshmukh, 2001). Manufacturing capabilities include research about competitive priorities, for instance cost, quality, delivery and flexibility, while strategic choices (also referred to as decision areas) include research about specific structural and infrastructural criteria, such as process technology, capacity, quality systems, work force management and the manufacturing organization itself. The following sections describe the essence of manufacturing capabilities and strategic choices.

2.2.1 Manufacturing capabilities

Skinner (1966) was among the first researchers to question the prevailing narrow role of manufacturing strategy that exclusively concentrated on cost-effectiveness. Instead he introduced the concept of manufacturing capabilities and suggested that the manufacturing function could do more than simply manufacture at the lowest possible cost. These generic manufacturing capabilities are also referred to as performance objectives or competitive priorities (Dangayach and Deshmukh, 2001):

- Cost: Production and distribution of products at low cost.
- Quality: Manufacture goods that meet high quality and performance standards.
- Delivery dependability: Deliver on time according delivery schedules.
- Speed: React quickly to customer demands and deliver fast.
- Flexibility: React to changes in the business environment, such as product mix changes, product design changes, and changes in production sequences.

Skinner (1969) stated that manufacturing firms are technologically constrained, i.e. their structural resources limit their ability to produce certain outputs. In that sense, trade-offs are inevitable. Since trade-offs must be made, guidelines must be available for setting performance priorities. Skinner (1969) referred to these guidelines as the trade-off model, which stated that no manufacturing system or unit can perform equally well to create competitive advantages across all manufacturing criteria (Sarmiento et al., 2008). The bottom line of the trade-off model is, however, that it is difficult and potentially dangerous to offer superior performance across all the aforementioned performance objectives simultaneous (Wheelwright, 1984).

2.2.2 The sand-cone model

The sand-cone model is a development in the research area of manufacturing capabilities. The proposition of the model is that trade-offs between some or all performance objectives can be overcome by following a sequential path in improving internal performance (Sarmiento et al., 2008). This sequence, according to Ferdows and De Meyer (1990), is quality, dependability, speed and cost-effectiveness. The term "*cumulative capabilities*" is used to describe high performance in multiple capabilities simultaneously (Flynn and Flynn, 2004). They are described as cumulative since they build upon each other, as illustrated by the sand-cone model (Fig. 12).

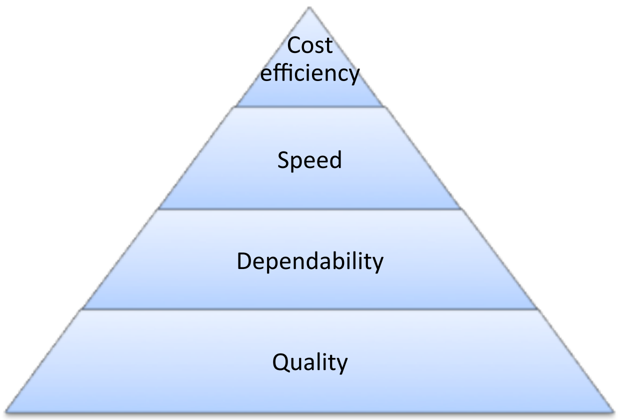

Figure 12: A sand cone model

Ferdows and De Meyer (1990) established the sand cone model based on research that compared the performance of companies in North America, Europe and Japan. Japanese manufacturers seemed particularly able to outperform their competitors in almost every capability (De Meyer et al., 1989). These observations supported the theory that manufacturing capabilities were cumulative and not the result of compromises and trade-offs.

2.2.3 Resource based view

The resource-based view (RBV) of organizational performance enhances human resources as a key component of organizational performance. The RBV has gradually been developed within a strategic context that, until the mid-1980s, focused mostly on external product market frameworks, such as Porter's (1980) model of forces driving industrial competition.

Proponents of RBV argue that firms' strategic position can be viewed from two perspectives, the resource perspective and the product perspective. The product perspective suggests that it is possible to align a firm's minimum resource commitment for different product markets by specifying the size of the firm's activity in these markets. Conversely, it is possible to identify optimal market activities by specifying the firm's resource profile. This premise may be especially true in an organization that has spent a large amount of capital in advance on manufacturing techniques that comprise manufacturing systems that demand skills and commitment for creating value.

The foundation of the RBV lies in the common premise that people in general provide organizations with an important source of sustainable competitive advantages (SCAs) and that management of human capital rather than physical capital is the ultimate determinant of organizational performance (Youndt et al., 1996).

The RBV furthermore posits the following prerequisites to access sustainable competitive advantages:

- Resources cannot be possessed by all competing firms.
- They must be difficult to imitate or duplicate.
- They must contribute to performance positively.

A resource in this context is something that can be considered as a strength or weakness for the firm, e.g. process knowledge, skilled personnel, trade contacts, machinery and equipment, capital or brand names, etc. (Wernerfelt, 1984). From a manufacturing perspective, RBV refers to the development of idiosyncratic manufacturing processes at plants. In this context, the RBV refers to building manufacturing capabilities with a strategic impact. Schroeder et al. (2002) suggests that internal and external learning within the manufacturing environment creates "*unique proprietary processes and equipment, which in turn leads to superior manufacturing performance*".

The RBV is consistent with other findings that manufacturing processes play an important role in creating competitive advantage. The difference between past manufacturing strategy research and the RBV is:

- Traditional MS research investigates the adoption of specific manufacturing practices. However, it does not address the effects of competitors imitating successful innovation and process technology.
- Traditional MS research does not consider the importance of in-house developed capabilities and proprietary processes that cannot be acquired in product markets.
- The RBV emphasizes the acquisition of tacit knowledge and learning for achieving sustainable competitive advantage (SCA).
- Manufacturing practices adopted by world-class manufacturers lead to competitive parity but do not lead SCA.

The purpose of RBV is to analyse a firm's resource position and look at strategic options based on the resource analysis. The analysis can identify types of resources that can lead to high profits. Today, one the founders of the RBV claims that resource-based theories have been developed and that it is widely acknowledged as one of "*the most prominent and powerful theories for describing, explaining and predicting organizational relationships*" (Barney et al., 2011) .

2.2.4 Theory of performance frontiers

The fields of operations management and manufacturing strategy have been developed over many years. However, these fields of research have also been criticised for theoretical inadequacy (Swamidass and Newell, 1987).

Schmenner and Swink (1998) assert that a key phenomenon within operations management is to understand why some operations are more productive than others and to seek explanations with the support of laws that have bearing on the phenomenon of differential factory productivity. Schmenner and Swink (1998) claim that "*we have not labelled them as laws, but in the terminology of the philosophy of science, that is what they are*". Some of these laws are deductively obtained and some of them are obtained from observation (table 3).

Table 3: Laws relating to factory productivity. Source: Schmenner and Swink (1998).

	Description
Law of variability	The greater the random variability is concerning demands, the process itself and the item its process, the less productive the process is. For example, see Hopp and Spearman (2008).
Law of bottlenecks	The productivity of a manufacturing process is improved by eliminating or better managing its bottlenecks. For example, see Dettmer (1997).
Law of scientific methods	Labour productivity can be improved by applying methods such as those identified by the scientific management theory. For example, see Hopp and Spearman (2008).
Law of quality	Productivity is improved as quality is improved and waste declines (referring to product design changes, material changes and processing changes). For example, see Adam et al. (1997).
Law of factory focus	Factories that focus on a limited set of capabilities will be more productive than factories that focus on broader array of tasks. For example, see Rosenzweig and Easton (2010).

Even though factory productivity is a key phenomenon to understand, some manufacturers seem to outperform others in several dimensions of performance (see the sand cone model section). These dimensions are captured by means of laws related to strategic context (table 4).

Table 4: Laws of manufacturing strategy. Source: Schmenner and Swink (1998).

	Description
Law of trade-offs	No manufacturing system or unit can perform equally well to create competitive advantages across all manufacturing criteria.
Law of cumulative capabilities	Improvements in quality are easy and basic, which makes improvements in other manufacturing capabilities, for instance dependability or flexibility, even easier. The order that manufacturing capabilities should be improved in is: quality, dependability, speed, cost and finally flexibility.

Instead of considering the law of trade-offs and the law of cumulative capabilities as rivals, Schmenner and Swink (1998) combines them to create the *theory of performance frontiers*.

The theory of performance frontiers is aligned with a common perception about MS concepts that strategic choices are broken down between choices affecting physical assets (structural decision) and choices affecting infrastructural issues such as operating policies. Schmenner and Swink (1998) suggests that these distinctions can be depicted as two frontiers: one frontier that is formed by choices in plant design and investments and one frontier that is formed in plant operations. The former is referred to as the *asset frontier* and the latter is referred to as the *operating frontier*. A performance frontier is also defined as the *"maximum performance that can be achieved by a manufacturing unit given a set of operating choices"* (Schmenner and Swink, 1998).

Figure 13 depicts a firm (firm A) that operates under a certain physical constraint (referring to firm A's physical layout and technology adoption) that forms the firm's asset frontier. Position A_1 indicates that the firm is underutilized and inefficient. In this scenario, firm A may improve its production processes to produce according to standard and thus reach position A_2. This movement towards the operating frontier is termed *improvement* (Schmenner and Swink, 1998). Position A_3 can further be achieved by alternating the production policy currently employed by the firm, for instance through adoption of JIT or lean principles. Moving the operating frontier closer to the firm's asset frontier or changing the slope of the frontier is referred to as *betterment* (Schmenner and Swink, 1998). If scenario A_3 is reached, trade-offs are faced among the performance dimensions. For instance, introducing new products at position A_3 will likely increase the average unit cost if the firm's operating policies and physical assets remain unchanged.

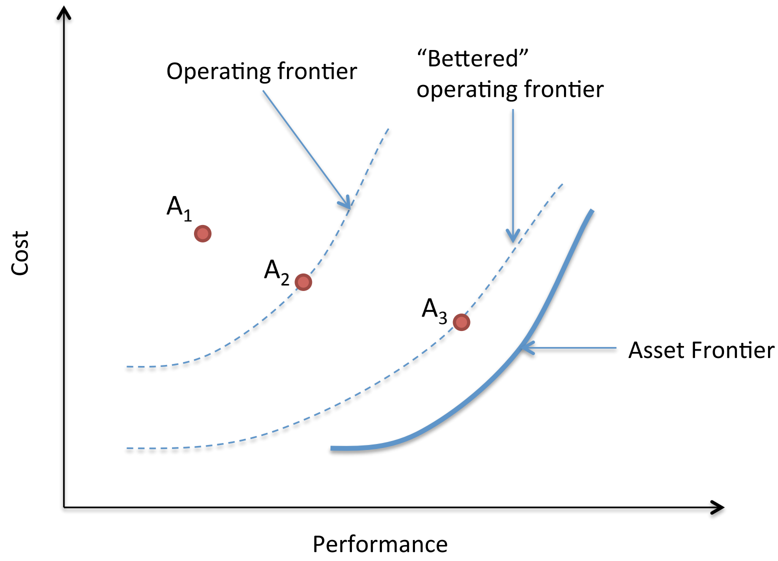

Figure 13: The performance frontier concept as explained by Schmenner and Swink (1998). Position A1 is underutilized and inefficient. Position A2 is limited by the firm's production polices. Position A3 is achieved by "bettering" the production policies.

Table 5 explains certain movements within the performance frontier diagram. The law of diminishing returns states that it requires less resource consumption rates to improve quality losses from 20% to 15%, compared to improving quality losses from 10% to 5%. That is, once the lowest hanging fruits have been picked and the easiest problems have been solved, it demands more and deeper improvement activities to find and solve more problems. The law of diminishing synergy states that the beneficial impact of a reliability improvement that originates from improved quality yields is greater from the reduction of 20% to 15% quality losses than the reduction of 10% to 5%.

Table 5: Laws adapted from microeconomic theory. Source: Schmenner and Swink (1998)

Observed laws	Description
Law of diminishing returns	As improvements and betterments move a manufacturing plant closer to its frontiers (operating or asset), a relatively increased quantity of resources is required to achieve each incremental benefit.
Law of diminishing synergy	Synergetic effects predicted by the law of cumulative capabilities diminish as the manufacturing plant approaches its assets frontier.

Vastag (2000) provides an alternative design of the performance frontier diagram originally presented by Schmenner and Swink (1998). Vastag (2000) notices similarities between the *asset frontier* and the capacity management literature's definition of *ideal capacity* (maximum output that can be attained at a plant) and the operating frontier and the corresponding definition of *practical capacity* (or measured capacity). As opposed to Schmenner and Swink (1998), Vastag (2000) argues that cost belongs to the performance dimension. Accordingly, inputs are under control while outputs are not. Instead, he rearranges the diagram and depicts the performance dimension on the vertical axis and the input dimension on the horizontal axis (Fig. 14).

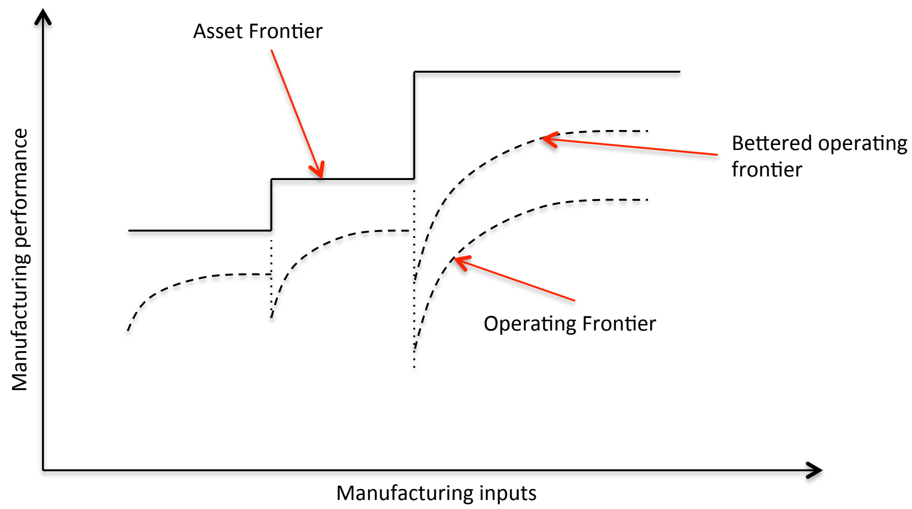

Figure 14: Vastag's figure of performance frontiers.

The horizontal input axis is described as an index of manufacturing practices that reflect manufacturing inputs (labour and materials), investment and choices in the manufacturing unit. Vastag (2000) suggests movements of the frontiers adapted to equivalent laws as stated by Schmenner and Swink (1998). However, asset-related improvements are suggested to follow a step function, implying that investments in industry technology are required to increase the output of production – otherwise the asset frontier will be constant. The operating frontier is represented as a concave trajectory path that is reflected by the law of diminishing returns. Vastag (2000) furthermore assumes that the operating frontiers may exhibit upward or downward jumps that cannot be attributed to investments in structural factors. These jumps are instead due to human factors (changes in work attitude and changes in organizational learning capabilities).

Both the Vastag (2000) and Schmenner and Swink (1998) approaches are aggregated attempts to form performance frontiers that can be used to evaluate where a firm currently is and accordingly where it should be in the future to remain or gain competitive advantages. Both attempts use various measures to indicate firms' location in the diagram. The next section covers the area of performance measurement.

2.3 Production system performance

In order manage something effectively, it has to be understood, and production systems are no exception. Achieving outstanding performance through management of human resources is a practice that has existed in civilizations as long as people have tried to achieve common goals (Wren, 1987). The academic field of management practices is, however, relative new, dating back to the late nineteenth century. One of the reasons for the development of management as a stand-alone discipline was the introduction of large-scale manufacturing operations. Before that, there were no incentives to study either work or management because all operations were carried out in small facilities under direct supervision (Hopp and Spearman, 2008).

The father of scientific management is arguably Frederick W. Taylor (1856-1915). The core of Taylor's management system was to break down a production process into its components and improve each component's efficiency. Taylor focused on manual labour and condensed his thoughts into four principles (Taylor, 1914):

1. The development of true science
2. The scientific selection of workers
3. Worker education and development
4. Friendly cooperation between management and workers

Even though Taylor's contribution to science has been debated and questioned over the years, it is clear that he defined the basic manufacturing management paradigm (Hopp and Spearman, 2008).

Today, management research covers a wide range of practices, from initial design to end-customer use and services. One of the fundamental models within operations management is the transformation process model depicted in Figure 10. Transformation processes occur at all levels within an organisation, for instance on the shop floor, transforming materials to products, or at the office, transforming invoices to production orders, etc. The problems in managing these transformation processes are usually the same, independent of operation – for instance, forecasting demand, aligning capacity with current and future demand (capacity management), system, product and service design (design management), establishing competitive strategies, etc. Management research is conducted to support managers in overcoming these obstacles and thus in developing their businesses and, in the long run, the society in which it operate. This section introduces the concept of *performance measurement* with special attention to the set of measures that are used throughout this thesis.

2.3.1 Performance measurement

To continuously develop and align a production system to its environment, it is essential to collect performance data. A key area within operation research is *performance measurement* (PM) and *performance measurement systems* (PMS). Performance measurement is a way to quantify operations, and performance measurement systems (PMS) is a higher-level system that involves how to design the feedback loop to control operations (Neely et al., 2005, Radnor and Barnes, 2007). The management part of PM is related to setting performance objectives and explaining why performance objectives are set the way they are.

Performance measurement from a historical perspective

Performance measures have historically been used within the discipline of *management accounting.* Management accounting's primary function is to provide information that is useful for managers in planning and controlling decisions (Chenhall and Langfield-Smith, 2007, Kaplan, 1983). Performance measures are a vital element in such managerial or cost accounting systems. The primary objective of performance measures since the Industrial Revolution has been to achieve financial stability and growth through emphasizing efficiency measures (Radnor and Barnes, 2007). Radnor and Barnes (2007) distinguish between three time periods of performance measurement history; the early twentieth century, the post-World War II period to the mid-1980s, and the mid-1980s to the present.

The first period is described as one in which the objective for manufacturers was to produce as efficiently as possible. This period was influenced by the work of Frederick Taylor. As a result, PMSs were designed to guide managers by reporting how efficient their operations performed. However, growing enterprises led to increased complexity and new challenges. For instance, firms acquired and built production plants at various locations and became multidivisional, providing a wide range of products and services.

The human relation movement that emphasized social factors as technical factors were emphasized in scientific management led to a broader scope of performance measurement.

The second period is described as a gradual shift from the predominant cost and efficiency concerns towards other concerns such as quality, flexibility and reliability. This period is characterized as a boom in quantification and measurement techniques linked to development of computational power. However, with low unemployment rates, it became vital to focus improvements on the quality of working life rather than efficiency. This led to development of quality circles and self-managed teams in which workers were given increased autonomy. The common perception in the 1980s was that financial measures alone were inappropriate (Wilcox and Bourne, 2003, Chenhall and Langfield-Smith, 2007).

The last period of time is described as growing dissatisfaction with traditional efficiency-related performance measures. Johnson (1991) asserted that decreased reliance on direct labour, increased capital intensity and more reliance on intellectual properties made traditional methods of matching revenues with costs invalid. This led to the development of multidimensional performance measurement frameworks such as the balanced scorecard (Kaplan and Norton, 1996). These new and innovative PMSs were characterized as customer-oriented, value-based, long-term oriented to evaluate, involve and improve (De Toni and Tonchia, 2001).

Purpose and application of performance measurement

The purpose of performance measurement is to guide an organization in line with its overall strategy (Wilcox and Bourne, 2003). In this context, performance measures are used to evaluate, control, communicate and improve processes to ensure attainment of these strategic objectives (Ghalayini and Noble, 1996, Melnyk et al., 2004). The importance of performance measures increases with greater input volumes. When complexity increases, performance measures provide "*the means of distilling the volume of data while simultaneously increasing its information richness*" (Melnyk et al., 2004). Performance measurement is thus a tool that provides data refinement. The greatest importance of performance measures is, however, as tools for people. In the end, the actions and decisions people make determine a firm's prosperity and success. The rationale for using performance measures is that they influence what people do (Neely et al., 1995). Furthermore, the effectiveness of a PMS depends on how it affects individual behaviour (Chenhall and Langfield-Smith, 2007).

The two most important variables of performance are generally considered to be *efficiency* and *effectiveness* (Radnor and Barnes, 2007). Efficiency is related to the notion of productivity, i.e. output dived by input. Effectiveness is related to the notion of goal attainment, i.e. the appropriateness of the output. Various explanations exists; for instance Prokopenko (1992) gives the following explanation: When a government agency trains unemployed people to help them find employment, the number of people trained per instructor is an efficiency measure and the proportion of trained people who obtain jobs is an effectiveness measure. Neely et al. (1995) assert that "*effectiveness refers to the extent to which customer requirements are met, while efficiency is a measure of how economically the firm's resources are utilized when providing a given level of customers satisfaction*". No matter the explanation, these two parameters are of importance, since they highlight the fact that there can be both internal and external reasons for achieving improved performance. Slack et al. (2007) depicted these reasons as five combined internal and external performance objectives: cost, dependability, flexibility, quality and speed (Fig. 15).

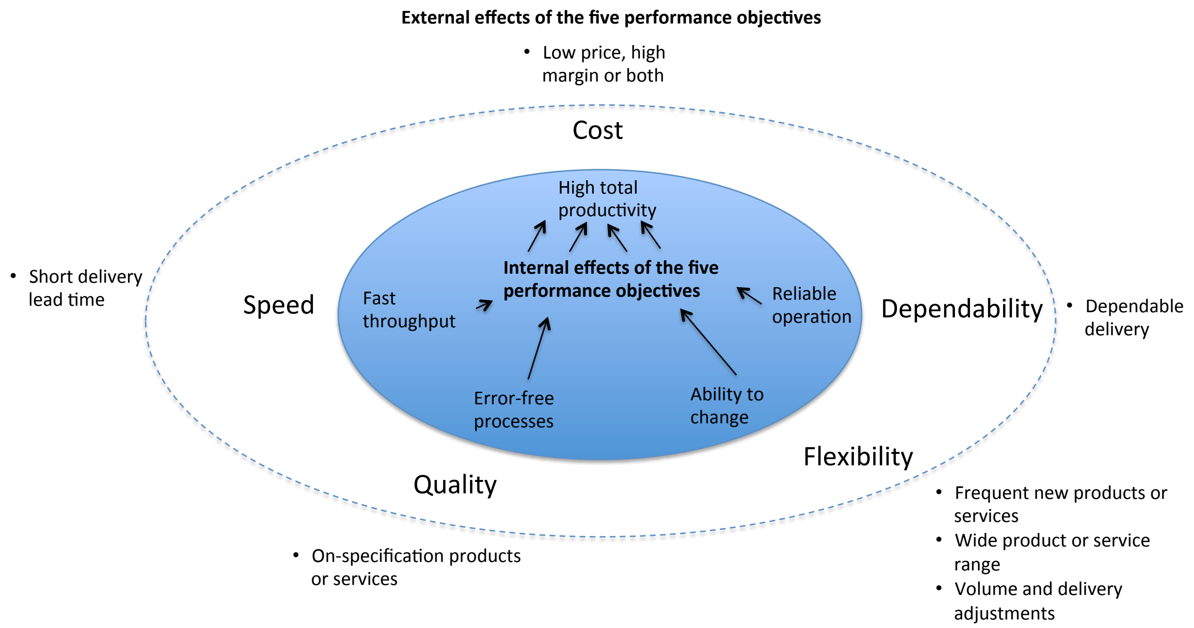

Figure 15: Performance objectives have both internal and external effects.

The quality objective – for instance, achieving higher product reliability – might lead to increased customer satisfaction (effectiveness); meanwhile, the number of warranty claims is reduced, lowering costs for providing internal repair operations (efficiency). Neely et al. (1995) stated that the level of performance a business attains is a function of effectiveness and efficiency, offering the following definitions:

1. *Performance measurement is defined as the process of quantifying the efficiency and effectiveness of actions.*
2. *A performance measure is defined as a measure to quantify efficiency and effectiveness of an action.*
3. *A performance measurement system is defined as a set of measures used to quantify both efficiency and effectiveness of actions.*

In practice, PMSs act at several hierarchal levels within a manufacturing organization. The PMS must be designed in such a way that lower level performance measures are aligned and effectively influence higher level aggregate measures that enable effective control and management of the manufacturing organization.

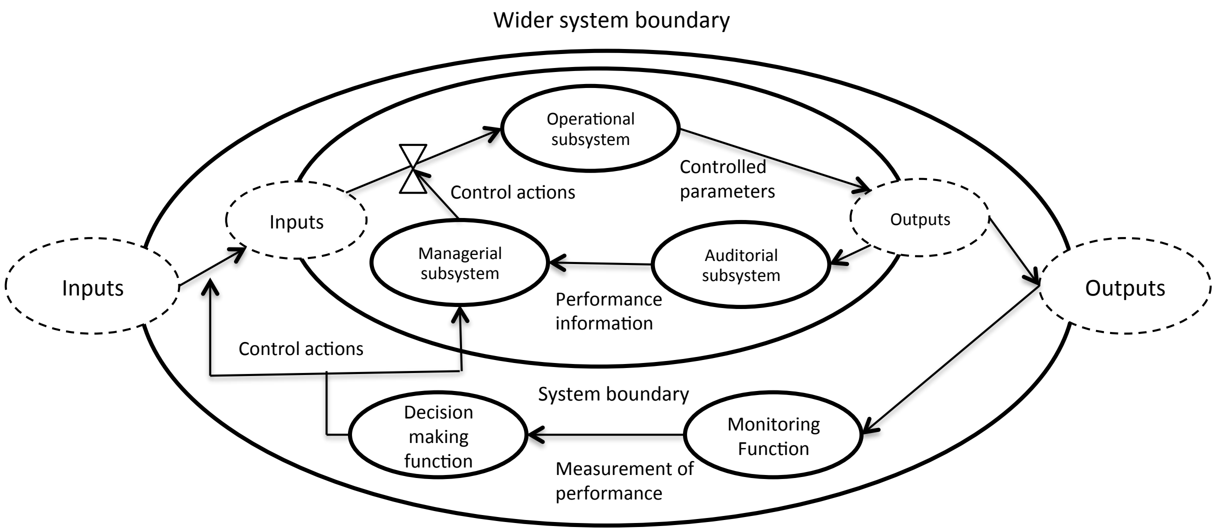

Figure 16: An example of a production system model adapted from Wu (1994)

Figure 16 depicts a production system model that consists of several hierarchal levels. The model emphasizes the feedback loop to control operations. The operational system hierarchy consist of three subsystems. The focus is the operational subsystem that transforms inputs into desired outputs. The second subsystem monitors the operational subsystem's performance (auditorial subsystem) and reports this information to a managerial subsystem that is responsible for goal-setting procedures and the decision-making process. The managerial subsystem thus controls the operational subsystem.

Performance measurement classification

The performance measurement literature provides a vast quantity of performance measures. Various classifications exist. For instance, Fitzgerald et al. (1991) distinguish between performance measures that relate to results, e.g. financial performance and competitiveness, and those that relate to determinants of results, e.g. quality, flexibility, innovation rates, etc. Fitzgerald's work indicated the need to identify performance drivers that enabled desired performance outcomes (Kennerley and Neely, 2002). Another classification is provided by Melnyk et al. (2004), suggesting that performance measures can be classified according to two attributes: *measure focus* and *measure tense*.

Measure focus concerns the focus of the measure. Generally speaking, two types of measurement data exist: financial (monetary) data and operational (non-monetary) data. Operational data refer to lead-times, cycle times, inventory levels, etc. A financial measure defines the pertinent element to monetary resource equivalents. For instance, instead of measuring the number of units in inventory, it measures the monetary value of the units. Whereas an operational measure defines pertinent elements in other type of resources, e.g. time or human resources, or as outputs, e.g. the number of defects or physical units etc.

The second attribute concerns how the measure is intended to be used. Melnyk et al. (2004) distinguish between *outcome-oriented* measures and *predictive-oriented* measures. The rationale for using outcome-oriented measures is that *by studying the past the present can be improved*. In contrast, predictive-oriented measures are measures employed to increase the chance of attaining an explicit objective or goal. For instance, if reduced lead-time is the explicit goal, predictive measures must reflect that goal. In this case, measures such as setup time, number of processing steps, number of buffers and cycle time are all measures that, if reduced, will result in the outcome concerned.

Three performance measures that are arguably important and used throughout the thesis are discussed below. They are productivity, profitability and capacity.

2.3.2 Productivity

Productivity is a component of performance and needs to be viewed as one performance criterion within a PMS that managers can assess, evaluate and make decisions about regarding the organization they are managing (Sink et al., 1984). Productivity, which is widely described as the ratio between input and output, can be classified as both *operational* and *financial,* as well as *outcome-oriented* and *predictive-oriented* (eq. 1).

$$productivity = \frac{output}{Input} \quad (1)$$

Bernolak (1997) asserts that productivity is about *how much* and *how well* a firm produces goods with a given quantity of resources. Productivity increases when a firm produces more goods with better quality with the same amount of resources. The same principles are valid for services. Productivity increases when a firm's service levels improve with equal quantities of resources.

Productivity is a multidimensional term, arguably representing the most important variable for governing production activities (Singh et al., 2000). There is thus a difference between a workstation's cycle time and a workstation's productivity. The cycle time measure refers to time that fundamentally consists of one dimension only and will not vary depending on the context it is used in. However, productivity's meaning varies depending on the context it used in and can be defined with different variables, for instance time, cost, output rates, input rates, etc. Productivity's context dependency thus entails different definitions. Tangen (2005) lists several authors' productivity definitions, both verbal and mathematical, suggesting similarities between these definitions but concluding that the creation of a totally common vocabulary is not an easy task. Moreover, Tangen (2005) discusses two characteristics based on Bernolak (1997) description of productivity.

First, productivity is closely related to the use and availability of a firm's resources. This implies that productivity is reduced if a firm's resources are used inappropriately or if there is a lack of them. For instance, specific operations will be idle if materials are missing. The second characteristic is productivity's close relationship to the process of adding value. While the term *value* is difficult to define, its opposite meaning is easier to define – *waste*. Productivity is thus improved to the extent that waste is reduced. The importance of waste reduction actions is covered first and foremost by the vast amount of literature in the areas of total quality management (TQM), just-in-time (JIT) and lean production (Shah and Ward, 2003, Hicks, 2007). Among the most cited authors in this area are Womack et al. (2007), originally published 1990, who made the notion "*lean*" famous. The book was inspired by Japanese manufacturing philosophy as presented by Ohno (1988). Ohno's book was promoted with the Toyota Production System (TPS) as an example that has inspired Western manufacturers to implement similar philosophies and practices (Schonberger, 2007).

It is, however, important to remember that productivity is a term that is widely used beyond the borders of the manufacturing firm. There are two basic forms of productivity: *partial productivity (component)* and *total productivity (aggregate)* (Löfsten, 2000). Aggregate productivity measures attempt to account for all inputs, such as labour, material and capital, whereas component productivity measures only consider one type of input, for instance labour or capital. Total productivity (eq. 2) is an aggregate productivity measure defined as "*the ratio of total output to all input factors*" (Ghalayini and Noble, 1996).

$$total\ producitivity = \frac{total\ output}{labour+capital+materials+miscellaneous} \quad (2)$$

The attempt to measure aggregate productivity faces the problem of heterogeneity (inputs are by nature different) and inputs are possibly intangible (Teague and Eilon, 1973). As a consequence, input parameters must be transformed into a single analysis unit, for instance man-hour equivalents or monetary units. Craig and Harris (1973) were among the first to introduce an aggregate firm level productivity model. To calculate total output, they used all units produced during a period of time multiplied by their selling price. They emphasized units produced rather than goods sold since productivity is an efficiency measure. They used the following approach to determine the value of inputs:

- Labour: Man–hours were converted into monetary units by multiplying total man-hours by an appropriate wage rate.
- Capital: Annuity cost of assets was used. Three aspects determine the annuity cost: the cost of the asset, the productive life of the asset, and finally the desired rate of return (cost of capital).
- Materials: Materials were calculated as purchased units (adjusted for inventory changes) multiplied by base-year material prices.
- Miscellaneous: Utilities (heat and power), government services (taxes), advertising, non-productive materials (offices supplies, etc.)

Aggregate models such as the firm level productivity model described above have been criticised for failing to acknowledge both practice and managerial perspectives (Löfsten, 2000). Instead they are designed to evaluate collective performance, such as a plant or an industry. In addition, all inputs correspond to a large quantity of data that are both timely and expensive to collect (Ghalayini and Noble, 1996).

Component productivity measures are designed to measure performance of a single activity or a limited area or department of a facility (Löfsten, 2000). They are for instance measurement of workers' productivity and measurement systems for planning and analysing unit labour requirements (Prokopenko, 1992). In contrast to aggregate measures, they are intended to assist managers in improving productivity. However, on shop floors almost any improvement can be regarded as a productivity improvement. But, "*it is not one, however, unless it increases output more than the increase in inputs needed to produce the same amount of output*" (Löfsten, 2000).

2.3.3 Profitability

Profitability is a traditional financial performance measure that compares a firm's income to its revenues and investments (Drake and Fabozzi, 2012). The difference in these ratios is typically whether taxes, interest and depreciation are included or not. For instance, a firm's net profit margin includes taxes and interest, while a firm's operating profit margin excludes taxes and interest. Profitability is thus the ratio between input (profit) and output (sales) as measured in monetary terms (Tangen, 2005).

From a managerial perspective, it is difficult to understand why profit margins increase or decrease, i.e. the underlying causes of profitability changes. It is clear that a firm's profit margin alone does not reveal much about a company's performance or ability to generate profits in the future (White, 2006). Additional information is necessary to evaluate performance, such as trends in profit margins over time and industry norms. Moreover, developments have occurred regarding these traditional profitability ratios. For instance, the Dupont schematics (Fig. 4) are return ratios that are decomposed into two ratios: one profitability ratio and one turnover ratio. These return ratios are better known as return on investments (ROI) and return on assets (ROA). There are advantages to performing this decomposition of a firm's profit planning. For instance, the Dupont schematics reveal all components that contribute to profits and the importance of sales is explicitly stated (Friedlob and Plewa Jr, 1996).

The downside of these aggregate return ratios is that they hardly captures micro level attributes that operations themselves have on profitability. As a consequence, the American Productivity and Quality Center (APQC) developed a model that disaggregated profitability into two components (eq. 3) that facilitate the managerial decision making process. These components are firm *productivity* and its *price recovery* ability (Banker et al., 1993).

$$profitability = productivity \times price\ recovery \tag{3}$$

In this model price recovery is the net effect on profits of changes in sales prices and input resource prices (Miller, 1984). The model reveals profitability changes due to price actions and relative volume (quantity) changes, as depicted in fig 17.

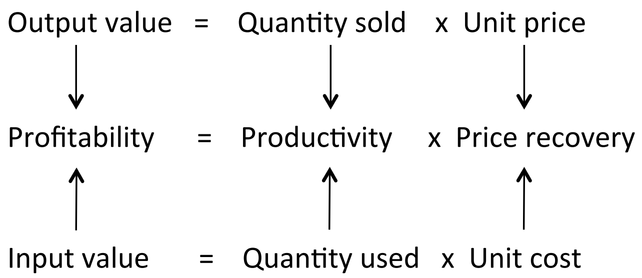

Figure 17: Profitability components. Source: (Prokopenko, 1992)

The idea of this approach is to let managers decide whether they should focus on pricing strategies, productivity improvements, or both. To analyse productivity's contribution to profits, all price changes must be removed from eq. 3 as shown in eq. 4 (Miller, 1984).

$$productivity\ contribution\ in\ period\ t = (sales^{D_t})\times(margin^{D_t} - margin_B) \tag{4}$$

Sales refer to deflated sales in one time period *t*, i.e. if prices would remain constant. *Margin* refers to deflated profit margin during a time period *t,* which would be the result if the cost of materials, salaries, rents, taxes etc. did not change (i.e. if effects of inflation did not appear). The result thus represents a physical or relative volume change in sales. Accordingly, if a firm's sales figures decline, its productivity will also decline independently of how efficiently the firm's employees work (Miller, 1984). Addressing this problem requires supplementary analysis, such as decomposing the productivity contribution into *volume influences* (sales) and *volume-independent influences* (e.g. employees, energy and other fixed resources that manufacturing processes consume, independent of sales volume).

2.3.4 Capacity

Capacity is an important measure in several respects. It is used in contexts stretching from strategic considerations (where, what and how much to produce) to daily basis planning considerations (Olhager et al., 2001). Long term planning refers to when and how much manufacturing capacity should change and is typically treated at aggregate levels rather than individual equipment levels. Intermediate capacity planning typically refers to the use of material requirement planning (MRP) systems that contain planned production quantities for a certain planning horizon (Zijm and Buitenhek, 1996). Capacity is also used in the context of cost accounting regarding the cost of excess capacity and how it should be allocated to products. Several definitions of capacity exist, which makes the notion ambiguous.

Coelli et al. (2002) have reviewed existing *capacity* definitions and concluded that two types of definitions exists: those that consider only physical information such as a quantity (volume) and those that include price information. The former capacity definition type is based on work performed by Gold (1955) and Johansen (1968) and is referred to as *plant capacity*. The latter type states that a company's plant capacity is the maximum amount that can be produced per unit of time with existing facilities and equipment, given available resources. This capacity definition type can take two forms. The first form is an estimate of the total amount that can be produced of any single product, given a specified quantity of allocated resources. This estimate is performed on the assumption that these resources are available and fully utilized and consequently measures the absolute volume of capacity, as well as changes to it (Coelli et al., 2002). The second form is an estimate of the composite productive capacity of a specified range of products and can thus be considered as a partial capacity measure. Capacity definitions that include price information are usually found in the economic literature, for instance when calculating profits due to certain capacity utilization levels. Coelli et al. (2002) provide capacity definitions that apply to the case of a single output technology:

- *Definition 1: The capacity of a plant is the maximum output that can be produced using a given technology*.
- *Definition 2: Capacity utilization is equal to the ratio of observed output to the capacity of the plant.*

Other capacity definitions are found in the cost accounting literature. The problem in cost accounting is how available (or excess) capacity should be allocated to products. Paranko (1996) provides some common capacity definitions. In practice, capacity measures usually start with a theoretical capacity that assumes an output 100% of the time. This capacity measure is referred to as *theoretical capacity*, *maximum capacity or ideal capacity*. From this measure, managers deduct time for allowances, breaks, non-planned production, holidays, etc. The measure obtained after this deduction is referred to as *practical capacity*. Practical capacity is used by Kaplan (1998) to describe the allocation of resource costs.

Section 2.3 has been concerned about production system performance and how it can be evaluated and controlled by applying performance measures. Three performance measures have been given additional attention since they are frequently used throughout the thesis. They are productivity, profitability and capacity. The next section describes how productivity can be analysed with certain methods, tools and techniques.

2.4 Shop floor productivity analysis

Saito (2001) asserts that productivity improvement measures can be classified into four groups: *Redesign of operations*, *automation and mechanization*, *use of mass production*, and *application of new technology*. However, today's business environment offers few opportunities for applying new technology. Furthermore, current market trends are shifting from mass produced products to, more individually adapted products, which requires a manufacturing organization that is flexible rather than capable of mass production. As a consequence, the most effective approach for reaching improved productivity is often to focus on the work process itself (Saito, 2001).

2.4.1 Productivity dimensions

Saito (2001) introduced a productivity audit procedure to assess three aspects of productivity: work methods (method), work performance (performance) and application of resources (utilization). According to Saito (2001), these aspects of productivity are regarded as sources of productivity losses in any business unit. Sakamoto (2010) and Helmrich (2003) referred to these aspects of productivity as *the dimensions of productivity* (eq. 5).

$$productivity = M \times P \times U \tag{5}$$

The method (M) factor contributes most to productivity (Helmrich, 2003). An example of an M factor improvement is to replace a manual weld operation in favour of a weld operation carried out by robots. The improvement is quantified by establishing a productivity ratio concerning the specific operation, e.g. the number of welded joints per hour. The performance (P) factor in eq. 5 refers to the speed of the activity. The P factor uses the same productivity ratio as the M factor, i.e. welded joints per hour. The P factor is determined by assessing the actual performance in relation to ideal performance. The (U) factor in eq. 5 examines how much of a specific time interval (e.g. available production time or planned production time) has actually been used to create value for the customer. Table 6 summarizes techniques and actions used for assessing each factor of eq. 5.

Table 6: System for analysing productivity losses. Source: Saito (2001)

		Operator	Machine	Material
Method factor	Actions	• Confirm percentages for basic functions • Estimate the operator reduction factor	• Determine actual machine time • Estimate the potential for reduction of machine time	• Determine losses caused by product design • Estimate the potential for improvement of yield
	Techniques	• Work sampling • Direct time study • Pitch diagrams • Human-machine charts • 4W (what, who, why, where) charts	• Pitch diagram • Sequence charts	• Design review • Value-added analysis
Performance factor	Actions	• Confirm present performance level • Estimate performance improvement potential (%)	• Confirm the facility performance • Estimate the potential (%) for improvement performance	• Confirm the quality of materials and parts • Estimate potential for increasing first-pass yields
	Techniques	• MTM analysis • Direct time study • Output analysis	• Work sampling • Material analysis	• Yield analysis • Analysis of failure causes • Analysis of materials
Utilization factor	Actions	• Confirm utilization loss • Estimate the potential (%) for improvement of the utilization factor	• Confirm utilization loss • Estimate the potential for improving utilization	• Confirm utilization loss (%)
	Techniques	• Analysis of setup procedures • Investigate the impact of staffing changes • Work sampling	• Down time analysis • Work sampling • Analyse space utilization	• Scrap rate analysis • Inventory analysis • Investigate alternative materials

2.4.2 Productivity assessment techniques

Abundant tools and techniques exist that are related to production system analysis, for instance those presented by Bicheno (2004). Table 6 covers some of the available productivity analysis techniques: work sampling studies, time studies (direct and predetermined time systems) and human-machine charts, etc. All of them can be used to assess and improve production systems. This section describes analysis techniques that are used throughout the thesis.

Time studies

Time studies can be broken down between direct time studies and time studies using pre-determined time systems. The former type is the simplest and requires only a stopwatch. Direct time studies are employed to measure manufacturing activities' cycle time, short sequences of work, etc. The purpose is usually planning related (for use in planning systems), performance related (measuring actual time consumption in comparison with planned times), and improvement related (measure before and after scenarios).

The latter technique, predetermined time systems (PTSs), consist of predetermined time elements representing basic motions such as walk, get and put, which are based on statistical evaluations and are referred to as predetermined times. The purpose of using PTSs is to predict standard times for new or existing work operations (Niebel and Freivalds, 2003).

Several PTSs have been developed since the early twentieth century, e.g. Methods-Time Measurement (MTM), Work Factor (WF), Maynard operation sequence technique (MOST) and several MTM modifications (MTM-2, MTM-3, MTM-UAS and SAM). MTM is the most common PTS in the world today (Kuhlang et al., 2011). The main differences between these PTSs are accuracy (referring to measurement errors) versus the time needed to analyse work activities. For example, an MTM-1 analysis requires 250 times the analysed cycle time to be accomplished. For example, a one minute work activity requires 250 minutes to be analysed with MTM-1. In comparison, an equivalent analysis with MTM-3 requires 35 times the cycle time to be accomplished. The difference is that MTM-3 provides less accuracy than MTM-1, i.e. deviations from the standard time are larger. Cakmakci and Karasu (2007) mention three benefits of using PTSs:

1. Predetermined time systems require a thorough analysis of current work methods, which entails definition of the standard work flow of the studied activity. The detailed analysis makes it easy to find problems and non-value added motions.
2. Predetermined time systems consist of basic motion elements that are determined in advance by statistical analysis. The standard time is obtained by summing up these elements. Accordingly, the result is protected from subjective judgements and performance ratings are not necessary.
3. Since predetermined time systems use predetermined time standards, any operation can be analysed even if it exists only in a planning phase. In contrast, a direct time study requires the real work to be analysed.

Traditionally, PTSs have been used for setting standard times in piece rate systems and manufacturing processes with characteristics of mass production (Cakmakci and Karasu, 2007). Nevertheless, it is possible to use PTSs in operations that continuously change or in operations that occur randomly, e.g. machine setups. Many operations on a factory floor are repetitive in nature. Thus, PTSs can be used to analyse the repetitive parts of these operations, even if some of the work content changes from product to product. Predetermined time systems may, however, be inappropriate if there are very small production volumes or extremely long cycle times (Nakayama et al., 2002).

SAM – Sequential Activity and Method analysis

Sequential Activity and Method analysis (SAM) is a PTS that provides operators and specialists (industrial engineers) with a common means to analyse work activities. SAM is comparable to MTM-3 in terms of accuracy and speed (Imd, 2004). SAM is based on work sequences, which makes the analysis deviation (the statistical error) larger but the user error smaller, since fewer decisions are requested. Accordingly, SAM demands less training and practice than other PTSs.

The basic design principle of SAM is a sequential analysis of four activities: *get*, *put*, *use* and *return*. For instance, get a screwdriver from the workbench, put the screwdriver on the assembly object, use the screwdriver and finally return the screwdriver to the workbench. In SAM, get and put are referred to as basic activities. In order to get an object, *supplementary activities* such as *step* and *bend* may be necessary. When using tools, *repetitive activities* may be necessary, such as *screw* or *crank*. The result of the SAM study is presented as a time unit called *factor*. One factor is equal to 0.00005 hours.

Work sampling

Work sampling is a technique to analyse machine and manual work by performing a large number of observations at random times or of random objects. The technique aims to investigate the percentage of time that is devoted to specific activities. A work sampling study of manual work aims to determine the amount of time operators are spending on different activities. The work sampling result provides a distribution curve (in percentages) of these activities. The aim of the work sampling study is to detect production system losses, such as waiting or rework-related activities.

A work sampling study conducted on equipment aims to determine the percentage of time that the equipment is idle, machining, handling tools, waiting for jobs, waiting for operators etc. Time studies may provide the same data as work sampling studies. However, the work sampling technique is considered to have some advantages over traditional time studies (Niebel and Freivalds, 2003):

1. Work sampling does not require continuous observation by an analyst over a long period of time.
2. Clerical time is reduced.
3. The total time spent by the work sampling analyst is usually less than conventional time studies.
4. Operators or assemblers are not subject to stopwatch observations.
5. A single analyst can study operations carried out in teams.

Overall equipment efficiency

Overall equipment efficiency (OEE) is a performance measure that measures equipment efficiency. The measure originates from the semiconductor industry's poor equipment utilization and low production yields (De Ron and Rooda, 2005). Overall equipment efficiency was initiated when Nakajima (1988) introduced the Total Productive Maintenance (TPM) concept. The goal of TPM is to achieve zero defects and zero breakdowns. The consequences of striving for these goals are increased production rates, reduced costs and reduced inventories (Muchiri and Pintelon, 2008). The purposes and uses of OEE are manifold. The measure can be used at different firm levels. For instance, it can be used as a benchmark for measuring and comparing equipment performance between different plants. The measure can also be calculated for machine lines in order to highlight poor equipment performance. And machine processes can be individually measured to indicate where TPM resources should be allocated (Dal et al., 2000). Total Productive Maintenance is based on three major concepts (Ljungberg, 1998):

1. Maximising equipment efficiency.
2. Autonomous maintenance by operators.
3. Small group activities.

Total productive maintenance is thus aligned with Saito (2001) concept that improvements should focus on the work itself rather than on wide-ranging improvement programmes (Ljungberg, 1998). The OEE measure considers three aspects of efficiency: availability, performance rate and quality rate. The relation between these parameters is described by eq. 6.

$$OEE = availability \times performance\ rate \times quality\ rate \tag{6}$$

Equation 6 does not consider capacity utilization losses such as planned downtimes, lack of material or lack of resources. Instead, its primary concerns are what Nakajima (1988) refers to as the six big losses:

1. Equipment failure or breakdown that causes quantity losses due to defective products.
2. Setup and adjustments that result in time losses and material waste due to setup operations.
3. Idling and minor stoppage due to short production interruptions.
4. Speed losses due to product design or insufficient operator skills.
5. Reduced yield due to start-ups or ramp-downs.
6. Quality defects and rework caused by equipment failures.

The first two losses are referred to as downtime losses and consequently affect the equipment's availability (eq. 7).

$$availability = \frac{planned\ production\ time - stop\ time}{planned\ production\ time} \tag{7}$$

The third and fourth losses are referred to as performance efficiency losses (eq. 8). These losses occur because operating conditions are less than optimal (Dal et al., 2000).

$$performance = \frac{ideal\ cycle\ time \times units\ processed}{planned\ production - stop\ time} \tag{8}$$

The last two losses relate to the number of defects (eq. 9). The quality rate decreases if the number of defect units processed by the equipment increases.

$$quality = \frac{units\ processed - defect\ units}{units\ processed} \tag{9}$$

2.4.3 Productivity potential assessment

The productivity potential assessment (PPA) method was developed between 2005 and 2006 by the Institute for Management of Innovation and Technology at Chalmers University of Technology, funded by the Swedish Agency for Economic and Regional Growth. The initial purpose of this initiative was to examine shop floor productivity in order to understand to what extent a production system's resources were utilized for productive activities. The method exhibits similarities with the work carried out by Goodson (2002) and Saito (2001). The method's focus is on shop floor operations, especially the utilization of human resources and machinery, combined with an overall analysis of the manufacturing system. The essence of the method is described below. A detailed description of the PPA method is provided by Almström and Kinnander (2011).

The entire study is conducted in one day by two qualified analysts. A qualified analyst is in this context a highly trained industrial engineer who has passed a course in the PPA method and completed at least two pilot PPA studies. The study results in a productivity synthesis based on a set of analysis parameters. The parameters of the PPA method are broken down into five different levels (Fig. 18). Each level is discussed below.

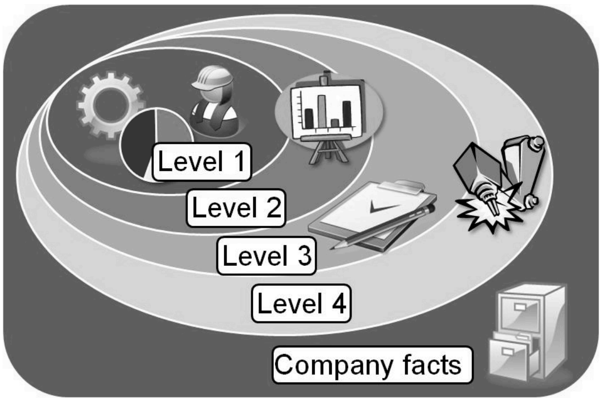

Figure 18: The levels of the PPA-method.

Company facts

Company facts are financial results, number of employees, types of products, etc. These data are collected as a prerequisite for categorization of the companies analysed. All data collected during PPA studies are entered in a database. Company facts facilitate comparisons of PPA results and the information can also be used to sort firms in the database by size, number of employees, sales volumes, products, etc.

Level 1

Level 1 is the core of the PPA method and refers to a study of manual labour and equipment efficiency. This study is conducted in a selected area of the production facility concerned. This area should be a bottleneck in the production flow. Level 1 is analysed with two techniques: work sampling concerning labour work content and OEE concerning equipment performance.

An important part of the PPA method is to break down production activities into *value added*, *non-value added* and *supportive* activities. This categorization provides a statistical distribution regarding the work sampling study. Each category is described in the following list:

1. *Value added*: Activities that add value to the product – for instance, assembly, loading and unloading equipment.
2. *Supportive*: Activities that must be performed to add value to the product – for instance material handling activities, reading instructions, mounting fixtures, etc.
3. *Non-value added*: Activities that do not add value to the product – for instance, assembly errors, repairing equipment, personal time, chatting with colleagues, etc.

The number of observations needed to create a statistically validated distribution varies with the number of activities defined (Niebel and Freivalds, 2003). The standard in the PPA method is to collect 480 observations at a time interval of 30 seconds, which corresponds to 4 hours of analysis. The number of observations is statistically validated based on the collection of three parameters (value added, supportive and non-value added). However, one purpose of the method is to determine whether those 4 hours are representative of a normal day of production. The second parameter of PPA level one is the overall equipment efficiency measure. Overall equipment efficiency data are measured by one of two alternatives. First, the company may already measure OEE. In that case, the analyst is responsible for validating existing data. The second alternative is that the PPA analysts manually measure OEE. The second alternative suggests that a limited quantity of data can be collected.

Level 2

Level two is a set of performance measures based on the competitive priorities discussed in Section 2.3.1:

- Inventory turnover [multiple/year]
- Delivery accuracy [%]
- Scrap rate [%]
- Customer complaints [%]

These parameters affect firm level productivity, either direct or indirect. *Inventory turnover* is a direct measure of productivity. It concerns how efficient materials are being consumed, as well as the production system's flow efficiency. Inventory turnover is measured as total income divided by total inventory (raw material, work-in-process and finished goods). *Delivery accuracy* is an indirect measure of productivity. The meaning of delivery accuracy differs depending on the industry. For instance, just-in-time manufacturers such as suppliers for automotive manufacturers are basically forced to deliver products with 100% accuracy, while construction firms are accustomed to delivery delays. However, the PPA method uses delivery accuracy as a measure of internal delivery performance. Scrap rate and customer complaints both refer to quality. They are both direct productivity measures, since they require additional inputs if the operations fail to deliver products according to specification or of sufficient quality.

Level 3

Level three parameters are not measures of productivity. Instead these parameters assess a firm's employment of various management practices and social parameters. This assessment level consists of four parts: *level of production engineering*, *level of ergonomics*, *physical work environment* and *psychosocial work environment*. All parts are examined with PPA questionnaires (appendix A). The first part (level of production engineering) measures a company's ability to run and develop production while maintaining a sound work environment. The level of production engineering is a questionnaire consisting of 40 yes-or-no questions. Many affirmative responses reflect usage of best practices. The questions are sorted into 11 topics: strategy and goals; work methods; maintenance; competence; cleanliness and order; material handling; changeover; continuous improvements; calculations; planning and quality. Altogether the 40 questions evaluate how close the manufacturing unit is to what the authors consider the ideal state of production engineering.

The remaining parts of level three assess social factors that indirect affect productivity. Indicators such as short-term absence, long-term sickness absence and personnel turnover rate are collected. These parameters are assessed using three different sets of questionnaires: physical work environment, workload ergonomics and psychosocial work environment (Appendix A).

Level 4

Level four concerns how a firm's present productivity potential can be utilised. However, the PPA method does not include a formal measure or approach for improvements.

Instead, a discussion is held between the analysts and company management, production engineers and operators to identify production areas that can be improved.

3. Methodology

This chapter describes the research methodology used for this thesis. It explains the overall research method, covering the research questions and the frame of reference. It explains what data collection methods were used and why, how data were analysed and the quality criteria of the research results.

3.1 Research approach

At the outset, this research initiative inquired into relations between shop floor productivity improvements and its results. The objective was to create an explanatory framework that addressed shop floor productivity and why it is an important issue by explaining the effects of improving shop floor productivity.

The thesis is positioned within the field of productivity management that is derived from operations management research. Operations management is a cross-disciplinary research area involving operations that include both services and manufacturing (Karlsson, 2009). However, this thesis is limited to existing production systems, with special attention on activities performed by human resources.

Historically, operations management (OM) research has been criticized for a variety of shortcomings, for instance focusing on a narrow instead of broad scope, technique-oriented instead of knowledge-oriented, an abstract instead of a reality perspective (Meredith et al., 1989). Early OM research has been found to be quantitatively oriented towards production and material control problems to derive prescriptive solutions (Meredith, 1993, Karlsson, 2009). This type of research is often referred to as rationalism (Meredith, 1998). However, European, especially Scandinavian, thoughts and ideas introduced the importance of work organization and worker conditions that later pointed OM research towards a more qualitative orientation with greater empirical focus (Karlsson, 2009). This type of research is often referred to as interpretivism, for instance using case study and field research methods, primarily to understand phenomena and address why they occur or not (Meredith, 1998).

This research is given a broad scope, combining several system levels, for instance various subsystems' interaction with a complete production system. The research is based on empirical evidence collected in real world settings with various data collection techniques. The research aims to be useful in practice (related to best practices) and contribute to existing operations management body of knowledge, providing academic value. The reasoning style is primarily inductive, which is associated with a hypothesis-generating approach to research that often corresponds with the umbrella term qualitative research (Williamson and Bow, 2002).

Research is often carried out as an iterative process. For instance, when a theoretical reflection has been based on a specific set of data, the researcher may want to collect more data to see if the theory holds or not (Bryman and Bell, 2011). This implies that an inductive research approach often entails deductive elements and vice versa (Bryman and Bell, 2011). Meredith (1993) depicts this process with a three-stage cycle: description, explanation, and testing (Fig. 19).

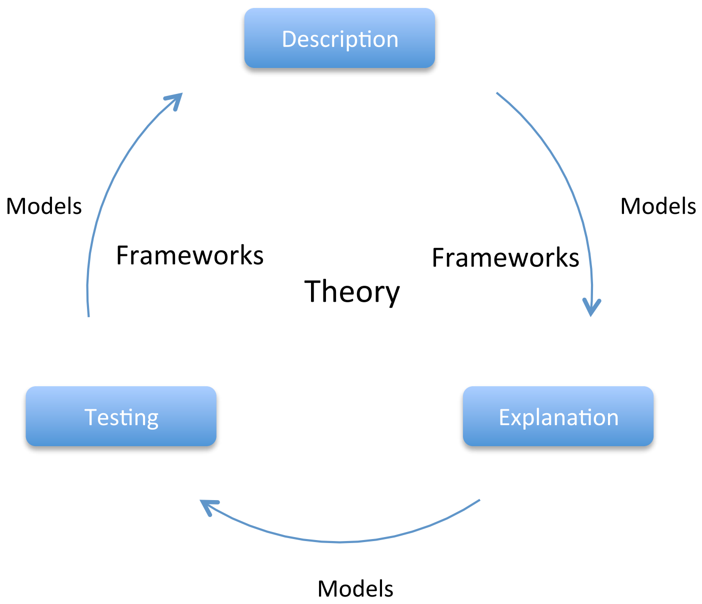

Figure 19: Iterative research process adapted from (Meredith, 1993)

The result of the first stage is a well-documented characterization of the subject of interest. A more detailed description about a specific phenomenon or event may require exploratory research in which the results may lead to further insight and understanding. Typical areas that need description are new manufacturing technologies, problems connected to these technologies, what operations managers' or operators' jobs consist of, or decision-making processes concerning adoption of new strategies or new imperatives, e.g. lean production, agile production or reconfigurable production. The explanation stage typically refers to a framework constructed for explaining cause-effect relationships that shape the dynamics of certain situations. This framework is generally supported by a frame of reference that aims to design specific studies or testable hypotheses. The framework, or set of frameworks, can be further developed into theories that describe principles or recurring events for one or several situations. Explanations have to address the underlying casual structure of the theory (Meredith et al., 1989). The final stage of the iterative research process is testing, which commonly involves a prediction based on the previous explanation stage, aiming to discover whether the prediction is true or false.

The overall objective of this research initiative is to create a productivity analysis model that is able to model a production system and explain the relationships among its constituent parts. Hence, such a model involves a combination of descriptive models that are expanded to explanatory frameworks that can be further tested to generate a theory. The difference between a conceptual model and a conceptual framework is the framework's explanatory power. For example, a model is a set of concepts used to represent or describe, but not explain, an event, object or process (Meredith, 1993). Meredith (1993) refers to Schonberger (1982) and his framework that considers the effects of just-in-time (JIT) on production management as an example of a conceptual system framework. Thus, this thesis aims to generate a theory that constitutes a set of frameworks, each of which has been iteratively generated throughout the research process and is thus a combination of inductive and deductive approaches.

3.2 Research method

The research method used for a specific research project depends on several parameters. Yin (2009) mentions three conditions that determine what research method to use for certain research inquiries: (a) the type of research question posed, (b) the extent of control an investigator has over actual behavioural events, and (c) the degree of focus on contemporary as opposed to historical events.

This research project is based primarily on two methods, *interviews* and *case studies*. The aim of the interviews is to elicit all manner of information within the specific area of interest, such as behaviours, norms, attitudes and beliefs (Bryman and Bell, 2011). Structured and semi-structured interviews are frequently related to *survey research* that involves attempts to avoid *survey errors*. Survey errors refer to the investigated sample's accuracy of representing the broader population (Blair et al., 2013):

1. Sampling error: The sample does not always reflect the population's true characteristics.
2. Sample bias: Members of the sample differ from the sample in a systematic fashion.
3. Non-sampling error: All errors that refer to the sample itself, i.e. administration errors, coding errors, recording errors, etc.

Case study research has been extensively used in social science as means of developing understanding of social phenomena in their natural setting (Williamson and Bow, 2002). Case studies are typically associated with studies in certain geographical areas, for instance a factory or a neighbourhood. A case study design differs from other research designs as it focuses on entities that have a certain function and purpose, for instance a production system. Case studies have three outstanding strengths relative to other research methods (Benbasat et al., 1987):

1. Phenomena are studied in its natural setting, meaning that a relevant theory can be constructed from direct observations.
2. Case studies do not only explain how phenomena occur or not, but also emphasize why they occur due to an inherent understanding of the nature and complexity of the phenomena.
3. Case studies are beneficial in early, exploratory studies where variables are still unknown and phenomena are not completely understood.

In contrast, Meredith (1998) mentions some disadvantages of the case study research method – for instance, the requirement of direct observations in terms of cost, time, and access, the lack of control and the complexities of context and temporal dynamics.

Overall, an observational rather than participative research strategy was used, since the aggregate objective was to create a production system analysis framework, i.e. to understand rather than to change. Case study research is often concerned with qualitative data; however, both qualitative and quantitative data collection and analysis techniques may be used (Williamson and Bow, 2002). Using several techniques for the same purpose is not a disadvantage, on the contrary, as it contributes several views of the same problem. Meredith (1998) refers to this as *perceptual triangulation*, i.e. the accumulation of multiple entities as supporting sources of evidence to assure that all facts collected are correct.

3.3 Literature review

The literature review provides a background and context for a research study, which means that it plays a crucial role for the entire research project. Williamson and Bow (2002) suggest 8 steps for writing a literature review:

1. Categorise literature into subject or topic areas.
2. Begin with an introduction to the topic. Include its significance and importance.
3. End the introduction with an overview of the contents of the review.
4. Organise the body of the review under headings that relate to the research questions.
5. Critically analyse relevant literature.
6. Write a conclusion that pulls the threads together.
7. End with the research questions that the proposed research will investigate.
8. Check that it is a critical and evaluative literature review.

This 8-step procedure has been used for both general and specific purposes. The former corresponds with the creation of a body of knowledge (frame of reference). The latter corresponds with specific research activities. The general literature review was performed to create knowledge about the constituent parts of a production system before analysing the relationships between them. This is an exploratory approach that primarily addresses relevant literature to assist in understanding recurring problems in the area of research. The general literature review was performed by means of a literature search on keywords, focused on the following areas:

- *Operations management and strategy (including productivity management).*
- *Production system engineering and analysis.*
- *Performance measurement and performance measurement systems.*

The literature review established the frame of reference for this thesis with the purpose of defining production systems and nomenclature for the reader. Another purpose of the literature review was to clarify the unit of analysis, i.e. existing production systems, and state limitations and research context.

The foundation of the literature review is a content model adapted from Slack et al. (2007), which consists of four key areas. The first area refers to the design of production systems and explains what a production system is, how it can be analysed and understood. The second area describes the field of performance measurement and how performance measures are used for production system analysis purposes. The third key area relates to productivity analysis and deployment of various industrial engineering tools and techniques. The last area refers to strategy, with special consideration paid to manufacturing strategy and its importance for production system development processes.

To further develop the productivity model and the explanatory framework, specific literature reviews were performed on the following topics:

- *Financial analysis and cost accounting.*
- *Operations management theory.*
- *Effects of production, or manufacturing, and productivity improvements.*

3.4 Research questions

Three research questions have been developed during the course of this research initiative. Each empirical study has contributed to this development in combination with knowledge gaps found in literature that have been continuously reviewed. Research question 1 is posed as, *How is shop floor productivity analysed and modelled?* The purpose of this question is to establish a foundation for the thesis by defining a production system model that is congruent with a set of available productivity analysis methods and models. The term *congruent* must be emphasised in this context, since it provides the rationale for stating such a question. This thesis focuses on the former part, that is, production system analysis rather than production system modelling. It is, nevertheless, essential to establish an unambiguous nomenclature and provide definitions regarding production systems in order to facilitate such research. Research question 1 is of an exploratory nature, seeking alternatives for analysing productivity consistent with parallel on-going production system modelling research.

Research question 2 is posed as, *How can shop floor productivity be improved*? This question follows naturally from RQ1. The question is divided into three interconnected research concerns: to investigate key variables of shop floor productivity, to investigate the linkages between these variables, and to investigate the effects of improved shop floor productivity. The purpose of RQ2 is to scrutinize shop floor productivity with the objective of establishing an analytical approach with the ability to quantify shop floor productivity and simultaneously incorporate a wider framework for productivity analysis. The first concern aims to characterize shop floor productivity by adopting a descriptive concept. The second concern aims to create an explanatory model that includes this characterization, and the last concern aims to collect evidence that supports this model (testing). Research question 2 is thus aligned with the research approach Meredith (1993) suggests.

Research question 3 is posed as, *What are the financial effects of shop floor productivity improvements*? This question can also be decomposed into a set of research concerns: The first concern refers to the strategic importance of economics and finance for manufacturing firms. This is the underlying rationale for the thesis, as it explains general business objectives and consequently why shop floor productivity is a vital parameter for manufacturing firms. The other concerns relate to the financial result parameters that are affected by shop floor productivity improvements and the relationships between them. The purpose of RQ3 is to gain an understanding of the economic effects that arise from shop floor productivity improvements. The first concern relies on existing theories of business objectives. The essence of RQ3 is explanatory, aiming to describe cause-effect relationships.

3.5 Applied research method

This research project can be divided into two separate parts. The first part of the research initiative corresponds to the Chalmers Electronics Production (ChEPro) project. This project was started in 2008 but was not officially staffed until the beginning of 2009. The ChEPro project was funded for 3 years and had an explicitly stated beginning and end. Table 7 represents ChEPro's research plan that was established in the end of 2008.

Table 7: ChEPro project plan

ChEPro project plan		2008			2009			2010			2011	
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Project start up	X	X	X									
Development of cost model for ChEPro				X	X	X	X					
Pilot breadth study					X							
Breadth study of 5 companies								X	X			
Evaluation										X	X	X
Overall results discussion											X	X
Final report												X

The underlying rationale for the ChEPro project was the assumption that companies in general do not know how their production systems contribute to the organization's bottom-line result. The objective of ChEPro was accordingly to clarify for the projects' participating companies that productivity improvements are important and necessary for retaining a competitive edge. The aim of the ChEPro project was to visualize how shop-floor productivity improvements affected bottom-line results by creating a cost model.

The second part of the research initiative refers to the time after finalization of ChEPro. The objective beyond ChEPro was to create a productivity analysis model to be used within different business branches, considering analysis and support for productivity investment decisions. The ChEPro project mainly covered the initial development of this productivity analysis model, concerning how shop-floor productivity can be analysed and improved, and to some extent its effect on financial performance measures.

During ChEPro, this early version of the productivity analysis model was referred to as production system assessment (PSA). In order to develop PSA two empirical studies were carried out. The first study, which in this thesis is referred as Study I, aimed to compare the productivity potential assessment (PPA) method with other assessment methods to understand it relative strengths and potential weaknesses and also for attaining a body of knowledge regarding options for doing production system assessments. Study I preceded ChEPro before it was fully staffed and acted as input for designing ChEPro's objectives and goals. The second empirical study (Study II) was carried out to test and validate the developed production system assessment (PSA) model. Each empirical study was furthermore preceded by literature studies in the areas of interest according to section 3.3.

The second period of time, mid 2011 to 2013, i.e. after finalization of ChEPro, was more economically oriented to inquire into the financial effects arising from typical shop floor productivity investments.

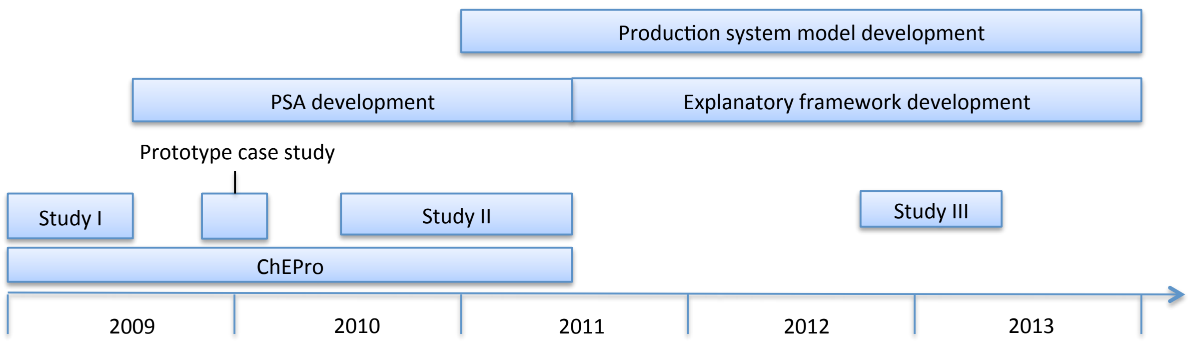

Figure 20: Research activities in chronological order.

Figure 20 depicts the course of the complete research initiative. A new PhD student (Richard Hedman) entered the research group in the beginning of 2011 responsible for developing a production system model able to incorporate the concepts used in the PSA model. From 2011 and onwards, two parallel research activities were carried out. Each empirical research activity is discussed in the following sections. i.e. studies I, II and III. The empirical findings are presented in Chapter Four. The empirical studies have furthermore contributed to the development of the explanatory framework that is this thesis main contribution. The development logic concerned with the explanatory framework is explained in section 3.5.4.

3.5.1 Study I - Production system assessment methods review

The Productivity Potential Assessment (PPA) method has been used in over 100 studies in the manufacturing industry worldwide. It is thus a well-documented method with a good track record. There are, however, several other production system analysis methods with similar purposes. Some methods have been developed in publicly financed research projects, while other methods are developed and used by single consultancy firms, and yet other methods have been developed by large OEM companies, one purpose of which is to evaluate suppliers, rate internal performance and benchmark departments.

The purpose of Study I was twofold. First, the study was an early approach to building a body of knowledge about production system analysis methods with special attention to shop floor issues. The second purpose was to determine the PPA method's strengths and weaknesses compared with similar methods. The primarily objective aligned with the purpose of creating a body of knowledge was to widen the research group's insights into how, especially consultancy firms and OEMs, use their assessment methods and acquire insights into these methods' content. The second objective was to establish a decision support tool for choosing suitable analysis methods for various occasions, that is, to answer the question of when a certain category of analysis methods is appropriate.

The review process was performed in two basics steps: data collection and data analysis. The study started with a literature review aiming to locate publicly available production system assessment methods equivalent to PPA. Keywords such as *productivity analysis*, *production system analysis* and *manufacturing system analysis* were used. The second approach was to use the research group's industrial network to find non-publicly available assessment methods, for instance those used by consultancy firms and OEMs. Firms that used PPA equivalents for assessing their operations were requested to attend an interview.

Data collection process

A semi-structured questionnaire was designed, aiming to give respondents the same context of questions to enable aggregation of their replies. The questionnaire was divided into two parts: *method identification* and *method mapping.* The first part consisted of eight questions to contextualize the interview and characterize each assessment method. The second part was to enable a comparison between the methods. The comparison was performed between seven aspects of a production system: market and strategy, structural aspects, infrastructural aspects, performance measurement, manufacturing development, work organization and work environment. The complete questionnaire appears in Appendix B.

Data analysis method

The analysis approach was derived from the format of the questionnaire. Three steps were performed: *method characterization analysis*, *method description analysis* and *method deployment analysis*. The characterization analysis aimed to distinguish the reviewed methods from a theoretical point of view. The description analysis aimed to differentiate the methods in terms of application and use, and the last analysis step was to compare PPA with the others methods.

The methods obtained from the literature review underwent the same analysis steps. The research group answered the questionnaire by interpreting the information provided by available documents. Ten assessment methods were analysed (excluding the PPA method). Five of them were based on interviews, and a few were analysed with publicly available documentation.

3.5.2 Study II - Multiple case studies

The initial idea that emerged in the ChEPro project was to extend the PPA method to consider firms' economic performance and how shop floor productivity can be improved. Two studies were designed in alignment with this idea. The first study was the *prototype case study.* This study aimed to establish a conceptual analysis framework, i.e. a developed PPA method. The latter study (Study II) was designed as a multiple case study to test, develop and validate the conceptual analysis framework established in the prototype case study.

Development of PPA started after the interview study had been finalized. A model was first created to conceptualize the idea in the project (Fig. 21). Research questions two and three both originate from this model.

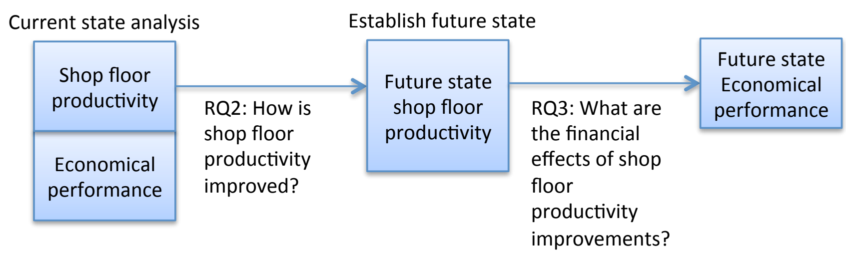

Figure 21: ChEPro idea conceptualizing model

This simple model was developed into a conceptual analysis framework. Figure 22 depicts the analysis framework resulting from the prototype case study. The working term for this framework was *Production System Analysis* (PSA). The PSA was regarded as an extension of the PPA method that included considerations for the method (M) and performance (P) parameters of the productivity dimension concept. The framework was derived from a literature study of relevant topics partly commenced in Study I.

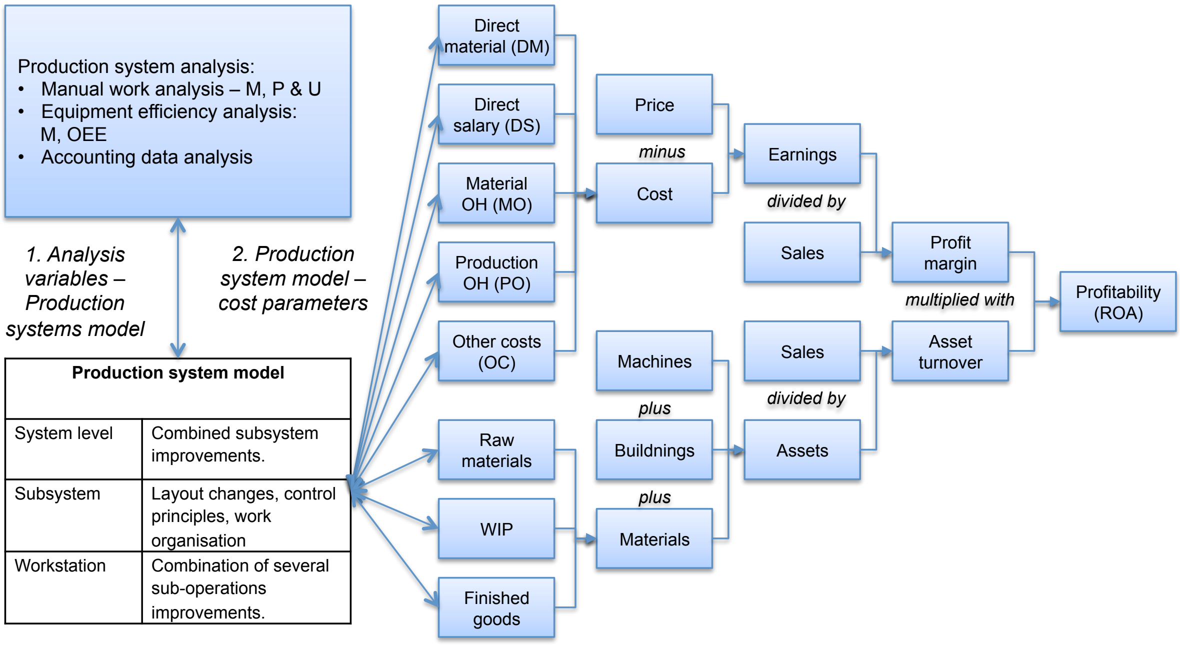

Figure 22: Production system analysis (PSA) model

The PSA model had two relationships that needed description and explanation. The first relationship was between the hierarchal production system model and the analysis variables (M, P & U). The concern was thus to describe the production system in terms of, for instance, M, P and U. The second relationship was between the production system model and cost parameters. For instance, what will happen to the cost parameters if the analysis variables are changed due to a productivity improvement?

The purpose of study II was to enable an investigation of these possible relations between shop floor productivity and firms' economic figures as reported in their financial statements. The objective was to test and develop the analysis framework depicted in fig 22. This objective was aligned with the thesis' objective of enhancing the importance of shop floor productivity. The following list explicit states the objectives for Study II:

- Test, validate and develop the PSA method
- Test the M, P and U concept in the electronics industry
- Enable a subsequent investigation of the relationship between productivity and profitability

Several research methods are available for these objectives. A conceivable method for RQ2 would be *action research*, for instance establishing a study that follows one or more parallel productivity improvement projects. However, the research project's organization and setup placed restrictions on time available to be spent with the participating companies, which relates to the disadvantages of the case study method that Meredith (1998) mentioned.

Instead, a more theoretical case study design was adopted such that some results were presented on a theoretical basis. The multiple case study design is discussed in detail below.

Unit of analysis

The unit of analysis is related to the fundamental problem of defining what the case or the field study is actually supposed to investigate and thus help researchers focus on the right things instead of all things. "*The definition of the unit of analysis is related to the way the initial research questions have been defined*" (Yin, 2009). Thus, selection of the accurate unit of analysis is the result of an appropriate research question design. For instance, the research question is most likely too extensive or too vague if no unit of analysis can be defined from it. These case studies contributed to RQ2, i.e. "*How is shop floor productivity improved?*"

The focal point of the prototype case study was to test the proposed analysis framework, i.e. make it possible to investigate RQ2. Literature from previous research thus served as a guide for defining the cases. Moreover, the multiple case studies aimed to collect data that could be used to investigate RQ2 and its research concerns. The unit of analysis for RQ2 was *shop floor productivity*.

Data collection process

The multiple case studies were conducted during a one-week study at each factory. Both the data collection and the improvement analysis took place during this week. Two researchers conducted the studies and the following schedule was used:

- Day 1 – Introduction and PPA study.
- Days 2 and 3 – Activity mapping and work method analysis (current state and future state analysis)
- Day 4 – Economic data collection and analysis
- Day 5 – Discussion and presentation of results

The first day was used to present the study's purpose and objective. An introduction was given to the company and normally the company had time to present their background and business. A factory tour took place to decide what production processes to analyse. Processes that were considered as problematic by the company were favoured for the analysis. A PPA study was then conducted that involved two work sampling studies at the selected production processes, usually one machining process and one assembly process. Days two and three were used to map all activities necessary to produce products within the selected production process. The work method analysis was used for improvement purposes based on the SAM method (see Chapter 2 for details). Day four was spent on conducting an economic analysis based on the company's annual report. The objective was to allocate costs from the annual report to the analysed production processes that contributed to improvement analysis according to the model presented in Fig. 22. Day 5 was used to present the results of the study and time was allowed for reflection on the week. The study involved meetings with the company's CEO or plant manager, production engineers, operators and assembly personnel, CFO or someone with financial responsibility, as well as one or more union representatives.

Sample selection

The research project had initially three participating companies. Initial development and testing of the conceptual analysis framework were conducted at these companies during the prototype case study. These companies were all related to electronics manufacturing, classified as Swedish information and communication technology (ICT) manufacturers. The relationships between these companies were one machine supplier, one contract manufacturer that used the machine supplier's equipment and a large telecom and IT company that used the contract manufacturer for certain assembly operations. For comparative purposes, the latter multiple case studies were conducted at ICT manufacturers as well. The selection of companies for the multiple case studies was based on a participating company's customer relations and the authors' industrial network.

Five case studies were conducted and consequently five companies in the Swedish electronics production industry were analysed. Four out of five companies were classified as small-to-medium (SMEs) sized companies with 50 to 250 employees. One company was considered as a large company (> 2000 employees). All participating companies produced similar products – circuit boards and complete box builds (i.e. products containing circuits boards) – and had similar production system structures. This production system structure can be simply described as a production flow consisting of raw material storage, an automatic surface assembly production line, manual assembly line, testing, packaging and finally delivery.

Data analysis method

Analysing case study evidence generally starts with an analytic strategy that can involve various techniques, for instance pattern matching, explanation building and time series analysis (Yin, 2009). Yin (2009) presented a work procedure for iterative explanation-building as follows

1. Make an initial theoretical statement
2. Compare findings of an initial case against such a statement or proposition
3. Revise the statement or proposition
4. Compare other details of the case with the revision
5. Revise again
6. Repeat steps 1-5 for other cases.

The objective of this analysis method is to generalize a set of results into a broader theory, in this research project a framework that consists of models and concepts to explain shop floor phenomena. The explanation building analysis procedure was performed in the multiple case studies. The theoretical statement was that the conceptual analysis system could be used for the intended purpose. Each iteration found weaknesses in the system's constituent frameworks that led to further development and resulted in theoretical publications .

3.5.3 Study III - Project Management study

The purpose of Study III was to further explore the relationship between productivity improvements and its results. The objective was to identify unexpected results emerging form productivity improvement actions – accordingly, to add empirical evidence to productivity-related implications for firms' economic performance. This was accomplished by investigating improvement projects that had been finalized, that is, projects that can be analysed in terms of measured effects (economic and non-economic), perceived but not measured effects (satisfaction, motivation etc.) and various other effects (project-specific effects).

Study III is between RQ2 and RQ3. The study aimed specifically to add knowledge to the theoretical framework that connects certain productivity improvement actions to other activities that could be regarded as an effect of these improvement actions. For instance, a typical productivity improvement project at a manufacturing firm may result in interrupted production schedules because production personnel are assigned to improvement activities instead of their normal scheduled production work tasks. This may further affect nearby operations that consequently affect the system's throughput rate of products, perhaps quality rates due to start-ups etc.

A conceptual model was designed to align the research concerns with previous research (Fig. 23). From this model a semi-structured questionnaire was developed to enable respondents to present completed improvement projects or similar improvement initiatives, from initiation through improvements and final results, i.e. a retrospective study. The questionnaire was designed to permit the respondents to fill research gaps, i.e. what the change driver (why) for the improvement project was, what problem solving methods were used (how), what the specific improvement action was, what the result was and what affected the final result.

All interview sessions were audiotaped, in total 10 hours among 7 improvement projects and transcribed to raw text. Before these interviews were conducted, an initial pilot interview was conducted for the purpose of analysing the relevance of the questionnaire – did the questionnaire design actually answer the research concern?

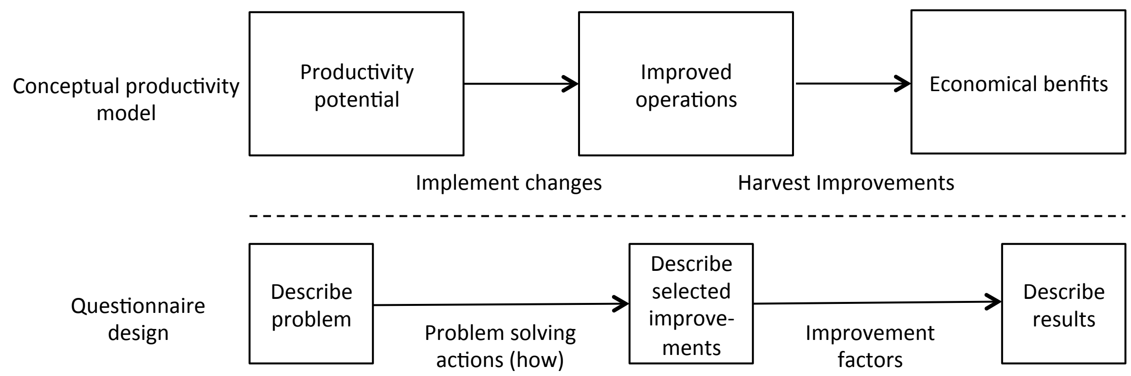

Figure 23: Management interview design process

Sample selection

Seven improvement projects were selected to examine various sectors: construction equipment, metal processors and fabrication, pharmaceutical production, mining, construction vehicles and automotive, to provide breadth and variety regarding improvement projects.

The managers of these seven projects belonged mainly to large organizations, i.e. with annual sales of more than €100 million (5 of 7 firms). The remaining companies had annual sales between €50 million and €100 million. The size and time consumption of the improvement projects varied considerably. For instance, specific project costs were calculated from €100 thousand to more than €10 million, indicating that the level of detail at each interview varied to a great extent.

Data analysis method

A method called *theoretical coding* has been used for analytical purposes (Auerbach and Silverstein, 2003). The analytical procedure is depicted in Fig. 24.

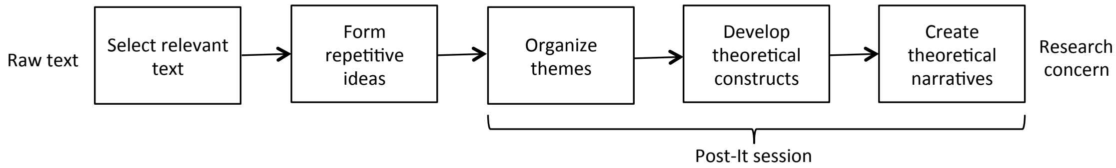

Figure 24: Qualitative data analysis method

The objective of the data analysis was to create a theory (hypothesis generation) based on the raw data transcripts. The first step was to state the research concerns and select all relevant text that was found in the transcripts related to the research concerns. When this step had been finalized, repetitive ideas were formed from the relevant text. A repetitive idea was an event or idea that seemed to return frequently in the transcripts. These ideas were subsequently arranged to higher abstract levels called *themes*.

A session of post-it notes was designed to support and improve the generation process of theoretical constructs. This session was carried out in one day including all authors and one external consultant. This type of investigation using different evaluators is termed *investigator triangulation* (Yin, 2009). The session with post-it notes was designed and inspired by the KJ (affinity diagram) method, commonly used for organizing and summarizing purposes (Breyfogle Iii, 2003).

3.5.4 Explanatory framework development

The purpose of the explanatory framework development activity was to condense empirical and theoretical results into a framework that can be used to explain the relations between the constituent parts of the production system model developed in the parallel research activity. This development activity was of iterative nature and relied primarily on literature studies within the areas of interest and the results from the empirical studies. An appropriate research method for this purpose is described by Lewis (1998) termed *iterative triangulation*. The iterative triangulation method consists of four phases: groundwork, induction, iteration and conclusion. A similar way of condensing the result for theory generating purposes was used for developing the explanatory framework provided in this thesis.

In practice, data have been analysed within and across selected cases aiming for developing constructs and ideas that match available data. Finally, the iteration procedure has extended these constructs in order to refine provided theory and the explanatory framework itself.

Figure 25 depicts a retrospective view of the development logic that has formed the productivity analysis model. The production system analysis model (PSA) developed in the ChEPro project was the precursor to the productivity analysis model. It was, however, clarified after the finalization of ChEPro that the model did not satisfy the objective of explaining financial effects of shop floor productivity improvements. Additional theory was thereby necessary which consequently was iteratively derived from new literature studies in areas foremost focusing on financial analysis and theories regarding progress curves to additionally strengthen the productivity analysis model.

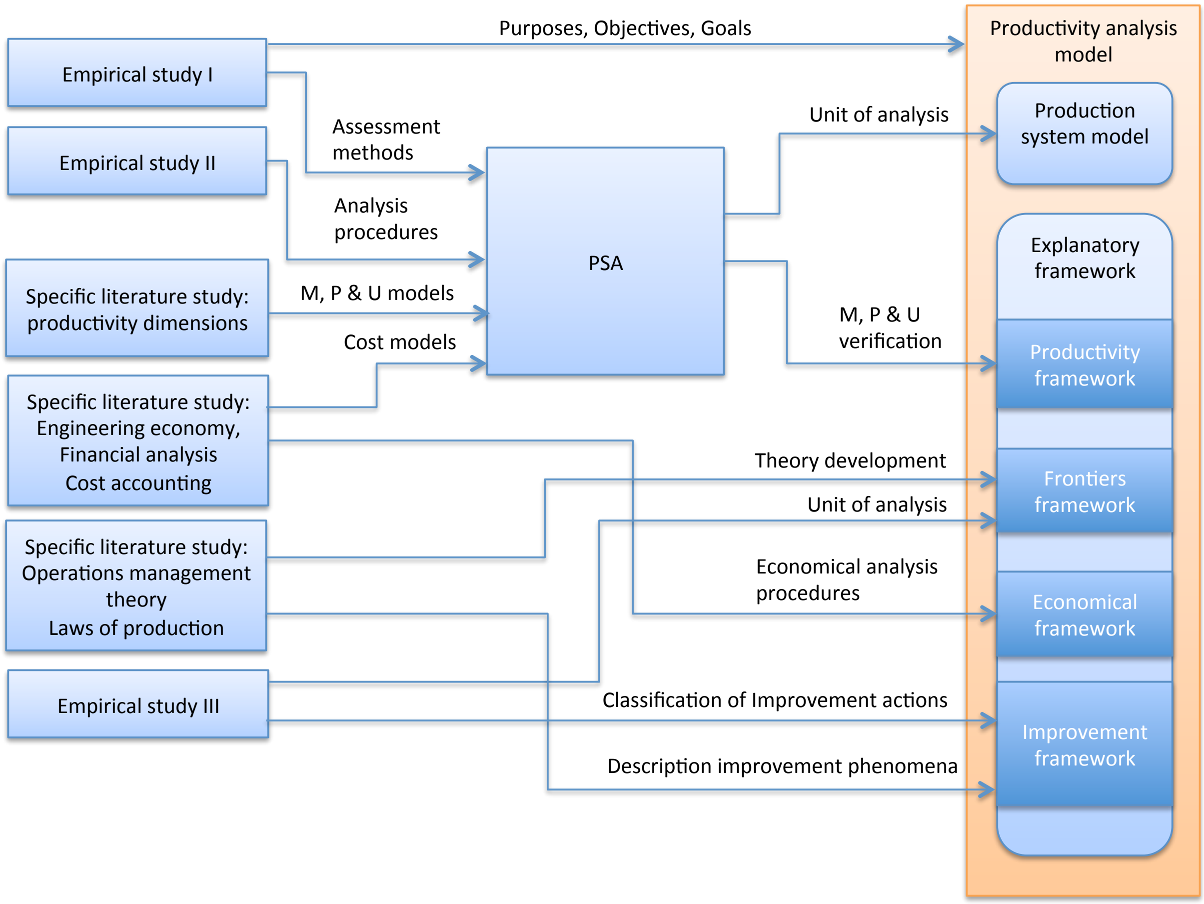

Figure 25 A retrospective development view of the productivity analysis model

Each arrow in figure 25 depicts items that contributed to the development of the productivity analysis model and its inherent set of frameworks and theory.

3.6 Business research criteria

The most recurring criteria for evaluating business research are reliability, replicability and validity times (Bryman and Bell, 2011). Furthermore, a theory's quality is determined by the degree to which is creative, useful and scientific (Lewis, 1998). Creative theories challenge existing pre-existing assumptions. Usefulness depends on the theory's ability to advance existing body of knowledge in the field of interest. Finally scientific issues refer to how the theory has been assembled from valid and operational constructs that enable testing and possible refutation.

3.6.1 Reliability and replicability

Reliability concerns the repeatability of a research study, i.e. whether the research results will be approximately the same if the study is repeated several times (Bryman and Bell, 2011). This issue is especially of importance in quantitative research, for instance regarding the stability of a certain measure – that is, if a repeated questionnaire presents different scores or values measured at the same object on two or more occasions, it might be due to an unreliable measure. Another closely related research criterion is replicability, i.e. the possibility of replicating the exact same study that previous researchers had conducted. This demands that research be well-documented and that other researchers be instructed in how the present research is or has been conducted – otherwise replication will be impossible.

3.6.2 Validity

Validity concerns the integrity of the conclusions that are generated from the research (Bryman and Bell, 2011). Validity can be decomposed into construct validity (measurement validity), internal validity and external validity.

Construct validity concerns whether the research measures used represent the concepts that they are supposed to measure and are closely related to a measure's reliability, i.e. the consistency of a measurement.

Internal validity concerns whether a conclusions incorporates a causal relationship between two or more variables (Bryman and Bell, 2011). This is especially important for explanatory studies seeking casual linkages (Yin, 2009). This implies that the internal validity of case study design is typically weak, since it produces associations rather than linkages.

External validity concerns generalizability of the study, i.e. whether conclusions can be extended beyond the specific research context. This is a common issue related to case studies in particular. For instance, can the results of a single case study be generalized to the entire population? Whether this is an issue or not has been discussed by several authors (Bryman and Bell, 2011, Yin, 2009).

The above-mentioned research criterions of the research presented in this thesis are discussed in chapter 6.2.

4. Empirical Findings

This chapter presents the findings of empirical research studies conducted between 2009 and 2013. Three studies have been selected that contribute to the results of this research initiative.

4.1 Study I – Production system assessment methods review

Ten production systems assessment methods were reviewed and compared with the PPA method. Some of them were obtained from the literature review and the others were used by industry practitioners. A brief description of each method is presented below.

Method 1 – Rapid plant assessment (RPA)

Rapid plant assessment is a methodology used to "*discern a plant's strengths and weakness*" (Goodson, 2002). Four to five analysts, preferably with varying capabilities and experiences, perform a short plant tour termed *the RPA tour*. During the factory tour the participating analysts use two rating sheets to assess the production plant. The first sheet includes 20 yes-or-no questions to be answered by the analysts. The number of affirmative responses indicates the factory's level-of-lean. The second sheet contains an assessment of 11 categories. This sheet is used to determine whether the plant uses best practices in the following categories: *Customer satisfaction*, *safety-environment-cleanliness and order*, *visual management system, scheduling system*, *use of space-movement of materials and product line flow*, *levels of inventory and work in process*, *teamwork and motivation*, *condition and maintenance of equipment and tools*, *management of complexity and variability*, *supply chain integration* and *commitment to quality*. A scale from poor (1) to best in class (11) is used, which means that the total score falls between 11 (poor in all categories) and 121 (all best in class).

Goodson (2002) also describes a more advanced application of RPA in which it is possible to estimate cost of sales (COS). The application values operations by collecting quantitative data such as the number of workers, number of salaried staff, average labour rate, average indirect labour rate, average hourly overtime, fringe costs, facility square footage, etc. Together with the rating sheets and the COS estimate, the RPA team has the ability to estimate how the manufacturing facility is performing and what the areas for improvement are.

Method 2 - Lean maturity tool (LMT), AstraZeneca[1]

The lean maturity tool (LMT) is an assessment method that is used within AstraZeneca's lean production programme. The LMT is used to assure that the evaluated facility follows agreed improvement plans, etc., according to the lean programme. An additional purpose of the tool is to locate advantageous shop floor practices that can be shared across AstraZeneca's operations. The LMT is performed as a peer-review, which means that various facilities in the organization assess each other. The purpose of doing so is to obtain an outside perspective and consequently contribute innovate thoughts and ideas. Normally three to five analysts perform the assessment in two to three days.

The LMT assesses AstraZeneca's operations in five strategic capabilities: processes, information, organization, human resources and leadership. Each capability is measured

[1] Information attained through interview with Peter Alvarsson, Lean Lead Sweden Operations, AstraZeneca Sweden Operations.

on a scale of one to five. Five is equal to a predefined lean ideal state (LIS). Each capability is divided into subgroups, which in turn consist of several topics that are reviewed by the analysts.

The results of the LMT provide the basis for both local and overall programme target settings, as well as monitoring progress towards the LIS. When targeting the current state, a diagram compares it with the lean ideal state to identify gaps that provide new objectives and targets.

Method 3 – PACE, Aberdeen Group[2]

The Aberdeen Group provides a model to conduct empirical studies that evaluate business pressures, actions, capabilities and enablers (PACE) in a certain business area. The content of the model is different depending on the business area that is investigated. Typically, the model is used to create an online survey that is designed to suit the specific business area. The questionnaire is designed to address the following topics:

1. What is driving companies to focus on the specific area of interest (pressures)? – e.g., cost pressures, market position, technology development, public policy decisions, etc.
2. What actions are these companies taking to address these pressures (Actions)? – for instance, a strategic approach such as a specific product or production development in response to the related pressure.
3. What capabilities and technology enablers do they have in place to support the specific area of the study (capabilities and enablers)? – for instance, key functionalities with specific competencies within the organization or different types of technological solutions.

Based on the online survey results, the Aberdeen Group provides a competitive framework divided into laggards, industry average and best-in-class companies. The results are presented in a written report, providing information about how these three groups perform on several performance measures. Each group is given various recommendations based on these companies' current situation and their effort to be more competitive or to stay ahead of their competitors.

Method 4 - LeanNavigator

LeanNavigator is the result of a Swedish project carried out by Swerea IVF, Volvo technology AB, Chalmers University of Technology and others (Harlin et al., 2009). The principal contribution is a framework termed the *Swedish Production System* (SwePS). SwePS can be seen as a generalized assessment method based on the Volvo Production System (VPS) assessment method. The purpose of this method is to serve as a platform for companies to successfully communicate and exchange best practices. The objective of the methodology is to support Swedish companies in building long-term strategic concepts and to develop their production systems based on the lean production philosophy. The ultimate objective is to establish a company-specific (company X) production system, i.e. *XPS*.

The input data that are required for the creation of a new XPS are collected by the company itself. As a consequence, there are no specifications regarding time

[2] The information is obtained through reviewing reports provided by the Aberdeen Group, www.aberdeen.com. For instance, "*The manufacturing performance management benchmark report*" (2006), "*Lean scheduling and execution*" (2007), "*Closed loop quality management – Improving customer focus from design to delivery*" (2009).

consumption for how the analysis is performed and who does it. One proposal is that a new XPS could be designed in one to three months (Harlin et al., 2009). The assessment method is divided into 5 building blocks with a total of 22 areas. These blocks are: quality, processes, core values, teamwork and continuous improvements and demand-controlled manufacturing. The 22 analysis areas are described with a development chart on 6 levels from *initiative* (0) to *perfection-world class* (5). The current state is addressed according to this development chart and targets are set at the level that reflects the desired future state. Each of these levels is divided into characteristics, application and effects (results) to give a more precise description and the outcome that the objectives (targets) actually generate.

Method 5 – Diagnostic Workshop, Volvo Cars[3]

The diagnostic workshop is a method used by Volvo Car's purchasing department together with the firm's site technical assistance (STA) group to assess Volvo's suppliers. The method was first introduced by Ford Motor Company. The intention of the method is to find improvement potentials at their supplier's production systems, with a focus on the shop floor level in order to minimize waste and lower the cost of supplied products.

The diagnostic workshop starts with an introduction to lean manufacturing. The next step is the "*manufacturing process walk,*" in which workstations, stocks, buffers, transports, etc., are evaluated (including layout, staffing, etc.). The analysis focuses on one specific product or a product family, i.e. not the entire production system. The data collection process is performed through the use of several analysis tools and techniques – for instance, current state maps, process flow analysis, work sampling analysis, and cycle time studies. In general, the team consists of two analysts who assess the plant in approximately three days.

The principal tool for developing improvement objectives is "*the cycle time compared to the takt time analysis*" tool. This tool is a combination of cycle time studies and work sampling studies. Each workstation within the production process of interest is analysed by a work sampling study by performing 100 observations per station. The work performed at each station is assigned to one of the following categories: value adding, non-value adding (non-avoidable), and non-value adding (avoidable). Cycle times are measured 40 times/station. The work sampling studies together with the cycle time studies create holistic knowledge about the entire production process as well as each specific workstation. Important measures of this method are the total utilization loss provided by the work sampling study and the balance losses provided by the cycle time study. Improvements are also suggested through a "*concerns and corrective action plan*" in which concerns, causes, and countermeasures are documented and identified.

Method 6 - Scania Production System (SPS), Scania CV[4]

Scania Production System (SPS) is similar to the Toyota Production System (TPS), a set of frameworks, methods and concepts based on a manufacturing philosophy that advocates the minimization of waste activities and the achievement of excellent service levels towards customers. The Scania Production System does not provide any specific assessment methods for production system analysis. Instead, SPS uses key performance

[3] Information obtained through interview with Lars Ohlsson – Project Manager, Lean Deployment, Volvo Car Corporation (Purchasing, STA).

[4]Information obtained through an interview with Allan Stenson Blixt, SPS Manager, SPS Office, Scania.

indicators (KPIs) at different hierarchal levels within the organization. These KPIs are continuously monitored and the results provide comparative measures among various manufacturing units. Typical KPIs within the *Department of Production and Procurement* are:

- Safety and environment: Health attendance, energy used per vehicle produced, CO_2 process and transport.
- Quality: Product quality and direct run.
- Delivery: Precision, reliability, inventory turnover rates (parts & components and finished goods).
- Cost: Vehicles produced per employee (productivity), production cost per vehicle.
- Leadership: Flexibility staffing and development plans.

Lower level parameters are monitored locally on a daily basis and macro level parameters are monitored monthly by the manufacturing unit. They both serve the purpose of supporting continuous productivity improvements. Company management sets higher-level goals and objectives. These objectives must be reflected in downstream KPIs. At the lower operative levels, Scania seeks continuous productivity improvements by involving every employee in seeking and improving productivity potential. For instance, shop floor operators write their own work standards for each workstation. The gap between current output and theoretical capacity according to a given standard visualizes the potential for improvements. The goal is to promote awareness of the productivity potential of employees at their local workplace.

Method 7 - Productivity improvement methodology

The productivity improvement methodology is an academic contribution by Herron and Braiden (2006). The foundation of this methodology is a model (matrix) that presents potential productivity improvements in manufacturing companies by addressing identified problems through the application of a set of lean tools. The methodology has been applied within different business areas, e.g. the food and beverage industry, engineering, automotive and purification systems, etc. The methodology is described in 3 steps.

Step 1 is to conduct the *productivity needs analysis* (PNA). This analysis provides an overview of a firm's current manufacturing status by the establishment of certain key productivity measures. This step also forms the basis for a detailed production efficiency analysis. The output of this step is a numerical score to quantify any correlation between selected measures and efficiency, i.e. the *intervention matrix*. The purpose of this step is to match performance measures with appropriate analytical tools that will be used for improving the firm's productivity.

The second step (step 2) is to define the plant's production processes and problems, and subsequently associate them with appropriate tools and measures in a *manufacturing needs analysis* (MNA). This step is performed through a plant tour in combination with interviews and workshops carried out with the plant management.

The third step (step 3) is to combine the PNA and MNA with the *training needs analysis* (TNA). The TNA assesses the workforce's level of understanding regarding the application of selected analysis and improvement tools.

The research team together with the company's senior production managers carries out the entire analysis. The managers are entrusted to supply accurate performance measure to the research team. However, to ensure data accuracy, the research team questions each measure validity and reliability. All data are thus collected during the plant tour, interviews and workshops. Possible problems are discussed during interviews with the senior managers.

The PNA is followed by a joint workshop employing a variety of decision-making tools such as the priority matrix. By establishing relationships between processes, measurements and problems, the specific problems of interest can be further examined by using lean tools. These tools are commonly used within industry, for instance genba kanri, kaizen, skill control, standard operations and 5S. They are evaluated with the priority matrix to find the best-suited tool for a certain type of problem. The outputs from the matrix (external) together with the company objectives (internal) are discussed during a workshop. The intended purpose of the matrix is to identify where productivity interventions would be best directed to generate the greatest benefits for the company.

Method 8 – Just-In-Time assessment

This method is an academic contribution provided by Brox and Fader (2002). The method is used within a strategic context to present differences in productivity between firms that have adopted JIT practices and those that have not. The outcome is a statistical analysis that presents the impact of JIT implementations and its effect on a firm's total productivity. For this purpose, a set of plant-level cross-sectional measures is collected from various manufacturing firms.

Data collection uses a survey instrument that includes interviews. Preferred respondents are plant managers, production managers, etc. The survey is either completed at the manufacturing facility "*on the spot*" or left in the hands of a manger who fills in the information and returns it by post. Time estimates for filling out the questionnaires depend on available information at the examined company.

The analysis method compares differences between input costs and the value of output produced (energy, capital, labour, material), i.e. productivity. The statistical analysis points out what JIT related techniques are being used and to what extent. Typically, these self-assessed figures indicate the extent to which these techniques and practices reduce set-up times, reduce defects, increase worker skills, etc. Calculations are subsequently performed to correlate each technique and practice with the extent of its usage, improvement attained and cost.

Method 9 – Plastal scorecard, Plastal Group AB

Plastal Group AB uses a scorecard to assess and benchmark internal manufacturing processes in four areas: injection moulding, painting, assembly and logistics. The benchmarking process is carried out by Plastal's *Process Development Group* four times a year. Within each manufacturing process, one "*champion*" is appointed to be the interlocutor with the Process Development Group.

The main tool for the assessment is the "*Scorecard*", on which the manufacturing process is evaluated. Scores are assigned between one (very poor) and five (world class). Typical performance objectives used in the assembly process are: quality, knowledge, organization, housekeeping, problem solving, internal material supply, area utilization, maintenance, production report system, start-up of new products and response.

Each of these performance objectives is subdivided into specific measures, e.g., total PPM-level rated by customer (quality). Each objective can be evaluated with either a yes-or-no statement or measured according to a 1-5 rating scale. For instance, customer complaints are evaluated on a scale from 1-5, where "*1*" corresponds to a PPM figure above 1500 and "*2*" corresponds with PPM figures in the interval of 1000-1500, etc. Every statement has a weight factor, which means that some statements influence the total score more than others. The scorecards in combination with other hard facts collected in the plants are the basic instruments for setting up action plans. These action plans contribute to the continuous improvement programme implemented at each facility.

Method 10 – Factory model, Solving EFESO[5]

Solving EFESO is an international consultancy firm providing services within a wide variety of businesses. When assessing manufacturing facilities, step one is to consider what the assessed company wants (i.e., setting goals and objectives) by performing a customer value analysis (CVA). Depending on what their client demands, efforts can be made to increase incomes, decrease expenditures or both. Costs are analysed by performing a *value stream cost analysis*.

The bundle of services that Solving EFESO provides is usually performed by two consultants in 3 weeks by focusing on one product or product family. Various lean tools are used, such as value stream mapping and Pareto diagrams, to locate frequent problems. Computer software supports the consultants in their data collection, i.e. *the factory model*. The consultants put great effort into understanding the process flow. From the process overview, problems are identified and cause and effect relationships are created to understand the main manufacturing issues.

4.1.1 Analysis and results

This production system assessment method review includes methods used in different contexts, such as internal benchmarking, statistical analysis and methods used by consultancy firms to provide customer required services. The differences between the evaluated methods, except that they represent different focuses and intentions of use, are: Time and cost, how data is collected and who collects necessary data and performs the analysis. The reviewed methods have undergone an analysis performed in three steps: a general *method characterization analysis*, a *method description analysis* and a *method deployment analysis*.

[5] Information obtained through interview with Johan Majlöv, Vice President, Operational Director Scandinavia, EFESO Consulting AB

Table 8: Method characterization

Internal audit	*Method 2 – LMT*
	Method 6 – SPS
	Method 9 – Plastal Scorecard
External audit	*Reference method – PPA*
	Method 1 – RPA
	Method 5 – Diagnostic workshop
	Method 7 – Productivity improvement
	Method 10 – Factory model
Self-assessment	*Method 4 – LeanNavigator*
	Method 3 – PACE (Aberdeen Group)
	Method 8 – JIT assessment

The first step in the analysis process was to characterize the reviewed methods. Three categories were established based on the description provided by Holmes and Overmyer (1972): internal audit, external audit and self-assessment (table 8). *Internal audit* is defined as audits made on-site, assessed by personnel at the facility or within the same organization. *External audit* is defined as audits made by independent consultants or researchers on-site. *Self-assessment* is defined as assessment methods that can be used on-site or off-site using predefined performance levels (e.g., LeanNavigator) or self-assessment through questionnaires or interviews (e.g., PACE).

The second analysis step of the review was to summarize and describe each method in the following areas:

1. *Method description*: Describes method characteristics, purpose of the method and whether the method is publicly available (public) or non-public (internal).
2. *Method application:* Describes how the data collection is performed, by whom, tools and techniques used, time consumption, and how the method reports results.
3. *Problem identification:* Describes how the assessment method addresses problems and what types of data are collected.
4. *Problem solving:* Describes how the method provides problem solving suggestions and priorities

The problem solving area was furthermore classified into three groups: *Systematic*, *comparison*, and *database*. *Systematic* refers to methods that provide a predefined solution or a solution algorithm depending on the outcome of the analysis. *Comparison* indicates that predefined scales are used to set targets and objectives. *Database* indicates that collected data are compared to a database of other analysis results in order to identify gaps and suggest improvement areas.

Table 9: Method comparison (method 1-4 and reference method)

	Reference method - PPA	**Method 1 - RPA**	**Method 2 - LMT**	**Method 3- PACE**	**Method 4 - LeanNavigator**
Description	External audit (public): Shop floor productivity analysis.	External audit (public): Discern a plants strengths and weakness based on lean measures.	Internal audit (non-public): Internal benchmarking looking for best practices.	Self-assessment (public): Benchmark business pressures, actions, capabilities and enablers.	Self-assessment (public): Support companies to build a long-term strategy based on lean philosophies.
Application	2 analysts, 1 day, shop-floor analysis, written report.	4-5 analysts, 1 day, shop-floor analysis, rating sheets.	3-4 analysts, 2-3 days, written report.	On-line survey, <1 day, extensive report.	Total management support, >1 month, continuous documentation.
Problem identification	Work sampling, OEE analysis, KPIs, production engineering related yes-or-no questions, work-environment study.	Production engineering and Lean production related yes-or-no questions, COS estimation.	Analysis is performed within identified capabilities and benchmarked between departments on a scale between 1 and 5.	Benchmarking database created within selected business areas	5 categories are analysed (quality, processes, core values, teamwork and continuous improvements), total of 22 manufacturing system areas are analysed on a development chart at 6 levels.
Problem solving suggestions	*Database*: Company results will be compared to others results	*Database*: Rating sheets, low scores = area for improvements	*Comparison*: Polar diagram, current states are targeted and compared to LIS, gaps are thereby identified.	*Comparison*: with the suggested competitive framework	*Comparison*: polar diagram, level identification, current state is compared with desired future states.

Table 10: Method comparison (method 5-10)

Method 5 - Diagnostic Workshop	**Method 6 - SPS**	**Method 7 – Productivity improvements**	**Method 8 – JIT assessment**	**Method 9 – Plastal scorecard**	**Method 10 – Factory model**
External audit (non-public): Assess automotive suppliers manufacturing improvement potential	*Internal audit (non-public)*: Evaluate hierarchal performance measures to improve operations.	*External audit (public)*: Assess productivity to generate improvements	*Self-assessment, (public)*: Estimate variable costs functions based on a statistical approach	*Internal audit (non-public)*: Assess internal manufacturing processes.	*External audit (non-public):* Increasing incomes, decreasing expenditures (costs) or both
2 analysts, 3 days, shop floor analysis, written reports	Total management support including operator involvement and emphasizing continuous improvement and continuous documentation processes	Assessment teams, plant tours, interviews & workshops, > 1 month	Self-assessment, interviews with plant managers or production manager, CEO, owners	Analysis is performed by Plastal's process Development Group 4 times a year by using rating sheets.	2 consultants, 3 weeks, software to support consultants (factory model), continuous reports
Current state map, process flow map, work sampling and cycle time studies	Micro scale KPIs (shop floor level), Macro scale KPIs (Facility and management level)	Productivity needs analysis (PNA), Manufacturing Needs Analysis (MNA), Training Needs Analysis (TNA).	Statistical analysis of the cost of inputs and the value of the output produced (six-point scale)	By the "Scorecard", Scores are assigned between one (very poor) to five (world class)	Customer Value analysis (CVA), process analysis and several KPIs are used to analyse operations
Database: Concern and corrective action plan	*Systematic*: Through lean forums and standardization (based on the lean philosophy)	*Systematic*: Selected lean tools by numerical ranking generate improvement plan.	*Database*: Company result will be compared to others results	*Comparison*: Action plans developed from the benchmarking results	*Systematic*: Consultants work more or less with coaching from case to case.

Tables 9 and 10 present the results of the second analysis step. The third and final analysis steps were performed to support management decisions regarding choosing appropriate methods for typical scenarios when production assessments are requested. The result of this analysis was a comparison table (table 11). The PPA method was used as reference method. The analysis was subsequently performed through comparison of three parameters: *width*, *depth*, and *time and cost*. Six areas of manufacturing practices were evaluated: market and strategy, physical structure, performance measurement, manufacturing development, work organization and work environment. *Width* was defined as the number of practices the analysis method covered. *Depth* was defined as the extent to which the method covered these practices.

Table 11: Decision support table

Method	Depth	Width	Time & Cost
Reference method - PPA	*reference*	*reference*	*Reference*
Method 1 – RPA	-	-	+
Method 2 – LMT	-	+	-
Method 3 – PACE	-	-	+
Method 4 – LeanNavigator	+	+	-
Method 5 – Diagnostic Workshop	+	0	-
Method 6 – SPS	N/A	N/A	N/A
Method 7 – Productivity analysis	-	+	N/A
Method 8 – JIT assessment	+	-	N/A
Method 9 – Plastal scorecard	+	-	-
Method 10 – Factory model	+	0	-

The final parameter, *Time and cost*, was defined as the required quantity of resources multiplied by the length of the study (days). A plus (+) means deeper, wider, or lower cost than PPA. A minus (-) means less depth or width than PPA. A zero (0) means equal as PPA. The recommendations were based on the authors' analysis of the feasibility of various analysis methods in different contexts.

Self-assessment methods based on questionnaires (e.g., PACE) give a brief hint of how evaluated companies perform from a favourable economic point of view. If striving for more and frequent performance updates, internal auditing is suggested by developing a company-specific method such as the LMT, alternatively use of external auditing method, for instance PPA or RPA. The natural next step is to create systems that continuously monitor operation performance, for example SPS. This is for many companies considered as the ideal state of their operations. A good start for getting there is through the adoption of design methods such as LeanNavigator. LeanNavigator may furthermore be used as a level-of-lean self-evaluation method, as well as an in-depth analysis of all aspects of the manufacturing system. LeanNavigator is, however, considered expensive, both in time and resource consumption.

Analysis before a major improvement programme may be tackled by the use of either external or internal audits. The use of consultants is considered to be an appropriate solution if the firm lacks internal capacity or appreciates the benefits of an outside perspective or other and new competencies. External auditing methods are suggested when the focus is on general productivity analysis or production improvement, or for auditing the cost cutting potential of suppliers, etc. One of the main reasons is the use of experienced analysts. For instance, the PPA method, the Diagnostic Workshop and the Factory model, should be performed by well-trained analysts. These analysts should also be capable of distinguishing between what seems to be good performance and what really is good performance. These methods are, however, at the same cost level, cost per consultant per day, but differ in the length of study.

4.1.2 Conclusions Study I

Study I analyses and discusses different production system analysis methods as a means of supporting and creating cost effective improvement projects. It emphasizes the PPA method by comparing it with similar analysis methods. The decision support table (Table 11) distinguishes between the reviewed methods in terms of depth, width and cost & time. The PPA method should be used when the intention is to cost-effectively obtain an external perspective of an organization's manufacturing performance and to compare shop floor level performance with competing companies. The strength of both internal and external audits is the actual shop floor observation and the fact that analysts may observe problems, for instance inappropriate work methods, layout deficiencies, insufficient material flows, etc. The *go and see for yourself* concept gives the analyst the possibility to collect invaluable information by talking to a firm's operators about the manufacturing process itself, e.g. their experiences, common problems, improvement suggestions, etc. These hands-on operator issues would not have been considered in interviews by phone or when management responds to questionnaires. Most of the methods collect and compare various performance measures, e.g. the PPA method's level 2 parameters. The number of publicly available methods that may provide objective comparison of manufacturing shop-floor operations and performance measures is, however, limited. It is thus concluded that PPA is one of the few methods with a proven track record that are available to all manufacturing companies. With its unique collection of manufacturing data, it can be used as an objective benchmark and a comparison with (anonymous) competitors' production performance.

4.2 Study II – Productivity improvements in the electronics industry

Each case study was conducted during a five-day on-site study. Day one followed the same schedule and routines as an ordinary PPA study. The traditional PPA study considers one subsystem only, for instance one assembly subsystem or one machining subsystem. However, in these studies two subsystems were analysed. The primary focus of day one was on the shop floor utilization parameter by conducting work sampling studies at two selected production subsystems and collecting OEE data. The other two parameters, method and performance, were analysed on days two and three. The productivity assessments were performed at the firms' bottleneck sections of their principal production processes. Two scenarios were established, one current state (CS) scenario based on the M, P and U investigation, and one future state (FS) scenario based solely on redesigning the work method. However, suggested solutions were not implemented at any company. The improvement proposals were instead left in the hands of the companies and thus considered as input for their future improvement effort. As a consequence, the only valid FS scenario is derived from the use of SAM regarding the work method. Future state considerations regarding utilization and performance improvements were thus estimated primarily on the basis of method improvement suggestions. All results of the PSA studies are discussed below.

Table 12 presents *level 1* PSA results. Each subsystem was classified based on the activities that were carried out within it. All subsystems that involved manual assembly were classified as *assembly* (ass.), and all subsystems that involved equipment setups, equipment adjustments and monitoring were classified as *operator* (op.). Table 12 also provides a short description of the studied production activities. Some subsystems involved several activities such as through-hole mounting activities, testing and packing (THM-to-packing). Through-hole mounting refers to manual assembly of electronic components onto a PCB. These activities were similar at all companies but not identical. The method design differed slightly depending on the product assembled, production layouts, workstation design etc. As a consequence, it is not possible to perform direct comparisons between the companies. Other differences could also be found in the organizational structure and control processes of the machine lines.

All FS scenarios were based on an improved work method design, for instance improved workstation design, facilitated usage of supporting tools and equipment, reduced walking distances, etc.

Table 12: PSA level 1 parameters

	Company A		**Company B**		**Company C**		**Company D**		**Company E**	
Classification	*Ass.*	*Op.*	*Ass.*	*Op.*	*Ass.*	*Op. Ass.*	*Ass.*	*Op.*	*Ass.*	*Op.*
Description	THM-to-packing	Set-up	THM	Set-up	THM	Preparation	THM-test-etc.	Set-up	THM	Set-up
M_{CS}	138 items/h	54 items/h	1077 items/h	54 items/h	1133 items/h	2577 items/h	200 items/h	46 items/h	966 items/h	54 items/h
M_{FS}	142 items/h	70 items/h	1363 items/h	60 items/h	N/A	N/A	400 items/h	72,6 items/h	1242 items/h	69 items/h
$M_{improvement}$	+2,9%	+29,6%	+26,6%	+11,1%	N/A	N/A	+100%	+57,8%	+28,6%	+27,8%
P	85%	N/A	100%	N/A	N/A	N/A	N/A	N/A	N/A	N/A
U	89%	70%	77%	90%	75%	82%	81%	66%	83%	70%
$M_{CS}xPxU$	104,4 items/h	37,8 items/h	829,3 items/h	48,6 items/h	849,7 items/h	1752 items/h	162 items/h	30,4 items/h	801,8 items/h	37,8 items/h
$M_{FS}xPxU$	107,4 items/h	49 items/h	1049,5 items/h	54 items/h	N/A	N/A	324 items/h	47,9 items/h	1030,8 items/h	48,3 items/h
OEE_{CS}	-	45%	-	40%	-	68%[6]	-	50%	-	45%
OEE_{FS}	-	50%	-	N/A[7]	-	N/A	-	55%	-	50%
$OEE_{improvement}$	-	+11,1%	-	N/A	-	N/A	-	+10%	-	+11,1%

[6] Selective soldering machine

[7] An external picking process was analysed and thus did not affect OEE

The cases with the operator classification presented theoretical method improvements ranging from 11% (company B) to 58% (company D). The productivity measure *items per hour* referred to the numbers of parts that were mounted onto the machine or machine related equipment per time unit. Equivalent measures were used for assembly activities but referred to the number of electronic components that were assembled during the work procedures. The latter measurement was more diverse, since some of the procedures involved several activities, such as through-hole mounting (THM), testing and packing (company A and D) that considerably reduce certain productivity results. Improvement potentials were, however, evident in all cases, ranging from 3% (company A) to 100% (company D). The extreme case (company D) was estimated as very high due to a proposed machine investment that in theory solved a bottleneck problem.

The performance parameter P was neglected (N/A) in most case studies. Clock studies were conducted in some but not all cases, to be compared with the ideal time yielded by SAM. However, due to differences in training and experience among the study objects, the results varied between 2.5 and 6 minutes when the ideal time was set to 3 minutes. It was also difficult to perform clock studies due to the inconsistency of the work procedures (especially true for machine operators). The cycle time for the work procedures continually changed depending on the product that was produced. Since a significant variation in time was evident in most cases, one conclusion was a lack of standardized work methods and obvious lack of training and education in these matters. Another reason for not conducting clock studies was time consumption for using SAM. During the case studies, analysing the ideal time was prioritised rather than the performance of the personnel to be able to create improvement proposals based on SAM. Thus, in some cases the analysts didn't have enough time to consider the performance parameter.

Final considerations were performed regarding the utilization parameter (U). The general case showed that utilization rates for manual assembly operations (average 81%) were better than for machine operators (average 75.6%). These results were in line with previous shop floor utilization research (Almström and Kinnander, 2008). The utilization parameter is strongly affected by the production system used by the companies, as well as by the work method design and the individual's capabilities and skills (training, fatigue, motivation, etc.). The typical manual workstation in the electronics industry was designed for production batches. Equivalent physical layouts and production organizations were evident in most cases, i.e. basic workstations with simple assembly tools.

The machine operators' utilization rates were difficult to interpret since they directly influence inputs (costs), and indirectly affect output. That is, machines produce the output while operator utilization affects their utilization rates. Equipment utilization rates were measured with OEE. Table 12 presents two OEE result parameters, current state (OEE_{CS}) and future state (OEE_{FS}). The OEE_{FS} rates were based on estimated improvements of the equipment setup methods. Measuring OEE for surface mounting assembly (SMA) equipment was difficult, however, especially the efficiency and quality parameters of the equation. The ideal speed of placing surface mounted components (SMCs) changes depending on the component placed. That is, there is an equal quantity of practical ideal machine efficiency values as the company's SMC part numbers, which usually come to several thousand. The latter problem was tracked to the reliability of the quality inspection equipment (manual calibration of the equipment) in combination with how the SMA equipment reported quality errors. The OEE values in Table 12 consider only the availability parameter of the OEE equation. Thus, true OEE values were less than those presented in this report (average 45% when excluding C), This result indicates that there is a great amount of unexploited machine capacity in the electronics manufacturing industry.

The utilization rates proved to be at relative high levels compared with the PPA investigation presented by Almström and Kinnander (2008). In contrast, aggregate performance measures such as inventory turnover and delivery precision proved to be at low-performing levels (table 13). Inventory turnover rates were remarkably low. This result was due to long internal lead times and high levels of work-in-process material. These results converge with the PSA level 3 results presented in Table 14.

Table 13: PSA level 2 parameters

	Company A	Company B	Company C	Company D	Company E
Inventory turnover	7.4	N/A[8]	4.6	4(8)[9]	10[10]
Delivery precision	94%	N/A	81.5%	85%	N/A
Scarp rate	0.25%	N/A	N/A	<1%	N/A
Customer complaints	2500 ppm	N/A	1631 ppm	300 ppm	N/A

Table 13 presents a measurement that describes the level of production engineering, i.e. the production practices the firms have adopted. The average score was 20 (maximum is 40) and the most evident improvement potentials were found in the following categories: planning, continuous improvements, changeover, strategy and goals. The common perception of the results in Tables 13 and 14 is that all firms have obvious potential to develop their production systems and thus to strengthen their competitiveness.

Table 14: PSA level 3 parameters (level of production engineering)

	Company A	Company B	Company C	Company D	Company E
Level of production engineering	19	N/A	21	25	15

The last objective of the case studies was to collect financial data to enable an investigation of the relationship between the set of performance measures used in the PSA study and the firms' economic figures. In order to fulfil that objective, a financial analysis was performed starting with the annual report at the facility level. To perform income statement comparisons between different facilities, it is important to distinguish

[8] The company did not collect this data.

[9] The company bought special electronic components for up to 5 years of storage (if these components were excluded).

[10] The company had in-house supplier storage that improved their inventory turnover rates.

between normal costs (recurring) and exceptional costs (non-recurring) (White, 2006). The companies' annual reports needed to be manually interpreted. That added some errors to the analysis.

Table 15: PSA cost break down

<table>
<tr><th></th><th>Company A</th><th>Company B</th><th>Company C</th><th>Company D</th><th>Company E</th></tr>
<tr><td>Material costs</td><td>68%</td><td>46%</td><td>72%</td><td>67%</td><td>66%</td></tr>
<tr><td>Labour costs</td><td>5%</td><td rowspan="2">38%</td><td rowspan="2">22%</td><td>10%</td><td rowspan="2">27%</td></tr>
<tr><td>Other personnel costs</td><td>15%</td><td>8%</td></tr>
<tr><td>Machine & equipment costs</td><td>2%</td><td>3%</td><td>3%</td><td rowspan="3">15%</td><td rowspan="3">7%</td></tr>
<tr><td>Energy costs</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>Other costs</td><td>10%</td><td>13%</td><td>3%</td></tr>
</table>

Table 15 presents the cost distribution for each company. The largest cost portion was found to be material costs (average of 68% if company B is excluded). Company B had considerably more product development resources (labour costs) than the other companies. All other companies had labour costs ranging from 18% to 27%. A remarkable figure is the low machine cost portion shown at all companies. The same type of component distributor supplied most of the companies, which meant that the companies were competing under similar conditions. Thus, to gain a competitive edge, the companies need to devote their long-term strategic efforts to creating an efficient production system that minimizes waste and utilizes its resources in the best possible way.

To measure profitability, the return-on-assets (ROA) ratio was selected. The relationship between ROA and shop floor utilization was examined with PSA. However, it was not possible to establish a casual relationship based on the available data. Nevertheless, some observed problems associated with using ROA in a short-term analysis like PSA are the difficulties of analysing the effects from historical events that shaped the balance sheet to its current state and to normalize the effects of surrounding events during a full business cycle.

4.2.1 Improvement example

The following example demonstrates how the productivity dimension concept (M, P and U) can be used in practice. The example is extracted from the first case study (Company A). It describes a setup activity for the surface mount assembly line.

Current state analysis

Figure 26 depicts a limited area of company A's production site. The numbered boxes (1-6) represent component carriers that contain the electronic components that will be assembled onto the PCB in the assembly line. The aim of the setup activity is to fill these carriers with electronic components that belong to the upcoming production batch. The setup activity can be performed offline, i.e. while the assembly line is operating. Once the current production batch has been assembled and inspected, the operators need to change the carriers that are mounted in the assembly line to the new carriers that have the next batch's components.

The current state workflow is illustrated in Fig. 26. Operator 1 (op 1) arranges batches of electronic component rolls to be mounted onto the carriers. Each batch is specified on an order slip. The first step is to pick these component rolls from an automatic storage and retrieval system (high storage). The second step is to transport these components from the storage to a workbench (product components). Operator 1 carried out these steps. Subsequently, operator 2 takes the component rolls from the workbench and loads them onto the carriers. Typically, this loading operation also requires some minor adjustments in order to fit the component rolls properly. Once a carrier has its complete set of rolls, operator 2 performs a function test to assure that the carrier's component feeders are working properly before the carrier is loaded onto the assembly line.

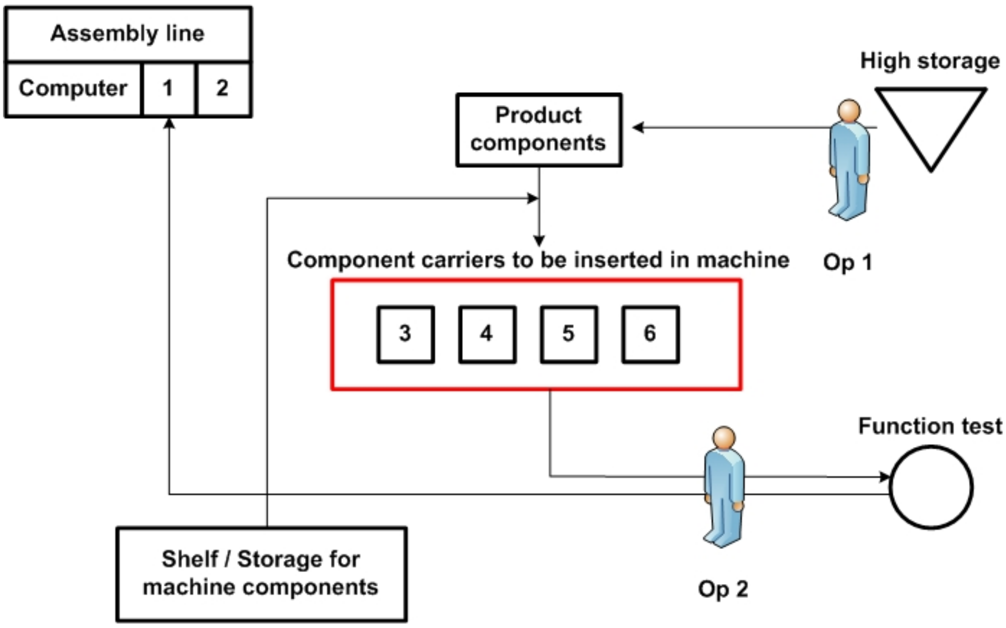

Figure 26: Set-up operation current state

The predetermined time system SAM was used to calculate the ideal cycle time for this setup activity. The result was 2.676 seconds for two operators, which corresponded for the specific production batch to handling 54 items (component rolls) per hour. No performance assessment was performed. That is, operators were assumed to work with a performance rate corresponding to 100%. Furthermore, a work sampling analysis revealed that the operators' utilization rate was 70%. A significant percentage of the non-value added time of time operator 1 had to wait when high storage was processing, i.e. retrieve component rolls.

Improved future state

The improved state focused on the time that operator 1 had to wait while the storage retrieved requested component rolls. The analysis showed that the average waiting time at the storage location was 45 seconds. The method analysis showed that this cycle time roughly corresponded to the complete work cycle for adjusting and loading rolls onto the component carriers. Consequently, minor re-balancing of the activities made it possible to design a U-shaped layout, as seen in Figure 27. The FS scenario proposed that the operator could adjust and load component rolls onto carriers while the high storage was processing the next order and thus reduce resource consumption by 50%, i.e. one operator performed the work cycle instead of two.

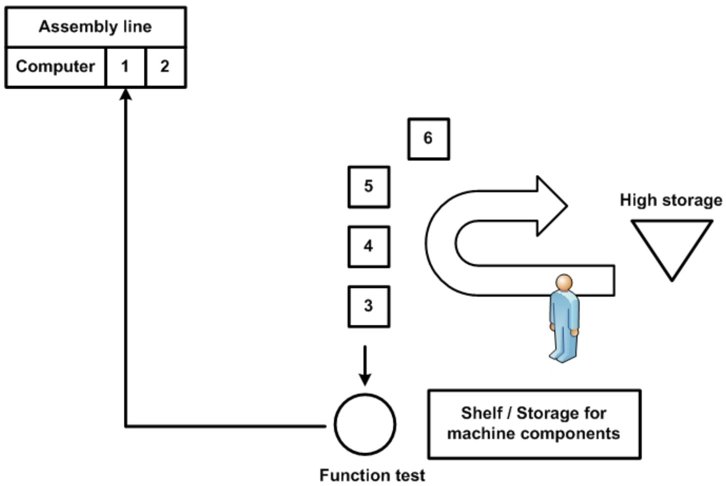

Figure 27: Set-up operation improved future state.

Table 16 summarizes the M, P and U parameters. With the proposed layout, only one operator was needed. The work cycle time, including all activities in the new layout, was calculated at 2,046 seconds, which corresponded to handling 70 items per hour, i.e. a method improvement of 29.6%. Most likely, the balanced flow would eliminate a significant percentage of the non-value added time, since the operator no longer has to wait while the high storage is processing. It was therefore reasonable to assume that the utilization rate would increase.

Table 16: Productivity improvement of the set-up operation

	Current state	Future state	Improvement
M [items/h]	54	70	29,6%
P [% of normal speed]	100%	100%	0%
U [% VA + S time]	70%	>70%	-

4.2.2 Conclusion study II

First of all, the case study results are aligned with the results obtained by Almström and Kinnander (2008), as they suggest that there is an evident shop floor productivity potential in the Swedish electronics industry. The largest potential was found in unused equipment capacity. Low equipment utilization rates are explained by the large number of customers in combination with a diverse and extensive product mix. Also, customers demand flexibility in terms of fast delivery on short notice. These conditions make changeovers to an important and often-recurring production activity. The importance of creating and sustaining an efficient production system that has the ability to cope with variations in demand and customer flexibility is evident. One way of creating this requested flexibility is through increased productivity in manual work tasks related to the automatic assembly line's setup activities. Also, the analysis pointed out that the studied companies mainly competed by being flexible and reliable rather than offering the lowest costs.

The case study objective of testing the productivity dimension concept turned out well and the improvement example verified this to a limited extent. Practical verification does not exist. The objective of creating a framework that explained relationships between shop floor productivity and firms' financial records was not established during the case studies. However, the practice of collecting financial data from firms' accounting systems was developed during each study. These practices also provided important feedback for further development of such a framework. The main problem during the case studies was to isolate the link between productivity improvement actions and the firm's financial records. This issue was thus set as a remaining research objective.

Final consideration was given to the fact that none of the five companies showed exceptionally good productivity results. This strengthened the concept that these companies did not prioritize cost as a competitive tool. Instead, factors such as geographical proximity to customers and good customer relationships were more important. However, creating an efficient production system with high productivity through smart and well-planned work method designs that result in high utilization rates will most likely provide the individual company with improved competitiveness in terms of increased flexibility and reduced costs.

4.3 Study III - Project management interview study

Study III was based on a simple conceptual productivity model presented in Chapter 3.5.3 (fig. 23). This model was subsequently expanded with aggregate themes that were attained through the deployed qualitative analysis method. Table 17 presents the interview results. Each cell in Table 17 consists of one theme. Furthermore, each theme was mapped to the improvement project in which it was evident, e.g. the theme *capacity* was regarded as a problem in 6 of 7 projects.

The most often-recurring problem within these 7 improvement projects was *capacity*-related, followed by *cost* and *quality*. Several solutions were considered to overcome these problems. The material flow was considered in 6 of 7 improvement projects, suggesting that structural improvements are common for reaching increased capacity. New material processing equipment was mentioned as improvements in 4 of 7 projects, followed by layout changes, work skill improvements, standardization and information improvements. All projects that were capacity-related experienced varying degrees of capacity increases when achieved. Locally, reduced direct costs were achieved in 5 of 7 projects. These figures were, however, not verified in the firm's annual reports. Lead-times were reduced in 4 of 7 projects, but only 1 project could actually show economic figures of a work-in-process capital reduction.

Table 17: Aggregate of interview results

Problem/issue	Project	Problem Solving actions	Project	Improvement/ change	Project	Improvement factors	Project	Results	Project
Capacity	A,B,D,E,F,G	Work Sampling	G	Material flow	A,B,D,E,F,G	Budget	A,B	Improved change/ innovation rate	F
Lead time	E	Holistic approach/ System	A,C	Layout	A,B,F	Unions	F	Improved percieved quality	A
Cost	B,C,D,G	Root cause analysis	A	Work organization	F	Authoritys/ govermental/ legisalations	A	Improved quality	A,B,F
Quality	A,B,F	Operator involvment	G	Assets/ equipment (purchasing)	A,B,C,D	Availbale improvement resources	A,D,E,F,G	Production losses due to improvement projects	C,E
New Product development	A	Work place/ Ergonomics analysis	B	Automation	B	Project control/ steering	B	Changed material handling processes	A,E, F,G
Flexibility	B	Clock/time study	C	Work skills	B,D,G	Culture	D,E,F,G	Simplified production control	E
Safety/ Ergonomics	A,B	Balancing analysis	C	Flexibility	C	Investment/ Purchasing competence	B	Improved work environment	A,B,F
		5S	C	Operator Responsibility/ guide lines	C,F,G	Lack of facts	B,F	Improved employee satisfaction	A,C
		Disturbance analysis	D,G	Information	C,D,E	Traning/ competence	B,C,F	Reduced lead time	A,C,E,G
		Self (operator) assessment	D	Standardization	C,D,G	Supplier involvement	B,C	Increased (percieved) stress	E
		Value stream mapping	E	Liberation of resources	C	Demand	B	Reduced direct cost	A,B,E,F,G
		Activity analysis/Go and see	F	Control system	D	Lack of support function	C,E	Increased indirect resource usage	B,F
		Work skill analysis	G	Cycle time	F	Quality of measurement systems	D	Reduced set-up time	E
								Project delays	A,B
								liberated resources	F,G
								Stop time (increased, decreased)	B,F
								Improved yield	B
								Increased capacity	A,B,C,D,E,F
								Reduced WIP	E

Interestingly, when looking at improvement (change) factors that are perceived as influencing the final results, they are likely to be related to internal efficiency. In 5 of 7 projects, available improvement resources were regarded as a limitation or enabler. In 4 of 7 projects, culture was thought to have an impact, followed by training and competence.

4.3.1 Relationship between the productivity dimensions and interview results

From a PM perspective, all constructed themes in Table 17 can be observed as either flow-oriented or related to internal efficiency. A production system can be regarded from a structural point of view, describing it as a set of elements that are connected by relations (Seliger et al., 1987). Such an element would be a production activity or several connected activities including material buffers. When using a structural system analysis perspective, it becomes evident that a specific technical unit, i.e. a specific hardware in the production process does not alone decide the system's output. Instead, the system's complete design must be considered, including buffers between activities. Thus, structural aspects can be described with the M parameter of the productivity dimensions, e.g. by an ideal activity or a system design. The common attribute of the method dimension is that improvements will affect the material flow directly (flow-oriented) and thus the capacity and lead-time of the analysed section, etc. Structural improvements will naturally influence the requirements for shop floor assets, such as labour. That is, the improvement will change the requirements for work skills and probably for the whole organization as well.

The internal efficiency perspective is instead related to the *P* and *U* parameters. In order to achieve material movement, resources must be consumed (labour or equipment), and the resources' performance and utilization rates will vary with several factors, for instance work skills and experience. The interview study contains evidence that most efforts were devoted to structural improvements, e.g. improving material flow. Structural improvements will impact the organization to a great extent, due to new process equipment development, installation, learning requirements, etc. However, judging from the theme constructs, the main productivity problem seems to be related to internal efficiency, using resources for the purposes initially intended. The productivity dimensions, M, P and U involve directly quantifiable phenomena only. The productivity dimensions do not consider innovation or change rate, perceived quality, work environment or employee satisfaction, etc., found in the results column of Table 17.

The requirements for a production system are determined by customer needs, followed by an enterprise and a subsequent manufacturing strategy to fully exploit these needs, i.e. related to the other two PM dimensions mentioned by Jonsson and Lesshammar (1999). It is well known that these needs change over time, which consequently impacts the production system's productivity. Given a fixed environment, it would be possible to adapt a production system to this environment by specialization, and thus by training and failsafe actions, trim the manufacturing organization to fully exploit the firm's capacity. However, due to this change factor, it has been shown that leaving some of the firm's capacity for adaptability or re-configurability purposes is generally leads to improved financial figures. Nevertheless, except for the PM dimensions strategy and external efficiency (environmental factors), M, P and U capture the essence of the remaining PM dimensions – flow orientation and internal efficiency. However, internal efficiency must be distinguished from resource slack (excess capacity), which should be a strategic decision to satisfy customer needs.

None of the investigated projects revealed or measured financial effects, except cost. Thus, the interviews resulted in theme constructs that compared improvements primarily with traditional non-financial PMs, such as lead-time, quality and capacity. Hence, there is still much to be learned about how these improvements actually impact financial measures. One of the main problems is to locate or isolate improvement projects to identify certain financial figures. The majority of the firms in this interview study used their internal organization for making improvements. Also, external (environmental) factors continuously affected financial figures, i.e. they are time-dependent. As a result, economic facts regarding internal resource utilisation are difficult to collect and link to specific projects.

This raises another important question; the importance of economic figures for motivating productivity investments. Several respondents said that investment projects are mainly selected with regard to the payback period, based solely on labour cost reductions or increased customer demands. This may indicate that decision-makers in general have accepted a lack of economic data, since effects provided by lead-time, inventory or book value reductions are commonly neglected. It is believed that involving these types of economic considerations in investment decision frameworks would increase the knowledge requirements placed on users, i.e. the role and function of the production engineering department, which is usually responsible for applying for internal improvement project resources.

Finally, the results presented in Table 17 may be industry-independent, i.e. the problems are usually the same but expressed or perceived in different terms. This commonality among industries supports the idea of a general productivity investment knowledge model.

4.3.2 Conclusion Study III

The purpose of study III was to add empirical knowledge of how productivity improvements impact financial results. Study III presents evidence that the most oft-recurring problems, improvement actions and their results, are possible to translate to the productivity dimensions M, P and U. However, the productivity dimensions do not consider innovation or change rates, perceived quality, work environment or employee satisfaction, i.e. phenomena that relate to human factors. The higher objective of relating productivity improvements, expressed as M, P and U, to financial results is not answered by the study. Thus, the inquiry still demands further research. Study III contributes to the academic research field of performance measure and operations management with the conceptual productivity model. The practical contribution emphasizes the importance of internal efficiency in capital investments. Furthermore, capacity was recognized as the recurring improvement objective in six out of seven improvement projects. This finding suggests that capacity is the main consideration for productivity investment projects.

4.4 Summary of empirical results

The result of each empirical study can be summarized in three categories:

- Miscellaneous results
- Contribution to research questions
- Contribution to explanatory framework

Miscellaneous results refer to general observations during the study that have practical or academic value for future work. For instance, the empirical studies may have resulted in academic publications or provided the participating firms with valuable inputs. The second category relates to the research questions. More specifically, how the studies have contributed to respectively research question. The final category explains how the study contributes to the explanatory framework that is presented in the following chapter. Table 18 presents a summary of each empirical study's results.

Table 18 Summary of empirical results

	Miscellaneous results	Contribution to research questions	Contribution to explanatory framework
Study I	• The result of study I was published in Sundkvist et al. (2009). • It emphasized the strength of assessment methods that include observations of reality. • It evaluated the PPA method's strengths and weaknesses.	• Study I contributed to RQ1 by reviewing 10 assessments and production system analysis methods.	• Study I supports the concept for doing rapid production system assessments and concludes that such assessment methods provides sufficient information necessary to analyse and improve production system performance. Study I has thus contributed by setting goals and objectives for the complete research project.
Study II	• The result of study II is published in Sundkvist et al. (2012). • Study II provided improvement ideas and examples for participating companies.	• Study II contributed to RQ2 by establishing a procedure for analysing and improving shop floor productivity. • Study II contributed to RQ3 with ideas for establishing a framework that explains the economical benefits of shop floor improvements.	• Study II did empirically test the practical usage of M, P and U. • Study II established the initial ideas for a financial framework. • Study II developed a practice for collecting cost accounting data and observed the problems of doing that.
Study III	• The result of study III is published in Sundkvist et al. (2013).	• Study III contributed to RQ2 by providing examples from various improvement projects and tied certain problem areas to certain improvement activities that subsequently was tied to certain results. • Study III examined several operational effects due to improvements actions that act as input to economical considerations (RQ3).	• Study III contributed to the improvement framework by investigating the effects from certain improvement actions. • Study III explains the importance of capacity as the ultimate goal for any productivity improvements.

5. An explanatory framework for productivity improvements

This chapter summarizes the empirical findings in an explanatory framework regarding productivity improvements. This framework links the empirical models emerging from the management interview study and the case study research with parallel research in systems modelling. The outcome is a descriptive model of a production system's constituent parts. This model is used as a foundation for the explanatory framework that considers the relationships between a production system's shop floor performance and its financial performance based on laws and theories provided by previous operations management research.

5.1 A Conceptual production system model

A generic definition of a production system is a prerequisite for modelling real world production systems. Figure 28 represents a real-world manufacturing plant. Systems can be described by means of hierarchal levels. The proposed generic definition uses factory, subsystem and workstation to represent a production system. The model is expressed using the Unified Modelling Language (UML).

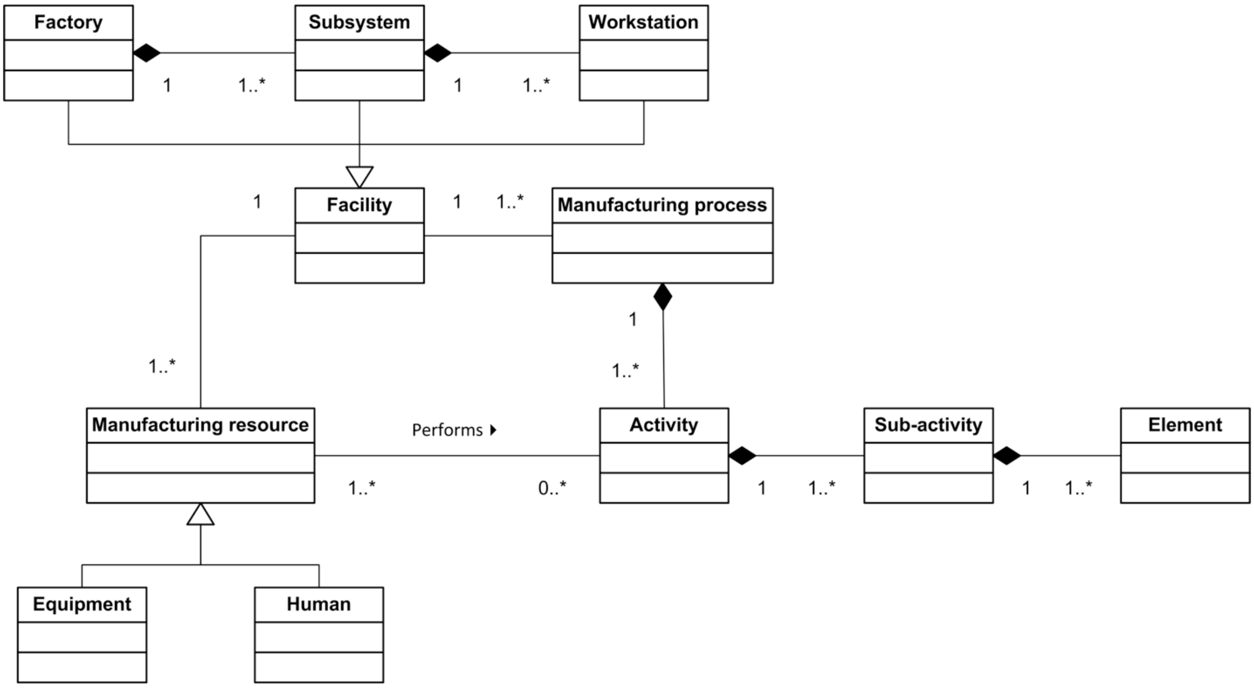

Figure 28: UML production system model (Hedman, 2013)

The top level of the hierarchy is *Factory,* which represents a real-world manufacturing facility and is limited by the walls of the modelled production system. A factory consists of one or several *Subsystems* that correspond to defined areas of the manufacturing facility, for instance the storage, painting or assembly area. A Subsystem consists of one or several *Workstations* that are defined areas. These different system levels are subclasses of the entity *Facility*.

In a Facility, one or several manufacturing processes are executed. "*A Manufacturing process is a structured set of activities or operations performed upon material to convert it from the raw material or a semi-finished state to a state of further completion*" (Iso15531-32). In modelling terms, a facility has one or several manufacturing processes. The hierarchal composition of the production system definition enables a manufacturing process to be described from the views of Factory, Subsystem, or Workstation. Hence, a manufacturing process can be seen as the entire process of transforming raw material into finished products (Factory view) or as a specific set of activities performed in a Subsystem or within a Workstation. The entities of Resource (with the subclasses of equipment and human resources) and Manufacturing process are defined according to ISO 15531-32. The decomposition of the entities of Facility and Activity in Figure 28 is not part of the ISO standard. In this thesis, the term manufacturing process is equivalent to production process.

5.1.1 Activity modelling

An activity within a production system is described as a verb, e.g. mount, assembly, control etc. Every activity within a production system has a purpose and objective. On aggregate system levels, this is to satisfy customer needs and can be compared to what Peter Drucker refers to as "*the manufacturing task*" (Drucker, 1954). On lower system levels, this is to satisfy internal customer needs, for instance the workstation that is next in line. The activity design is thus fundamental to capacity considerations. How much production capacity is necessary? What type of manufacturing resource can handle this capacity requirement? And how can the activity be designed in the best possible way to suit its purpose and objective?

An activity consists of one to an infinite number of *sub-activities*, and each sub-activity consists of one to an infinite number of *elements* (Fig. 28). Elements are the smallest constituent parts describing an activity, for instance get, put and use. When elements are put together in a logical chain, they become a sub-activity. Accordingly, when sub-activities are put together in a logical chain, they can be described as an activity. For instance, the activity – assembly product A – consists of the sub-activities of assembly component A with B, assembly component C with D, and finally of assembling all components to Product A. Within each sub-activity, e.g. assembly component A with B, elements are used, e.g. get screw, insert screw in component A, get screwdriver, etc.

The common characteristic of all activities is that they demand time to be performed. The ideal state of an activity's time consumption does not exist until a manufacturing resource is allocated to perform the specific activity. Different resources can thus perform the same activity. As soon as a resource is allocated to a specific activity, it can be modelled as a production process. A production process will consequently be assigned an ideal capacity that depends on the activities it has to perform. In practice, a production process' output can be measured. The output of a production process depends on its relationships to other processes, as well on the inputs to the process. Chapter 5.1.3 describes a production process in detail.

Activity classification

The production system model in Figure 28 deliberately excludes material flow. Instead, material flow is indirectly modelled as direct activities that move the material towards its customer or indirect activities that do not directly move the material closer to its customer but are necessary to achieve the material movement (Fig. 29).

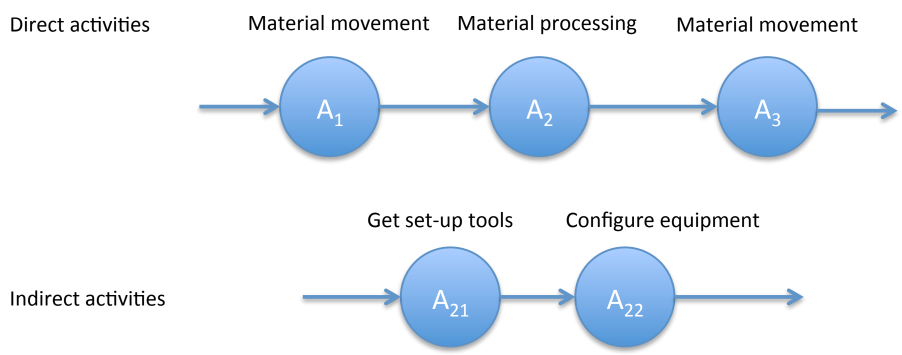

Figure 29 Activity classification

An activity can thus be either direct or indirect depending on its context. For instance, a quality control activity is direct if it is in line with a machining activity. However, if the quality control activity is decoupled from the machining activity, it is an indirect activity. All activities that are performed to support direct material flow, for instance refilling machine components and transporting components necessary for certain direct activities, are also regarded as indirect activities.

5.1.2 Resource modelling

All physical objects (human beings, computers, machines, buildings, etc.) are represented as resources in the production system model. According to (Iso10303-1), a resource is *"any device, tool and means, except raw material and final product components, at the disposal of the enterprise to produce goods and services"*.

The underlying rationale for the production system model is that resources perform activities. The entity *Resource* includes two subclasses: human and equipment. Human resources are regarded as specific means with a given capability and a given capacity. These means are regarded as being able to be involved in the manufacturing process through assigned tasks. Each resource, equipment and human, is described using the resource characteristics defined in ISO 15531-32 (table 19).

Table 19: ISO 15531-32: Definitions of resource characteristics

Attribute	**ISO 15531-32 definition**
Resource administration	Describes administrative information of a manufacturing resource.
Resource capability	Describes the functional aspects of manufacturing resources. In particular this comprises the specification of tasks of the activity that a manufacturing resource can execute.
Resource constitution	Describes the constitution of manufacturing resources. The description of the constitution comprises information about the actual status of manufacturing resources.
Resource capacity	Describes the capacity of manufacturing resources. The description of the capacity comprises information about the potential workload of manufacturing resources.

The attribute *resource administration* possesses information about the activities and consequently the manufacturing processes that the resource is assigned to. It also specifies the resource's cost per time unit, e.g. cost for salaries, depreciation costs, service costs, etc.

The attribute *resource capability* has a list, or a reference to a list, of the activities that the resource can perform and consequently comprises a specification of the activities that the resource can execute. A human resource would typically have flexible capabilities, since humans can perform almost an endless variety of activities. Furthermore, a human resource's capabilities can normally be trained to involve more activities. Equipment would typically have a short capability list, and it is not possible to train equipment to learn more capabilities (excluding the concept of artificial intelligence). A resource's capabilities can further be classified into performance related attributes for each activity. In the human case, these attributes can be categorized as skills-related and personal-related. Skills-related refers to how well educated and trained the resource is in specific activities, and personal-related refers to the resource's physical and psychological ability to carry out certain activities. For equipment, these attributes address reduced performance due to the current machine condition and its need for service and maintenance.

The attribute *resource constitution* concerns equipment-related attributes such as functions, tolerances, and technical specifications. Accordingly, this entity is not applicable to human resources.

The attribute *resource capacity* is defined as the "*capability of a system, sub-system or resource to perform its expected function from a quantitative point of view*" (Iso15531-1). Resource capacity is thus a multidimensional attribute according to the ISO standard, since it considers both the resource itself in terms of capabilities and the related activities it is supposed to perform in order to achieve an expected function. A distinction can thus be made between the functions a resource can perform and how the resource performs requested functions. The former is termed resource capacity and refers to a resource's capabilities and when they can be used. The latter refers to process capacity, i.e. how the resource's capabilities are used for producing goods and services.

Other authors' descriptions of resource capacity are presented in Chapter 2.3.4. However, in this thesis resource capacity is decomposed to three parameters: available capacity (CAP_A), planned capacity (CAP_{PL}) and utilized capacity (CAP_U). Available capacity corresponds to a defined time that a resource is available and can be scheduled for different tasks – for instance, 24 hours per day or another relevant time interval, e.g. 8 hours per day. Planned capacity (CAP_{PL}) is the specific time a resource is allocated to perform planned activities, such as a production order, equipment maintenance or transport of goods. The difference is that planned capacity refers to the time that a resource is allocated to a certain activity, while available capacity refers to the time that a resource is not allocated to any specific task. Utilized capacity (CAP_U) is the portion of time a specific set of resources is used for activities that either support material movement or directly move material closer its customer as described in Chapter 5.1.1. Utilized capacity is thus a *result parameter* of the production system design and its configuration, while available and planned capacity is referred to as system *design parameters*. A thorough description of the capacity notions is found in Chapter 5.1.4.

5.1.3 Production process modelling

The production system model defines a production process at the moment one or several resources are assigned to perform one or several activities. The purpose of defining a production process within the production system model is to enable a process capacity analysis.

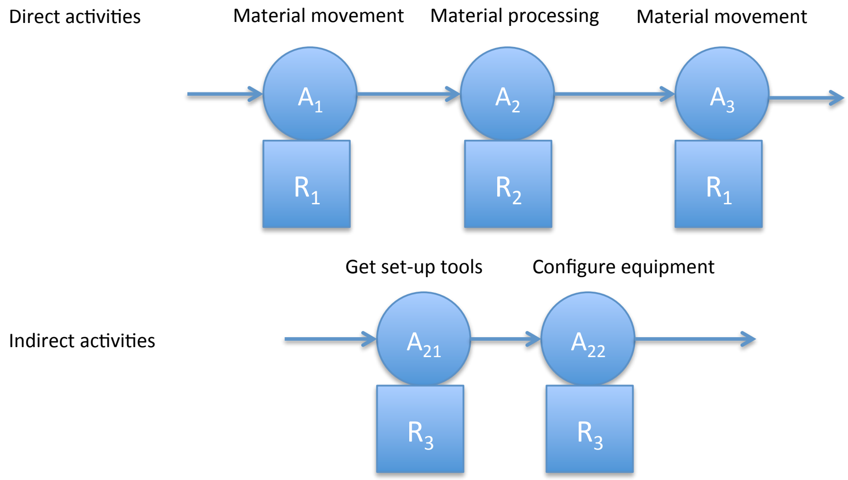

Figure 30 A production process

Figure 30 depicts a defined production process performed by three resources. Resource 1 (R_1) is a material handler, resource 2 (R_2) is a machine that processes materials and resource 3 (R_3) is a machine operator.

A defined production process has identified all activities that are necessary to perform a certain function requested by a customer. The process definition includes the interrelationship between activities. Figure 30 depicts a production process consisting of three direct activities and two indirect activities supporting the material flow. Three resources carry out these activities. The arrows explain the interrelationship between the manufacturing process' activities, commonly referred to as precedence diagrams (Benjaafar and Ramakrishnan, 1996). For instance, activity A_1 must be carried out before activity A_2 can be initiated, and so forth. In practice, it is uncommon that resources are allocated to one activity only. Instead, resources are shared to produce several products and to enable machine set-ups for each product family or each specific product produced within the factory. This will affect the production process' capacity, since other processes that share the resource might restrict it.

Production process classifications

A production process can be categorized as automatic, semi-automatic or manual. An automatic process does not demand any human interaction to perform activities. It is questionable whether fully automatic processes exist in reality (Hayes and Wheelwright, 1979). Semi-automatic processes demand various degrees of human interaction, and manual processes consist of manual work only, for instance manual assembly.

5.1.4 Capacity modelling

In general, *capacity* describes abilities and limitations (Van Mieghem, 2003). Capacity is decomposed into resource and process capacity for analytical purposes to explore a production system's abilities and limitations. The aim of the analysis is to improve the system as well as to understand its inherent limitations. Those limitations consequently require investments to overcome. Before presenting a detailed description of the capacity notions used in thesis, requested capacity (CAP_{RQ}) is discussed.

Requested capacity (CAP_{RQ}) is the capacity needed to meet customer requirements. Thus, CAP_{RQ} is neither a design parameter nor a result parameter; it is a demand and can be assigned values based only on assumptions. It would be possible to align and optimize a production system's capacity to CAP_{RQ} in a static world. However, CAP_{RQ} is dynamic, which consequently results in production process designs that actually provide over-capacity or an under-capacity compared to CAP_{RQ}, and accidentally a perfect match. As described in 5.1.2, the capacity of a firm's resources can be analysed with CAP_A, CAP_{PL} and CAP_U. However, to fully analyse a production system's capacity, it is necessary to involve the way that the system's resources perform activities. This analysis refers to *process capacity*. A production process' capacity can be decomposed to ideal capacity (CAP_I) and real capacity (CAP_R).

Ideal capacity is the capacity of a production process as determined by using predetermined time systems incorporated into time equations known from time-driven activity based costing (TDABC). This method was established by Kaplan and Anderson (2007) and is explained in detail in Chapter 5.8.3. The ideal capacity is, however, provided by calculating the standard time for all activities included in a defined production process. All those activities can be expressed in a time equation that yields a given operation's standard time corresponding to a productivity measure. All time parameters within the time equation should be set in accordance to predetermined time systems for labour. The time standard for activities performed by equipment should be set in a stable processing environment. Ideal capacity describes the capacity of a process as the number of units produced during a given period of time, which corresponds to the throughput rate of the process. The throughput rate is established by dividing the total number of products produced during a given time period with a relevant comparison number. The result is a throughput rate measured as products produced per hour (or a relevant comparison number). Intellectual capacity, for instance innovation rate, change rate, or other human resource related capacity rates are not considered in this definition. The definition used in the production system model implies a specific ideal capacity for every defined time equation.

Real capacity, $CAP_{R,}$ is the measured capacity provided by a defined manufacturing process at a specific moment of time. Real capacity is thus a measurement of capacity that includes all conceivable losses incurred by either the defined manufacturing process or by other surrounding processes. Real capacity can also be used for analysis purposes by comparing it to the process' ideal capacity.

Capacity analysis

There are several available definitions of *capacity*, *availability* and *utilization* that may lead to misconceptions. Economic theory often refers to *capacity utilization (CU)* as the relationship between a system's potential and realized output (Fare et al., 1989, Morrison, 1985), while production-related theory refers to unutilized capacity as availability losses (Zequeira et al., 2008). To avoid misconception, the following notions are used.

The ratio between a production system's planned capacity (CAP_{PL}) and available capacity (CAP_A) is referred to as *resource availability* (A_R). Resource availability (eq. 10) does not consider the activities that are performed, thus not the output of a production process. Resource availability strictly refers to *resource capacity* as described in Chapter 5.1.2.

$$resource\ availability = \frac{CAP_{PL}}{CAP_A} \quad (10)$$

Resource utilization (U_R) is distinguished from availability since it explicitly considers the activities that are executed by a manufacturing process' resources (eq. 11).

$$resource\ utilization = \frac{CAP_U}{CAP_{PL}} \quad (11)$$

However, resource utilization (U_R) does not explicitly consider how activities are performed, for instance whether a resource performs a certain activity with reduced speed compared to a given time standard. Losses induced by the production process design and performance losses due to insufficient capabilities are described in Chapter 5.3. However, resource utilization refers to the activities that are carried out during a given time period. Resource utilization is thus the ratio between the measured time spent on planned production activities (direct and indirect activities) and the planned production time (CAP_{PL}). Time that is used for activities that do not contribute to material movement, for instance waiting for materials, is regarded as a resource utilization loss. A common measurement technique for this purpose is work sampling (Niebel and Freivalds, 2003). Figure 31 illustrates how resource capacity is analysed. The red areas in Figure 31 indicate time losses. Resource availability time losses are regarded as design decisions, while resource utilization losses are regarded as results.

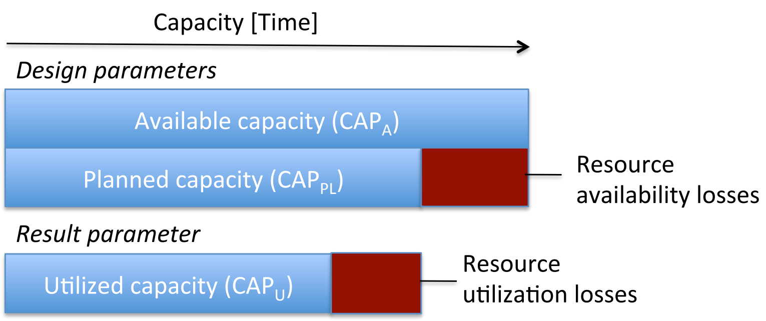

Figure 31: Resource capacity analysis

Process capacity is distinguished from resource capacity since it considers the output of the process measured as a throughput rate (eq. 12).

$$Process\ utilization = \frac{CAP_R}{CAP_I} \quad (12)$$

Process utilization (U_P) involves performance aspects, such as *how an activity* is performed, not only the activities that are performed. A detailed description of how the capacity of a production process is measured appears in Chapter 5.3. The red area in Fig. 32 visualizes process losses measured as output per time unit. These losses can be decomposed into performance and utilization losses, which are also explained in Chapter 5.3.

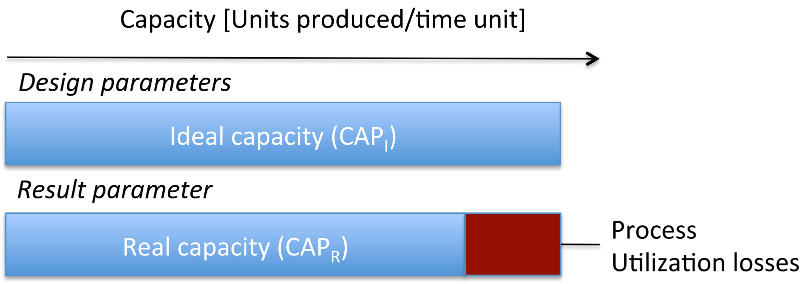

Figure 32: Process capacity analysis

To summarize, a production system may deliberately maintain overcapacity, i.e. CAP_{RQ} is less than CAP_R, which implies that CAP_A may be far larger than CAP_{PL}. Availability is thus a managerial decision (design parameter). From a resource utilization point of view, it is not interesting to know what resources are doing during unplanned time, since they are not allocated to any activities. Resource utilization must thus be measured during planned production time. Furthermore, utilization can be considered from a resource perspective (resource utilization) and a process perspective (process utilization) that enable two options for capacity analysis. Table 20 presents a summary description of the capacity parameters.

Table 20: Capacity parameters

Parameters	Description
CAP_{RQ} – Requested capacity	Requested capacity (CAP_{RQ}) is the capacity needed to meet customer requirements. Requested capacity is dynamic and can be assigned values based only on assumptions.
CAP_A – Available capacity	Available capacity (CAP_A) refers to capacity measured as the time that is provided during a specific period by the production system's resources.
CAP_{PL} – Planned capacity	Throughout a work shift, the company's master production schedule (MPS) system allocates specific resources to particular activities. This time is referred to as planned capacity (CAP_{PL}) or planned production time.
CAP_U – Utilized capacity	Utilized capacity refers to the portion of planned production time used for performing direct and indirect activities. Utilized capacity is a result parameter that depends on production system design.
CAP_I – Ideal capacity	Ideal capacity (CAP_I) is equal to the throughput rate of a defined production process. Ideal capacity is established by means of time equations described in Chapter 5.8.3. Furthermore, the time equation's content should be generated by predetermined time systems.
CAP_R – Real capacity	Real capacity (CAP_R) is the result of production system design and its configuration, accounting for all losses within the system. The ratio of CAP_I to CAP_R will indicate a capacity potential of the analysed manufacturing process, given defined limitations.

The output of a manufacturing process can ideally be quantified with CAP_I and measured with CAP_R. A process' output can also be measured from various different perspectives. For instance, conformed quality and on-time delivery are expected from a customer perspective. Relatively low production costs are expected by the owners. If customer requirements fluctuate to great extent, flexibility of the manufacturing process' capacity is expected, etc.

The determinants of each hierarchal analysis level will fundamentally vary, i.e. is it a set of processes' output or a single process' output that is analysed? For instance, process design will have a direct impact on a single process' output. But at higher system levels, determinants such as layout and product portfolio will determine the output. Each increase in hierarchy calls for new result determinants. A manufacturing process is analysed through the decomposition of CAP_R. The production system model is the foundation of this analysis while demanding analysis tools to collect input data and empirical and fundamental models that present relationships between current state and future state solutions. Chapter 5.2 characterizes process improvements, while Chapter 5.3 describes the analysis tools used for improvement purposes, as well as the improvements that can be made and how that can happen.

5.2 Modelling process improvements

The objective of a manufacturing process improvement fundamentally varies. A manufacturing process should initially be designed to ensure that customer requirements are met, that is to satisfy requested capacity (CAP_{RQ}). Two basic needs must be satisfied by the manufacturing process: the quantity of goods that the customer requests and timely delivery. The underlying design problem for a manufacturing process is thus variations in requirements (Hopp and Spearman, 2008). Variations imply that a manufacturing process' throughput rate of goods must either be aligned with the average requested capacity but retain inventory to handle variations or be designed to handle peak variations that correspond with being over-specified during periods of low or non-existent demand. Since requested capacity is dynamic and changes with time, strategic trade-offs must be made in light of these two alternatives. Strategic issues are discussed in Chapter 5.4.

In on-going operations, real capacity will differ from requested capacity to a certain extent and match only by accident. A typical process improvement should hence align real capacity with requested capacity with regard to demand variations. Manufacturing process improvements can thus be made whether requested capacity is increasing or decreasing.

From a single manufacturing process perspective, there are two available improvements options:

1. *Output-oriented improvements*: The objective is to increase the manufacturing process' throughput rate to satisfy increased demand. Improvements are made to increase ideal capacity (CAP_I), i.e. improve the process' activity design, and real capacity (CAP_R), i.e. improve how the process' resources perform activities to avoid increased resource allocation compared to the current state of the process.
2. *Input-oriented improvements*: The objective is to reduce allocated resources to alignment with lower demand. Improvements are made to increase CAP_I and CAP_R to reduce the quantity of allocated resources compared with the current state of the process.

Both options benefit from increased throughput rate, either to utilize planned capacity better for increased output (output-oriented), or to increase available capacity (input-oriented). For instance, an improvement that increases resource availability for releasing resources for the purposes of performing other activities, e.g. introducing new products, improving variation handling capabilities and continuous improvement work. Alternatively, eliminate these available resources and thus the cost of maintaining them. From a single process point of view, output-oriented improvements enable input-related improvements. Output-oriented improvements can thus be described as an increased throughput rate that enables the same or lower resource consumption rate to process equal or more output than the current state of the manufacturing process.

A facility has a defined set of manufacturing processes. Each manufacturing process is related to a single requested capacity. Resources are usually shared between these single manufacturing processes, which implies that the real capacity from a factory view depends on how resources are shared within its set of manufacturing processes. How these resources are shared is a subsequent result of how the individual processes' requested capacities change. This problem can be addressed in many ways, starting with customer requirements, how are they affected by the sales and marketing department, and what can be done within the facility to handle these demand variations. Hence, from a factory view, different design parameters must be considered than with the workstation view. Accordingly, capacity improvements of a set of manufacturing processes are described as an increased throughput rate of the defined system or a reduced resource consumption rate than the current state of the system as enabled by throughput rate improvements or improved resource allocation among those individual processes.

Capacity improvements are thus relative measures that compare a current state with a future state scenario to reduce the process' resource consumption rate relative the process' throughput rate. The outcome of an improvement action is a result of several factors (internal and external): how customer needs are controlled via advertisement and sales, how resources are shared, how the production system is designed, how products are designed, etc. Consequently, a distinction from other improvements is preferable, especially for manufacturing process developers that research relationships between improvement actions and measureable effects.

The value of improvements

The effect of a process improvement must not only consider output-related or input-related capacity, but also the value of the requested capacity and consequently the value of the process improvement. From a financial perspective, it is evident that some manufacturing processes are valued higher than others, i.e. they generate more return on the initial process investment.

A distinction can thus be made between capacity improvements that consider the value of improvements and those that do not consider the value of the improvements.

1. Productivity improvements – A relative measure that considers the relationships between resource consumption rates and processes' throughput rates without regard to financial effects.
2. Profitability improvements – A relative measure that considers the value of relative capacity improvements.

The distinction between capacity improvements as productivity and profitability is used in the context of this thesis. These terms have other meanings in other contexts. Nevertheless, it is clear that a profitability improvement is the result of a successful productivity improvement. Hence, it is natural to discuss capacity improvements as the result of productivity improvement actions, followed by profitability improvements as a result of capacity improvement actions.

The production system model is the foundation of the capacity analysis. The production system model describes real world production systems from different hierarchal views: workstation, sub-system and factory. These hierarchies are chosen from a practical viewpoint. However, from a capacity analysis perspective, it is only necessary to distinguish between a single manufacturing process and a set of manufacturing processes. A set of processes is by definition influenced by the relationships between them, which may be conceptually disregarded in a single process. Thus, every view within the production model can be analysed with the same set of measures, but the conclusions that can be drawn from the analysis differ depending on whether the manufacturing process is regarded as single process (process perspective) or a set of processes (system perspective). Chapter 5.3 explains how productivity improvements can be modelled from a process perspective and a system perspective.

5.3 Modelling productivity improvements

Productivity improvements are made to increase the throughput rate of a process. As previously discussed, productivity improvements are a relative concept that considers resource consumption rates in relation to the output of a production process. A manufacturing process' productivity is modelled with the productivity dimensions of *Method* (M), *Performance* (P) and *Utilization* (U). The classifications of productivity dimensions have three objectives, the first two adapted from Sakamoto (2010):

1. Separate productivity contents from an industrial engineering technique point of view.
2. Adopt new approaches to each productivity dimension.
3. Quantify improvements.

The first objective is to separate a manufacturing process into content that can be analysed with specific analysis tools, such as method analysis with predetermined time systems (M), performance analysis with clock instruments (P), and utilization analysis with work sampling techniques (U). The results of these analysis tools are used as input to the production system model.

The second objective is to use the information provided by those analysis tools of productivity dimensions to improve the current state of the defined process. Various improvement approaches can be employed, for instance by making many small incremental single processes improvements, which can be compared with radical improvements by employing new techniques and innovations that revolutionize the current manufacturing process' productivity.

The third objective of productivity dimensions is to quantify improvements that enable comparisons between the current state and the proposed future state scenario. For instance, it is impossible to employ work sampling studies and performance analysis techniques in non-existing systems, which is fundamentally the result of a production system design. A future state scenario can, however, be generated by using pre-determined time systems without consideration of utilization and performance issues. Furthermore, adding empirical findings such as learning curve theory to the future state scenario analysis may provide reliable input to use for decision-making support. The aim of quantifying improvements thus serves two purposes: being able to follow up improvements and facilitating the decision-making process.

It is suggested that a bottom-up approach can be used, starting at low aggregation levels when modelling productivity improvements. The objective of this section is to present the way that a manufacturing process' real capacity can be decomposed into productivity dimensions and explain the relationships between a single manufacturing process and a set of processes, i.e. a system. The productivity dimensions have previously only been used for analysing labour productivity. Nevertheless, a similar decomposition can be used for analysing equipment productivity.

Figure 33 depicts a representation of a manufacturing process. Three direct activities must be performed to transform inputs to requested output. The determinants to ideal capacity are these activities' *method design* (M), and the determinants of the real capacity of the manufacturing process include consideration to the resource's performance (P) and utilization (U) parameters. Consequently, the ideal capacity of manufacturing process can be analysed without consideration of its resources, while its real capacity needs to consider the resources that perform those activities.

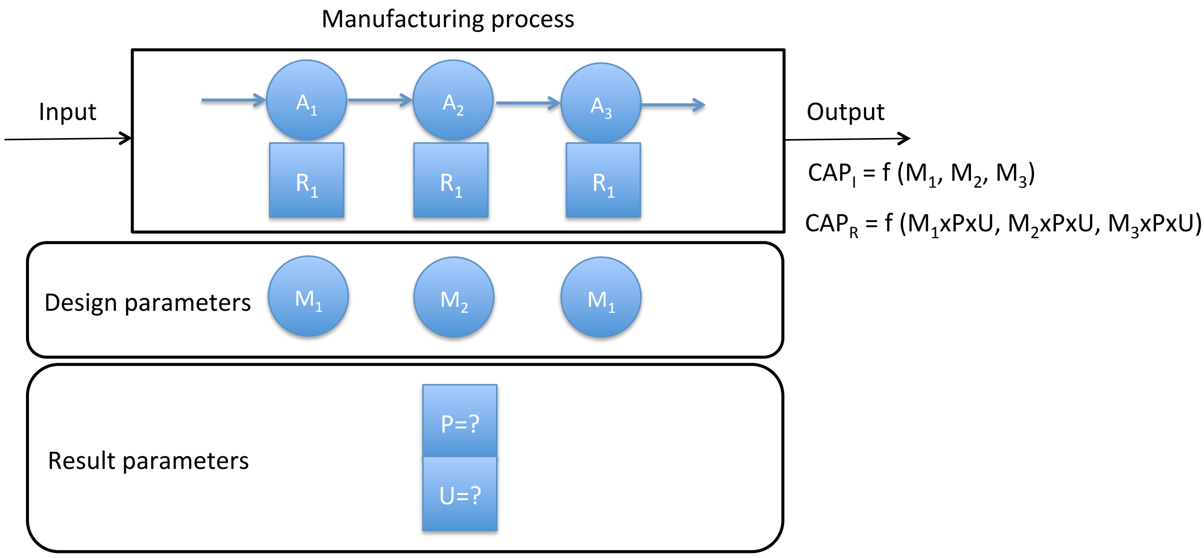

Figure 33: A manufacturing process can be analysed with the productivity dimensions M, P and U.

When decomposing real capacity to quantifiable productivity content, it is necessary to decide whether it is the activities' method design (M) or the capabilities of the employed resources that need to be improved, i.e. is it the method design that makes the output of the process less than ideal, or is it insufficient resource capabilities that make the output less than ideal?

Each productivity dimension is discussed below starting from the method design point of view and later on from the resource capability point of view, i.e. human resources and equipment. The approach is the method design that is subsequently divided into process design and system design parameters. Process design refers to a single activity's method design with no interaction with other activities, while system design considers relationships within a set of processes. Each design parameter corresponds to certain improvement actions. The result of the real capacity analysis provides the foundation for the productivity analysis.

5.3.1 Method design analysis and improvements

Each activity within a defined manufacturing process corresponds to a *method design* (M) that is set by a time standard generated by predetermined time systems for labour or equivalents for equipment. The method design considers whether appropriate tools and work sequences are used for each activity. For instance, the activity *assembly product A* can be decomposed to several sub-activities and elements as described in 5.1.1. They must be performed in a certain sequence in order to successfully finalize the assembly. The method design considers how this assembly sequence is carried out. For instance, how far does the assembler need to walk to get the tools needed for the assembly sequence? Where are the required nuts and bolts located? Is a manual or electric screwdriver used, etc.? The time standard for the assembly sequence given by the predetermined time system corresponds to the time of one single work cycle, i.e. the *cycle time*. The inverse of the cycle time yields the throughput rate of the work cycle, i.e. the ideal capacity (CAP_I).

There are two fundamental design parameters that consider method design (M):

1. *Process design*: The design of a single activity must satisfy requested capacity and human needs and capabilities or equivalent equipment capabilities.
2. *System design*: A single process' design must simultaneously be aligned with regard to its surrounding processes (various requested capacities).

An ideally designed method provides conditions for human resources to perform at a 100% nominal performance rate, resulting in zero quality defects, and can be utilized at 100% during planned production time, given agreed allowances. Thus, a defined manufacturing process' ideal capacity is set by the method design. If equipment performs an activity, ideal capacity is set in stable processing environments. Manufacturing process losses are categorized as either performance or utilization losses and can be measured only at the resources that are performing the activity concerned. The process and system design is thus one determinant of real capacity. The other determinant of real capacity is the resource's capability to perform the process' activities. The following synthesis is from a method design perspective, i.e. how it influences the resource performing it. The discussion starts with the process design perspective and ends with the system design perspective.

Process design analysis

The method design from a process perspective will always cause some utilization and performance losses, either at the workstation level or at the aggregate system levels. These two loss parameters can be decomposed into several variables that enable a more detailed analysis (Hedman, 2013, Almström, 2013).

Utilization losses are work content that does not contribute to material flow. That is, the system's resources spending time on activities that cannot be categorized as direct activities or as indirect activities, for instance waiting, rework or activities that are performed incorrectly. It is necessary to decide whether the production process needs to be redesigned, whether the resource performing the activities needs to be supported, or whether the equipment that is used in the process is causing the utilization loss.

The first utilization loss variable is explained as a *system design utilization rate* (U_S). First, a production process is never initially designed to cause utilization losses. For instance, a machining process is not designed to produce non-conformed products, and an assembly process is not designed to use wrong tools for wrong purposes. However, U_S might be evident in production processes, either as a balance loss between workstations or as a balance loss within a semi-automatic workstation, e.g. when an operator waits for a material processing activity to finish. The root cause for this type of loss varies to a great extent. Other processes, for instance IT-systems or documentation procedures that are related to the actual production process, might also incur system design utilization losses. It is termed system design utilization rate since individual processes never cause this type of utilization loss if regarded as an isolated process.

The second utilization variable is explained as *need-based utilization rate* (U_N). This refers to the human resource's need for relaxation and personal time to maintain a defined method design during a long period of time. This allowance time is usually specified in trade union agreements and domestic legislation. For example, a method design may consist of several heavy lifts within a work cycle. The PTS used for setting the method design accounts for heavy lifts with additional time allowances. However, it is reasonable to believe that processes containing a large number of heavy lifts will in the long term influence the performance of the resource performing it in terms of fatigue.

The last category refers to *disturbances affecting utilization* (U_D), which are random disturbances caused by the specific resource that performs the activity. The method design will influence the outcome of those disturbances. The complexity of the method design will typically affect U_D. An assembly process that is designed with fool-proofing considerations, for instance that enables a certain type of screw to be positioned at a certain location, is one example that avoid disturbances and subsequently avoids rework as a result. Design management considerations are usually thought of in production preparation design methods, for instance design-for-manufacturing (DFM) or design-for-assembly (DFA). It has been argued that design management initiatives that strive to build quality into the product rather than inspecting for quality have a positive impact on quality yields (Radhakrishnan and Srinidhi, 1994). However, attaining superior quality outcome design management must be balanced with process management (Ahire and Dreyfus, 2000). Other typical U_D loss examples are if a driven assembly line is stopped, if equipment that should be used in the production process is not working properly or if work instructions that should be available from the information system are not available, etc.

Performance losses refer to the second loss parameter. Performance losses are direct and indirect work content that is performed with lower throughput rate than the throughput rate yielded by the time standard. By definition, the standard should provide conditions for the process' resources to perform activities with nominal performance rates. Method designs compensate, as previously mentioned, for additional force and weight requirements. However, it is reasonable to imagine that method designs that include many heavy lifts and additional force requirements will in the long run affect both performance and utilization as stated in the need-based utilization description. In that case, support tools or similar process design changes are necessary to provide those resources with suitable conditions for maintaining the process standard.

Process design improvements

Process design improvement potentials are established by using predetermined time systems or equivalents. A process design improvement will affect the process' ideal capacity. It will also affect the process' real capacity considering utilization and performance losses as previously explained. Among typical improvements that will affect ideal capacity are reduced walking distances to get tools and materials and facilitated assembly content by designing ergonomic and easily accessible fixtures. Among improvements that will affect the performance and utilization dimensions are cleanliness and order at the workstation, marked tools and equipment, and various support tools for heavy weight lifts and pick-to-light systems for supporting picking operations. As discussed by Ahire and Dreyfus (2000), process design management should be balanced with product design management in order to attain the most significant improvements. However, product design considerations are outside the constraints of this thesis. Table 21 presents typical process design parameters and typical improvement actions adapted from Kuhlang et al. (2011).

Table 21: Single process design improvements

Design areas	Improvement actions
Layout – Workplace design & workplace alignment	• Planning and realisation of U-cells. • Ergonomic design of workplaces. • Ease of assembly. • Ease of equipment and tool handling. • Decouple direct activities from material flow. • Combine several workplaces into one. • Implement easily re-configurable flows. • Enhance interaction options among employees.
Technical modifications	• Improve information and feedback flows with manufacturing execution systems (MES). • Match technical capacity with customer requirements. • Use small, inexpensive machinery where suitable. • Manual material handling instead of expensive material handling equipment where suitable.

System design analysis

A production system has a defined set of manufacturing processes. Production system design refers to how these set of single production processes are related to each other. A factory's physical layout and its inherent control system must be considered. The productivity analysis of a set of processes differs from an analysis of a single process' productivity. The main difference is the conclusions that can be drawn from the analysis. The system design will affect the system's performance and utilization rates. Both result parameters will be discussed from a system design perspective. A utilization analysis at the system level can be performed with two options:

1. Analysing the average process utilization of each of the system's single processes.
2. Analysing the average resource utilization from a specific factory view, e.g. the workstation view or the subsystem view.

The first option reveals the single manufacturing process that is problematic from a process utilization perspective and is thus equivalent to the process perspective. For instance, the manufacturing process of product A seems to induce significant process utilization losses compared to the manufacturing process of product B. This type of analysis indicates that product A either suffers from a design problem (design management issue) or that the process design for product A needs to be improved.

The second option results in an average resource utilization distribution, by analysing a defined workstation, a defined subsystem, etc., that operates more than two defined manufacturing processes, e.g. products A and B. This option reveals aggregate resource utilization losses induced by the system design. A distinction can thus be made between process utilization and resource utilization. Using work sampling techniques, etc., will only assess resource utilization rates (U_R).

System utilization losses are present in the system design utilization rate (U_S) category. Among these utilization losses are balancing losses between single processes, i.e. the result when the system's processes are designed with different throughput rates. Another system design aspect is how variation will affect the system's utilization rate. Using inventory buffers before and after critical process steps can avoid this type of utilization loss but at the expense of the system's throughput time (Hopp and Spearman, 2008). Some variation examples are: customer demands, each individual manufacturing process has an inherent process variation, the product mix causes variations, the input material always varies regarding quality and tolerances. Activities performed by human resources will always vary with respect to time consumption, quality yield, etc. Material processing activities will also vary to some extent with respect to time consumption and quality yield. Consequently, variation exists everywhere and any time and is the main source of system utilization losses.

Disturbances affect utilization rates (U_D) and need-based utilization rates (U_N) at the system level are losses incurred by single processes' failure to conform with the standard. When resource utilization is measured (i.e., an average utilization distribution among several manufacturing processes), it may become evident that a single process is affecting the whole system. From a system perspective, it is important to locate the source of the system's utilization loss. Thus, there are only system design losses incurred at system level, but the single process U_D and U_N may affect the system's real capacity, depending on the system design.

Performance losses at the system level can be traced only to a defined process' bottleneck activity, or a system's bottleneck process. These activities will affect the whole process or the whole system if they are performed with a lower throughput rate than nominal. This performance loss will be measured as a utilization loss at other workstations since they need to wait due to the performance loss in the bottleneck process.

System design improvements

System design improvements aim to improve the system's ideal capacity, i.e. the system's throughput rate. The most fundamental improvement from a system design analysis perspective is to standardize method designs employed within the defined system. There are numerous purposes for standardizing production processes, but the most relevant is that the standardization allows the system's activities to be measured and analysed. In turn, standardized production processes ease the planning of operations, follow-up and feedback procedures (short-term) and improvement procedures (long-term). A more radical system improvement is to change the complete layout of the factory, for instance redesigning a functional layout to a flow-oriented layout. System improvements also consider strategic decisions about available capacity (CAP_A), i.e. how much available capacity is needed to provide the requested service level. Table 22 presents typical (but a very limited selection of) system design areas and improvement actions.

Table 22: System design improvements

Design areas	Improvement actions
Process organisation and work organisation	• Implement a flow-oriented layout to facilitate planning operations and reduce throughput times. • Implement high-performance work practices (HPWPs). • Improve system utilization through the alignment and design of individual processes that include design aspects to prevent U_S losses induced by the system's resources.
Manufacturing control system	• Optimize production schedules and work distribution (job scheduling). • Reduce fluctuations in order frequency and work content.
Continuous improvements	• Identify needs & wants, schedule improvement tasks, appropriate goal setting etc. • Organize improvement activities. • Establish standards for analysing and evaluating results. • Identify improvements based on knowledge gained from other improvements. • Establish and facilitate communication channels (visual management, benchmarking, "war rooms", etc.)
Product design	• *Align design management with process management*

To summarize, the method design (M) establishes the ideal capacity (CAP_I) of a defined production process. However, the ideal capacity of a system depends on the relationships within its set of processes. A process' real capacity considers its associated resources. These resources can be trained, they can practice their skills to perform activities according to process standards, and they can be subject to human resource practices such as those referred to as *high-performance work practices* (Combs et al., 2006). The next discussion is based on a resource perspective, i.e. how its capabilities affect the output of a defined production process.

5.3.2 Resource analysis and development

Resources are modelled as either human or equipment in the production system model. A distinction is made in the following section between how human and equipment resources affect a process' real capacity compared to the method design.

Productivity analysis of human resources

Human productivity considers only manufacturing processes that are semi-automatic or manual, i.e. processes that include manual work content. Human resource's utilization rates (U) and performance rates (P) are, as previous explained, associated with the method design (M). These result parameters can be decomposed into less aggregate variables as explained in 5.3.1.

Human resources do not contribute to system design utilization rate (U_S) losses at the workstation level. However, reduced U_S rates at the system level are the result of varying resource capabilities, i.e. human resources induce variation in the system. Thus, the human resource's contribution to utilization losses is only present at the workstation level as personal allowances (U_N) and non-conformed output (U_D). Need-based utilization rate is a personal capability that represents endurance in various terms. Disturbance-based utilization rate is a skill-related capability, i.e. the ability to *do things right* during planned production time, i.e. maintain the process standard. A process standard represents an ideal capacity for a manufacturing process executed by experienced labour with normal human capabilities. An experienced worker would typically completely memorize such a standard, which is a capability that may be both positive and negative from a productivity perspective. The positive aspect relates to increased throughput rates, since the worker doesn't need to look in work instructions and thus reduces the time spent on that specific activity. The negative aspect is that the worker might not work according to the standard and cause unexpected variations and quality defects. Reading the standard, i.e. the work instruction, may thus be included in the method design for the purpose of reducing defects.

A real-world production system has a mix of experienced and inexperienced human resources. This mix also provides a mix of capabilities. The effect of having resources that cannot perform according to process standards can be analysed by decomposing the performance parameter into two variables – *skill-based performance rate* (P_S) and *personal performance rate* (P_P).

A human resource that *does things right* all of the time but not according to the time standard consequently lack the skills to perform at standard performance rates. This is the typical situation of inexperienced labour, which consequently needs training and practice to improve its performance skills. Many firms use competence matrices to evaluate their human resources. A common way to avoid this type of problem is to establish pilot production lines or workstations decoupled from the main production line, where operators can be trained and educated before starting up production on the main line.

The other performance loss, personal performance rate, relates to the human resource's physical and psychological ability to perform according to standard. It must be understood that all human beings are different, and some of them lack this ability or are in unfavourable psychological situations that affect their work situation negatively. This type of performance loss is not discussed any further but is indeed an important topic. The production system can also be designed to motivate (or require) increased performance rates. A driven assembly line is a typical example in which labour is required to perform according to standard (a method design parameter).

It is clear that the real capacity of a defined manufacturing process is the result of the resources' capabilities and corresponding method design. Table 23 summarizes how human resources' capabilities affect a process' real capacity. These variables can be analysed at the workstation level. The variables are a dynamic that is always alternating. At the system level, this variation is measured as system design utilization rate losses. A well-designed production system seeks to minimize variation by establishing processes that provide the foundation for human resources to perform according to given standards. Furthermore, the production system must also be designed for handling variation to a certain degree.

Table 23: Labour productivity variables (Almström, 2013, Hedman, 2013)

	Variable	Explanation
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 to the PTS norm) independent of the work task.
	Skill-based performance rate (P_S)	The skill-based performance rate measures the individual's speed of performing a specific work task depending on previous training and experiences that the individual has for performing the task.
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 workplace. It includes paid breaks and losses before and after a break.
	System design utilization rate (U_S)	The system design utilization rate is defined as balance losses designed as part of the system. These balance losses can be found at the assembly line as well as losses in semi-automated workstations.
	Disturbance-affected utilization rate (U_D)	Disturbance-affected utilization rate corresponds to the losses caused by various random disturbances. It includes the time from discovery of the disturbance until the work is performed at full speed again.

Human resource development

A utilization and performance analysis of human resources reveals insufficient capabilities and corresponding losses, regarding both the human resource itself and the production system it operates within. Improving a human resource's ability to perform certain activities at the shop floor level would undoubtedly lead to increased real capacity. This is especially of importance when firms introduce new manufacturing processes (Fioretti, 2007). In such scenarios, production managers are aware that the new process will be subjected to numerous time delays and idling problems for various reasons. However, with time the production process will start to yield better results. How and why a manufacturing process yields better results with time is partly captured by the learning curve (Figure 34).

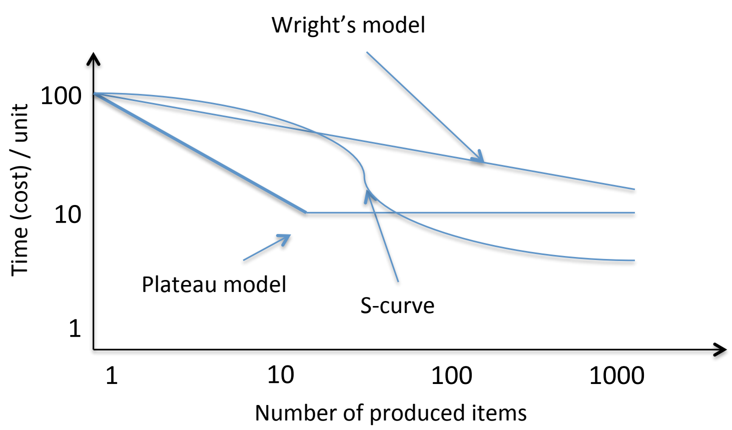

Figure 34: Examples of different learning curves (Anzanello and Fogliatto, 2011)

The learning curve theory states simply that the cycle time of repetitive manufacturing tasks decreases with cumulative production at a uniform rate (Fioretti, 2007). Learning curves generally capture the aggregate learning effect. Previous research has attempted to use different proxies for experience in order to understand the causality shaping these learning curves. The original formulation of learning curves used cumulative output as a proxy for experience (Adler and Clark, 1991). Furthermore, a distinction can be made between individual (learning curve) and organizational learning (progress curve).

The difference between a learning curve and a progress curve is that learning curves are used to describe labour learning at lower system levels, for instance at the work station level. Progress curves capture not only learning, but changes in materials inputs, product technologies and managerial technologies (Dutton and Thomas, 1984, Nembhard and Uzumeri, 2000). These effects may thus reflect improvements not necessarily resulting from increasing knowledge or experiences. Real capacity as described in 5.1.4, can be used as a proxy for such a progress curve. Figure 35 translates a typical progress curve into the context of this thesis.

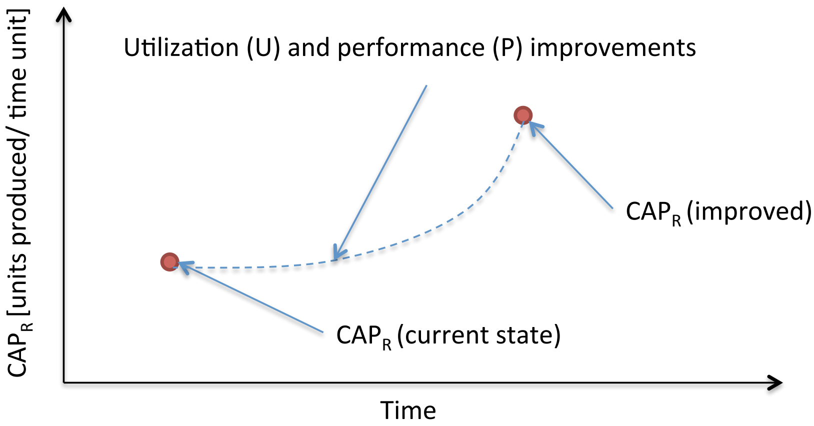

Figure 35: Real capacity as a proxy for a progress curve

The real capacity of a defined process is determined by the performance (P) and utilization parameters (U). Improving these parameters will result in increased CAP_R. The difficulty is to predict the shape of the improvement curve. Based on available research, it is clear that the improvement curve is affected by numerous parameters, one of which is experience. Dutton and Thomas (1984) have made an attempt to analyse the factors that influence the progress curve with respect to the learning curve rate, i.e. the speed of improved learning. Four causal categories were developed:

1. Technology progress of capital goods: Investments in capital goods creates a changing environment that contributes to progress effects measured at aggregate system levels.
2. Labour learning: Labour learning through repetition of manufacturing task. This effect relates to traditional learning curve theory. Another observation is that direct labour improvements are often caused by improvements to indirect staff's behaviour and learning processes.
3. Local system characteristics: Various progress rates have been linked to differences in organizational structures, preferred customers and product mixes. Also the ratio of between machining and manual assembly operations (i.e. degree of automation) and the length of the cycle time causes differences in the progress rates.
4. Effects of scale: Economies of scale are reductions in costs due to increased sales. However, the total unit cost reduction may also be a result of labour learning, not only the absorption of fixed costs.

Klenow (1998) asserts that productivity growth from learning by doing (first-order learning) decreases as experience accumulates with technology and that the improvement rate is specific to each production technology. This would indicate when it is time to update technology, i.e. when the improvement rate stagnates. High rates of production enable firms to learn more quickly in line with the scale effect. That is, firms accelerate their technology adoption in peak times and delay them during difficult periods. This implies that even though demands are low, it is better to run production at an ordinary pace to reduce the work length of the day, etc., rather than levelling out work tasks during a shift. Adler and Clark (1991) adds to the learning curve theory of how first-order learning (i.e., learning by doing) and second-order learning (i.e., induced learning) interact. They suggest that second-order learning can disrupt as well as facilitate first-order learning. For instance, an engineering change that presents a clear benefit from an assembly point of view may cause temporary disruptions before its beneficial effects are realized. That is, second order learning initiatives may lead to other changes with cascading disruption effects (Adler and Clark, 1991).

Figure 36 presents a proposed progress curve based on research results and observations. It is clear that every change (improvement) may cause a temporary drop in capacity rate at the beginning of the improvement initiative. As production continues, first order learning in combination with the effects of scale will improve the process' output. Second-order learning, i.e. training programmes, will also influence the progress rate. As time passes (i.e. with cumulative production), a plateau is most likely reached, i.e. the standard of the production process is attained. To increase the capacity rate even more demands either a technology investment or an engineering change, for instance in the product itself (product design management) or in the method design currently used (process design management).

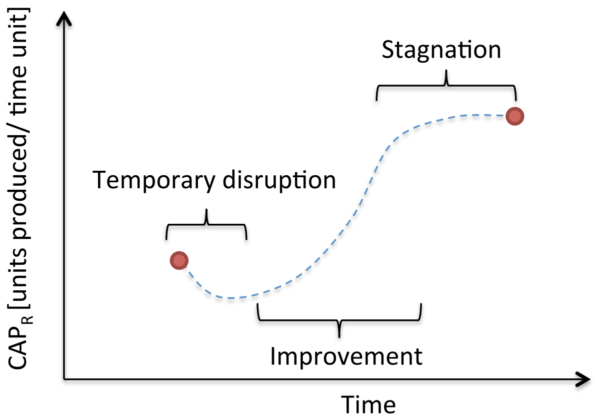

Figure 36: Real capacity improvement curve based on previous research of learning curve theory

Real capacity improvements are made to achieve performance and utilization rates that correspond to a given standard, i.e. the method design previously explained. However, this development is intended to achieve more than just performing according to standard. That is, building capabilities to continuously improve the firm's production processes that can be used to gain a competitive edge over the firm's competitors.

How human resources contribute to a firm's competitive edge over its competitors has been examined in literature related to manufacturing strategy in the context of the resource-based view (Wernerfelt, 1984). The resource-based view (RBV) distinguishes between resource capabilities that can be acquired and those that are developed internally within the firm. Jay Barney, one of the pioneers of the RBV, argued in the early

Nineties that sustained competitive advantage derives from resources and capabilities that are "*valuable, rare, imperfectly imitable, and not substitutable*" (Barney et al., 2001). That is, all firm's cannot possess these capabilities and they must be difficult to duplicate to confer competitive advantage (Schroeder et al., 2002). The RBV differs from other manufacturing strategy research in several respects. For instance, traditional strategy research does not recognize the importance of proprietary processes that cannot be obtained in factor markets, and it does not explicitly address the effect of competitors imitating successful innovation (Schroeder et al., 2002). That is, the creation of unique resource capabilities through continuous process improvements must be the higher-level purpose of improving a firm's production processes. One criticism of the RBV is that it tells managers to develop and obtain valuable, rare, imperfectly and non-substitutable resources, but not how this should be done (Kraaijenbrink et al., 2010).

This thesis argues that at less aggregate system levels this development can be explained by the progress curve, i.e. how increased capacity rates are achieved. Knowing how the resource's capabilities are developed is also important for cost control, forecasting and strategic planning issues. Also, it would be valuable for managers to understand the variability of learning processes between workers, etc., as well as between processes. Such insights would facilitate resource allocation to certain processes with certain characteristics (Nembhard and Uzumeri, 2000). Table 24 summarizes design areas that relate to human resource development and gives examples of improvements actions.

Table 24: Examples of human resource development actions

Design areas	Improvement actions
Work force training, support & coaching	• First-order learning, i.e. learning by doing (also called informal, behavioural, tacit etc.). • Second-order learning, i.e. learning that is induced by managerial decisions (also called formal, cognitive, explicit etc.). Second order learning refers to production workshops and quality circles to achieve motivation and extend skills among employees. • Enable abilities for handling several types of jobs. • Learning how to use tools and equipment properly. • Work instruction development. Simple and comprehensible documentation. • Enabling continuous support and coaching.
Product & production development	• *Continuous technology investments creates an evolving culture within the firm.* • *Engineering changes.*

There is a fundamental distinction between human resources and equipment for productivity dimension analysis purposes. The method design provides a time standard for activities carried out by manual labour, while the method design for an activity carried out by equipment is not given by a predetermined time system. Thus, ideal capacity cannot be generated with the same industrial engineering technique for activities performed by equipment as human resources.

Productivity analysis of equipment

Equipment's ideal capacity is product-specific and depends on the properties that are required by the process' customers. For instance, a metal-cutting activity can be performed with different cycle times depending on the cutting tool that is used. The tool itself has restrictions on cutting speeds and feed depths. The tool in association with the cutting parameters used will affect the result of residual stresses, tool wear, surface finish, etc. Thus, the ideal capacity for processes that include equipment is a result of previous experience, the type of equipment and techniques that are used, and current process knowledge in association with customer requirements. All those parameters can be related to the creation of unique resource capabilities.

Furthermore, this implies that ideal capacity must be established for every requested capacity and that the established ideal capacity is valid only for the equipment's current machining parameters. Finally, ideal capacity should be established only in stable material processing environments. Thus, there is a difference between optimization and idealization of a process performed by equipment. Process or production engineers can optimize a machining process by changing those machining parameters. A process' ideal capacity describes only the throughput rate for a stable current state. Furthermore, equipment is, with a few exceptions, operated by human resources. This means that a semi-automatic process' practical capacity is determined by the utilization and performance rates generated by the *process design* in association with the activities carried out by human resources for preventive and corrective actions, preparation tasks, and monitoring, etc. Figure 37 presents a process map for a semi-automatic production process. It is evident that the process' real capacity depends on the operator's (R_3) capability to operate the equipment.

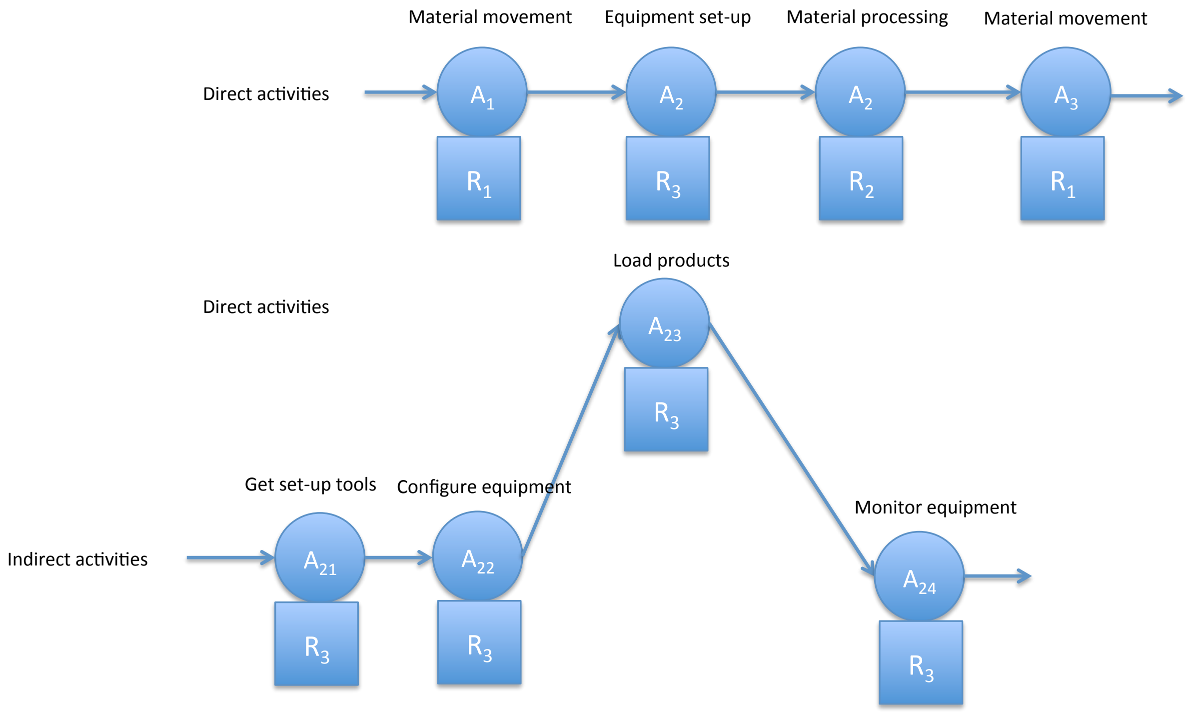

Figure 37: Process map of a semi-automatic production process

Compared to human resources, equipment has only two states – either it is on and directly contributes to material flow (direct activity), or it is off and does not contribute to material flow. From an industrial engineering point of view, it is difficult to understand specific process parameters (direct activities), such as internal tool changes, or material transportation within the machining process. However, understanding the causes of activities that do not contribute to material flow is many times more important than optimizing the equipment's process parameters. For instance, lean practices such as Just-In-Time (JIT) and continuous flow production involving quick changeover methods are the most frequently used practices addressed in the substantive literature in the context of high-performance lean manufacturing (Shah and Ward, 2003). These practices apply especially to avoidance of waste activities (i.e., non-material movements), suggesting that the primary focus should be on process or system design and human resource development.

Nevertheless, equipment's performance and utilization rates are essential to providing requested capacity levels to satisfy customer requirements. A productivity analysis can be performed with the same set of variables as are used for human resources.

Performance rate (P) losses are direct work content achieved with a lower throughput rate than the throughput rate yielded by the process' ideal capacity. The decomposition of performance into skill-based and personal-based rates is not valid for equipment since it cannot be taught or motivated to perform better. However, according to available research of machine efficiency, typically performance losses are referred to as ramp-up time or ramp-down time (Dal et al., 2000, Muchiri and Pintelon, 2008). Ideal capacity must, however, include this type of loss in the standard, since the process requires ramp-up and ramp-down time. This is typically a process optimization issue and thus regarded as a method design improvement rather than a performance loss. Thus, performance losses do not exist in a stable machining processes. The only performance losses that can actually be observed are losses caused by inexperienced operators who deliberately operate the equipment with a reduced throughput rate than the standard, or by the fact that no standards currently exist, which implies that there is no stable process. In fact, the performance parameter of equipment exists only to highlight operators' capability of running the equipment according to standard, or on the contrary, their genuine knowledge that the equipment should be run at lower speeds due to deficiencies in the input material or other deficiencies that might require a lower throughput rate to be quality approved.

System design utilization rates (U_S) are primarily set-up time, waiting time, balancing losses between several workstations and waiting due to completion of orders. Waiting for operators is also a U_S contributor if the system is designed in such a manner that the human resource is the bottleneck. Other typical system design losses at the workstation level are those caused by the human resource that operates the machine. The most oft-recurring U_S loss is waiting time due to an operator's lack of attention. System design utilization rate losses cover all losses for preparing equipment online, i.e. requiring the equipment to stand still.

Need-based utilization rates (U_N) refer to the portion of time needed for service and maintenance actions during planned production time. That is, both preventive and reactive maintenance and service actions. Whether planned maintenance and services are carried out during planned production time is an open question. However, available capacity will be affected, since the resource will be occupied for a period of time. More importantly, equipment utilization rates that evidently present a large portion of need-based utilization losses indicate a problem with the process technology itself.

Disturbance-based utilization rates (U_D) refer to stop time caused by equipment breakdown such as tool breakdowns, program errors, measurement errors, etc. Disturbance-based utilization losses will always exist due to variations in the raw material, tool life, lubricants used in the process, etc. It thus difficult to identify the root cause problem for disturbance-related utilization rates. Table 25 summarizes performance and utilization rates for equipment.

Table 25: Summary of Equipment productivity dimensions

	Variable	Explanation
P	Equipment performance rate	The equipment's operating status (condition) might be affected by wear and tear caused by cumulative production that affects the performance rate. Nominal performance rates are set in stable production environments.
U	Need-based utilization rate (U_N)	Need-based utilization losses are the portion of time that equipment is idle due to planned or unplanned service & maintenance actions.
	System design utilization rate (U_S)	System design utilization losses are those incurred by setups that require the equipment to be idle for a period of time, etc. Another typical problem is that time equipment is idle due to waiting for materials or operators.
	Disturbance-affected utilization rate (U_D)	Disturbance-affected utilization rates refer to downtimes due to tool wear (tool lifetime), defective input materials, utilities breakdown or unsatisfactory quality of other support material.

Equipment development

Technical modifications can be made to improve the process design. However, the utilization analysis' primary purpose is to analyse the human-related activities that need improvements. For instance, improvements should focus on the maintenance and service processes that are performed by service technicians if equipment presents a high portion of need-based utilization losses. However, the root cause of the problem might be the current technology itself. But improving the corrective actions carried out by the maintenance personnel will result in increased real capacity. Table 26 presents some typical equipment improvements.

Table 26: Examples of equipment development actions

Design areas	Improvement actions
Maintenance and service	• Improve related maintenance and service processes and facilitate these processes with supportive tools and equipment
Technical modifications	• Fixtures to simplify setups • Facilitate setups with supportive tools and equipment
Continuous improvements	• Continuously monitor and follow-up equipment performance, i.e. implement manufacturing execution systems (MES) to facilitate follow-up procedures.
Product design	• *Align design management with process management*

5.4 The revised performance frontiers (RPF) theory

Productivity improvements were described from an industrial engineering point of view in the previous section. That is, how to find productivity potentials and what these productivity potential-related improvement design areas are. An essential problem, however, has still not been discussed. For practitioners, the fundamental problem is how improvements should be implemented. For instance, a production system may consist of several production lines that provide a mix of products that subsequently satisfy various markets. Hence, which production process should be improved with the knowledge about the system's inherent deficiencies and how should these improvement investments be made?

The essential core of this problem is of a strategic nature (see Chapter 2.2). A pioneer in this field is Wickham Skinner, who called in 1969 for a coherent design around strategically-based objectives by viewing the production system as a key element in a firm's business strategy (Skinner, 1969). However, Skinner's basic set of ideas of *manufacturing in the corporate strategy* (MCS) has been challenged by others, building foremost on cumulative capabilities rather than trade-offs between them (Clark, 1996). Instead of regarding strategic choices as static options, recent research has adopted a dynamic standpoint by involving trade-offs through selection, development and exploitation of superior capabilities (Hayes and Pisano, 1996). Today's research has more or less refined the concepts that were presented in the late Nineties. The main focus has been on testing and validating the original theories rather than developing new theories (Schroeder et al., 2010, Rosenzweig and Easton, 2010, Sarmiento et al., 2008). There are also examples in which manufacturing strategy theories have been adapted and extended to adjacent research areas, for instance Supply Chain Management (Seuring, 2009).

This section provides a synthesis that bears upon the theory of *performance frontiers* presented by Schmenner and Swink (1998), which has been further discussed and developed by Vastag (2000). The theory itself was not entirely new. The same theory had been used under various names, such as *the production function* or *the trade-off curve* (Schmenner and Swink, 1998). The theory posits that a factory can have "*a maximum performance,*" given a set of operating choices (Schmenner and Swink, 1998). The performance frontiers are aggregate trajectories based on lower item-level measurements, such as product cost and investment in training. The performance frontiers theory provides an aggregate framework for facilitating strategic decisions. Aggregation is of vital importance in strategic decision-making processes. Otherwise, the decision process risks getting lost in details and never succeeding in presenting the big picture necessary for choosing a correct strategic path (Vastag, 2000).

This synthesis also discusses the content of the frontiers and its implications for theory and practice, which are generally more aligned with those presented by Vastag (2000) than those presented by Schmenner and Swink (1998). The theory developed in this thesis is referred to later as the *revised performance frontier theory (RPF),* while the theory presented by Schmenner and Swink (1998) is referred to as the *original performance frontier theory* (OPF).

5.4.1 Assessing performance frontiers with productivity dimensions

This synthesis is performed at two abstraction levels: single production processes (process perspective) and multiple production processes (system perspective). The process perspective describes the fundamentals of the RPF theory. The system perspective describes a higher abstraction level. Conclusions that can be drawn at the lower level of abstraction may not be valid at the higher level due to the production system's inherent complexity compared to the single production process. The system perspective thus explains the RPF theory's limitations. The production process' resources determine the synthesis' abstraction level. The system perspective is adopted if the production system's resources are regarded as shared between two or more production processes. The alternative process perspective is adopted when the production system's resources are regarded as isolated from the surrounding production processes. The process perspective is discussed first, followed by the system perspective.

Process perspective

The RPF theory is aligned with Skinner (2007) and Vastag's (2000) concept that a production system is structurally and infrastructurally constrained. The theory presented by Schmenner and Swink (1998) explained that these frontiers were formed by choices of plant design and investment (asset frontier), as well as choices of plant operations (operations frontier). The distinction between process and system perspectives has implications for the theory presented by Schmenner and Swink (1998). These implications are discussed in the following section.

The operating frontier

Two distinctions can be made with previous research using previously stated capacity definitions (Table 20) and the productivity dimensions model presented in Chapter 5.3. First, the infrastructural constraint corresponds to a defined production process' ideal capacity (CAP_I). Ideal capacity is determined by the production process design and the surrounding production system design, which include production policies such as production flows, layout considerations, planning sequences, etc. Consequently, ideal capacity would represent the operating frontier for a defined production process that contains no losses. As stated, ideal capacity is defined as a throughput rate (units produced per time unit). This capacity rate can be assessed with different performance measures, such as quality, speed and cost. However, cost is regarded as one of the competitive priorities, and as such it is a function of investments in equipment and the production system itself and should thus be included in the performance dimension (Vastag, 2000). This thesis argues that ideal capacity is suitable as a proxy for manufacturing performance, since capacity defined as a throughput rate is the result of the interaction between these performance dimensions. Furthermore, Vastag (2000) depicts the performance frontiers as functions of *manufacturing inputs* (index of manufacturing practices). This approach is found to be somewhat vague, since it is difficult to establish causality between what Vastag (2000) refers to as *manufacturing inputs* and corresponding *manufacturing performance*. The second distinction is to use *time* as a proxy for what Vastag (2000) calls manufacturing inputs. Time will not in itself change a production process' ideal capacity. However, the cumulative production volume during a period of time along with explicitly induced improvement actions will affect the ideal capacity.

Accordingly, the operating frontier for a single production process can be depicted as in Figure 38. The vertical axis in Figure 38 represents *process capacity* while the horizontal axis represents a time period. During this time period, improvement actions are taken to step up the frontier that results in increased throughput rates for the production process. The operating frontier thus reflects improvements (or changes) over time regarding the ideal capacity. This approach can thus be used as a historical review of a production process development or as a prediction of a future development scenario based on previous experience and knowledge of similar progress curves.

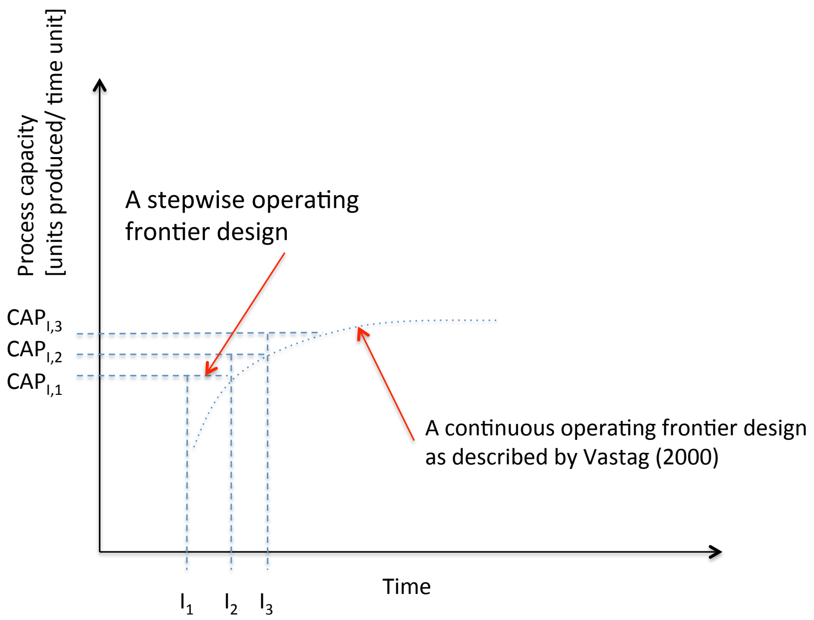

Figure 38: The operating frontier is represented by CAPI

The shape of the suggested process' operating frontier follows the same trajectory that planes down with cumulative improvement actions as described by Schmenner et al. (1998). However, it is argued that the progress curve improves step-by-step rather than continuously. I_1, I_2 and I_3 refer to improvements of the production process' method design. Each design improvement is implemented at one point in time that consequently increases the production process' ideal capacity stepwise. The trajectory path (small dots in Fig. 38) implies that method design improvements are initially easy to achieve by picking *low hanging fruits*. However, as the method design gradually improves, it becomes more difficult to realize improvements that consequently demand additional resources for further improvements and follow the law of diminishing returns. For instance, the first method design improvement (I_1) may be achieved through use of an aggregate pre-determined time system analysis method such as SAM. This method is relatively fast and covers the big method design improvements. However, as the method design improves, less aggregate PTS analysis methods are required, such as MTM1, MTM2 or MTM3, which need additional time consumption and a higher level of expertise to achieve additionally improved method designs.

A process utilization analysis compares the production process' ideal capacity (CAP_I) with its real capacity (CAP_R), i.e. its measured output. Improving a production process' real capacity is, as previously discussed (see Chapter 5.3), accomplished with two options. The first option is to improve the method design (M). The second option is to improve the resource's capability of performing the production process' activities according to the given standard. Method design improvements are equivalent to an *engineering change* of the production process (Fig. 39). Improved resource capabilities are referred to as *workforce training* (Fig. 39). Figure 39 uses an equivalent progress curve for real capacity as described in Chapter 5.3.2.

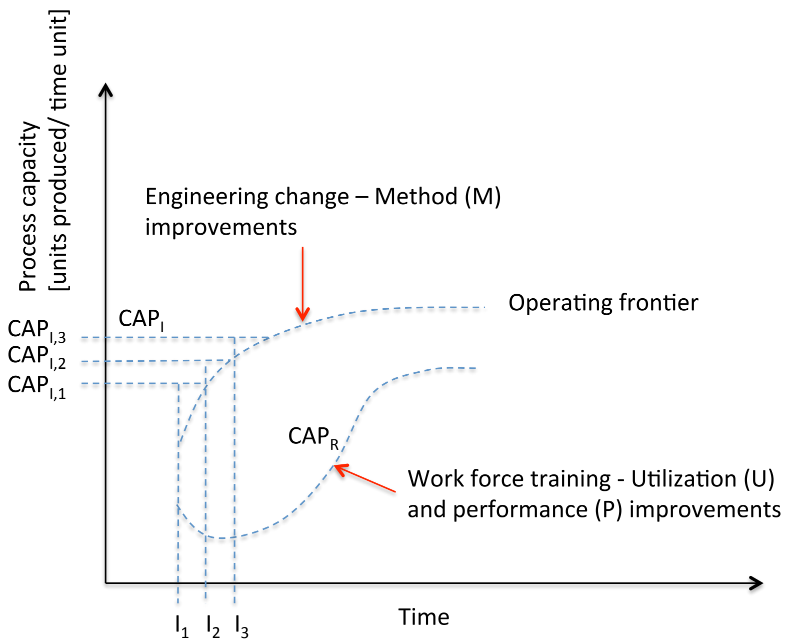

Figure 39: The operating frontier improves with engineering changes and the real capacity progress curve is affected by these changes, as well as explicitly induced workforce training.

From a process perspective, workforce training serves as means of increasing process utilization, i.e. the utilization (U) and performance (P) parameters. The aim of these improvements is to reduce the distance to the operating frontier (Fig. 40). An exception can also be added to Figure 40. In practice it is possible to achieve throughput rates higher than ideal capacity, since human resources can perform faster than the process' corresponding normal speed. However, the general aim of workforce training is to reach the process' ideal capacity. Figure 40 also depicts engineering changes. The real capacity curve is to follow the progress curve previously explained, most likely with an initial drop as described by Adler and Clark (1991). This implies that each engineering change corresponds to a temporary process utilization loss that is reduced along with cumulative production volumes.

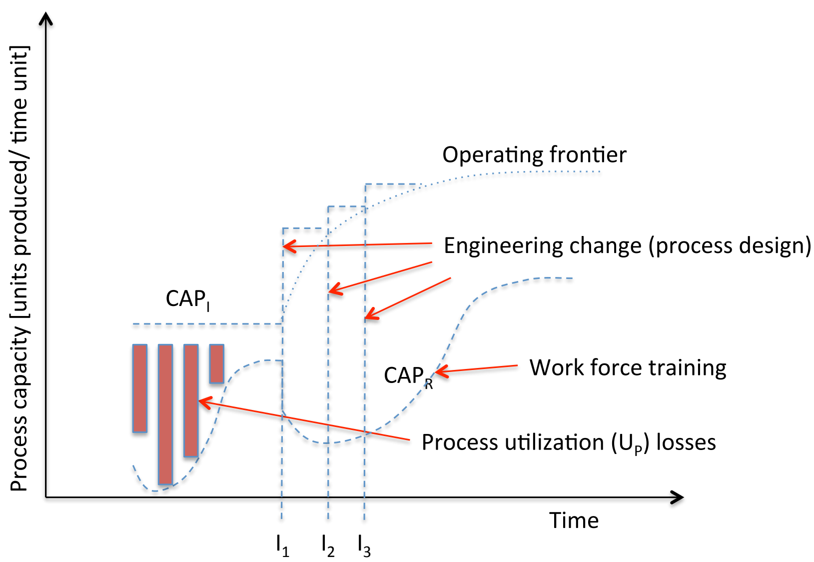

Figure 40: Increased real capacity (CAP_R) is achieved through engineering changes, workforce training or both simultaneously

A production development process measured as output per time unit may thus be plotted on a process capacity-time graph (Fig. 40). The result of this development depends on several factors, including learning effects, firm characteristics, technology adoption and scale effects. Figure 40 refers only to workforce training and engineering changes to existing assets, i.e. real capacity improvements achieved without investments in new assets.

The asset frontier

The OPF theory explains that the asset frontier corresponds to a production system's physical and technological constraints and consequently its theoretical maximum capacity. However, previous capacity definitions and explanations used in this thesis imply that it is not possible to determine a production process' capacity unless the activities that the process' resources are allocated to perform are known. Otherwise, the only measurable capacity is the resource-related *utilized capacity* (CAP_U). Vastag (2000) agrees and asserts that "*the asset frontier only exists on paper*". Indeed, the imaginary asset frontier can be increased by investments that would typically show up in the fixed asset portion of the balance sheet. That is, in theory the asset frontier will be increased due to the theoretical capacity increase that the investment can generate during the same processing time as the old equipment was subject to. Thus, the asset frontier would represent the imaginary *one-best-way* to produce a product or a service with current fixed assets.

However, the fundamental problem with this standpoint, which also mitigates against the asset frontier that Schmenner et al. (1998) proposes, is that it is impossible to establish. It is irrelevant to discuss an imaginary capacity that a production system may or may not have, since that is based on a perfect product or service that enables all activities to be perfectly designed to permit all resources to perform at the top of their available capacity and capabilities. In turn, this capacity should be equivalent to the most profitable fulfilment of customer requirements.

More importantly, imaginary capacity does not help managers make better decisions, since it does not provide any useful practical information. It is thus irrelevant to talk about an asset frontier measured as an output or equivalent process performance measure, since it does not exist. However, the possible advantage of depicting an asset frontier is to enable a comparison with competitors, i.e. to benchmark a firm's assets against its competitors. The value of such a comparison is interesting for investment considerations, for instance if the firm's current assets are competitive enough or if the firm needs investment in technology to gain superior competitive advantages. Nevertheless, it is argued that this type of fixed asset analysis is fundamentally different from the capacity analysis that can be carried out with the RPF theory described in the thesis. The asset frontier analysis is aimed at investment decision in new assets, and the capacity analysis is aimed at investments in existing assets.

Consequently, instead of plotting the imaginary asset frontier, it is suggested to plot how production process improvements affect the production system in terms of resource utilization and resource availability. This analysis enables more relevant information for decision makers regarding a firm's existing assets. A second graph must thus be constructed to plot utilized capacity (CAP_U) instead of ideal and real capacity as a function of time. Figure 41 depicts how a defined facility view (workstation, subsystem or factory) utilizes its resources.

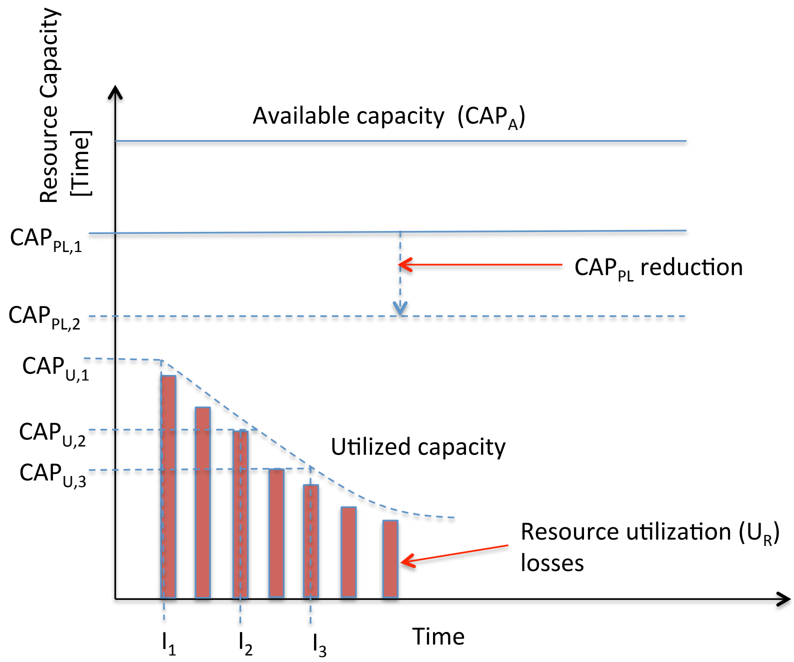

Figure 41: Utilized capacity is plotted as a function of time.

A production process improvement that yields a throughput rate increase through an engineering change or workforce training will reduce the time allocation necessary to meet current requirements, i.e. the planned capacity for a certain production task will be reduced from (as an example) $CAP_{PL,\ 1}$ to $CAP_{PL,\ 2}$ (Fig. 41). Utilized capacity will, however, remain at the same level if real capacity increases are achieved without upgrading the firm's planning system. That is, the firm's resources will be idle due to the improvement and the utilized capacity will thus consist of increased system design utilization rates (U_S). If the planning system is upgraded, it will subsequently lead to increased resource availability (CAP_A-CAP_{PL}). Freed-up resources can be used for other production processes, alternatively enable adoption of more competitive production polices (trade-offs).

Trade-offs

The OPF theory explains that trade-offs are faced when a firm is approaching its asset frontier. However, the law of trade-offs must be treated differently since the RPF theory argues for abandoning the asset frontier.

First, trade-offs are not apparent until a system perspective is considered, i.e. the production process' resource must be considered as shared. Trade-offs primarily concern how requested capacity should be met (Skinner, 2007). That is determined by the production policies employed by the firm as a consequence of its current production strategy. The most obvious example is production batch sizes. Ideal capacity will be reduced if small production batches are processed due to increased setup time in comparison to processing time, given that the set-up time remains constant independent of batch size. In that sense, the operating frontier will be lower due to a policy change decision but still be represented as the ideal capacity for the new standard. This is depicted in Figure 42.

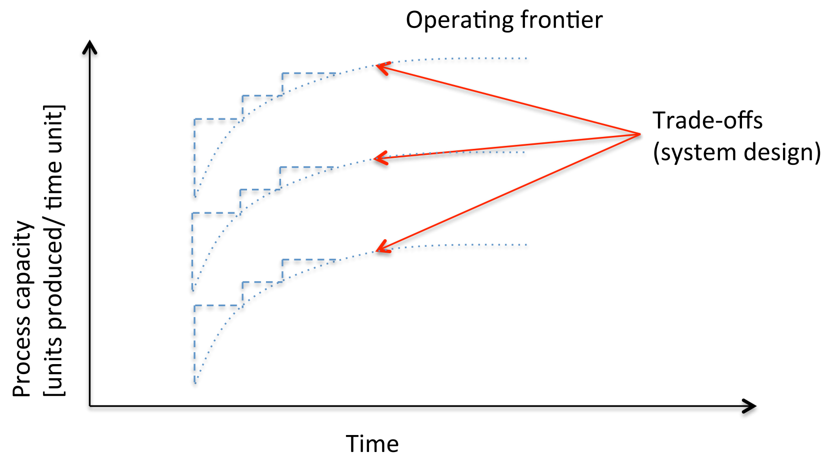

Figure 42: The operating frontier is altered up and down due to production policy changes.

For example, assume that a customer requires 365 units per year. A firm can handle this request in several ways. At one extreme, all units can be produced in one single batch. Alternatively, each unit can be produced within a one-piece flow production system. This is a production policy trade-off, and the decision has implications for the production process' ideal capacity by altering its location in the process capacity-time diagram (Fig. 42). Modig and Åhlström (2012) refers to this trade-off scenario as the *efficiency paradox*, resource efficiency (focus on costs) versus flow efficiency (customer focus).

Trade-offs will also affect utilized capacity within a defined factory-view. Utilization losses are described as disturbance-based, need-based and system design utilization rates. Process improvements through engineering changes and work force training affect all of these variables. Trade-off changes primarily affect system design utilization by including or excluding activities within a production process. The effect on a production process' real capacity due to policy changes are thus difficult to accurately determine.

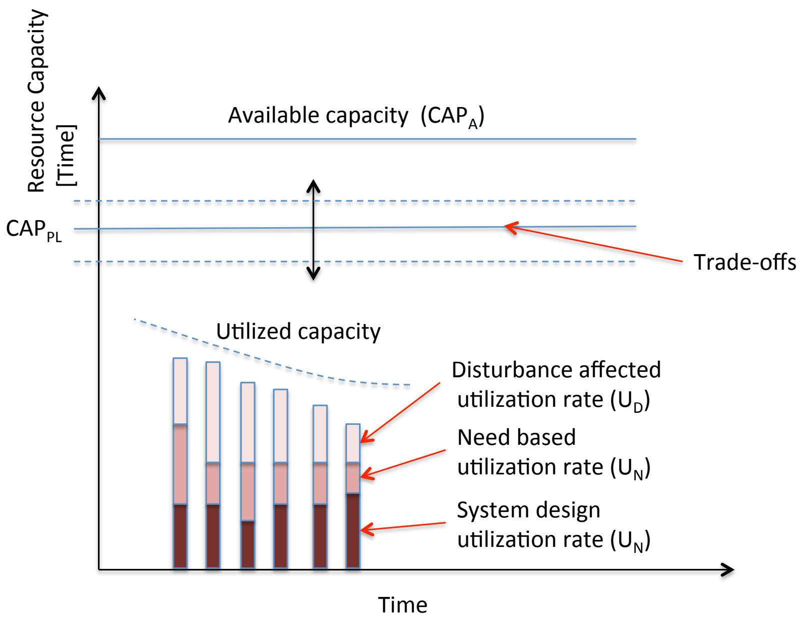

Figure 43: Production policy changes (trade-offs) affects utilized capacity

From a process perspective, system design utilization rates can be disregarded. As a consequence, utilized capacity curves as in Figure 43 are suggested to follow an equivalent improvement curve as the process' real capacity improvement curve. From a system perspective, system design utilization rates are included. This has implications for a defined factory view's progress curve and is discussed in the next section.

The RPF theory should be used in consideration of the capacity that customers are requesting, when, and how much are they willing to spend for that capacity. By understanding these issues, a firm's production system can be designed to meet requested capacity, now and in the future. Accordingly, production managers should make decisions based on their knowledge of the market in which they operate and knowledge of their current production system capacity and how it will be affected by a production policy trade-off, etc. It is thus evident that a manufacturing strategy without a market focus, or without alignment with a business strategy cannot be successful, since these trade-offs depend on it. The operating frontier can be explained from a process perspective as a function of the production process design and the production system design (trade-offs), and the manufacturing strategy should determine how both of them are to be designed or redesigned.

System perspective

The OPF theory's strength is its ability to aggregate item level performance measures to performance frontiers that act as a means of facilitating decision-making (Vastag, 2000). A central aspect is thus to enable the RPF theory to represent multiple production processes within the same operating frontier. However, the system perspective provides limited analysis possibilities for several reasons. These reasons are discussed below.

Building on previous explanations of a single process' operating frontier, is it possible to aggregate several processes' operating frontiers ($CAP_{I, process}$) to one system frontier ($CAP_{I, system}$)? The relatively simple answer is yes. By definition, each defined single production process corresponds to one ideal capacity. Putting these processes together into a system can be modelled the same way as single elements are sequenced and arranged to form a single production process. The production system design problem would thus be to balance each process' ideal capacity so that each single process' corresponding requested capacities are met. Figure 44 depicts a production system that includes three production processes. The system's ideal capacity is determined by the processes' ideal capacities.

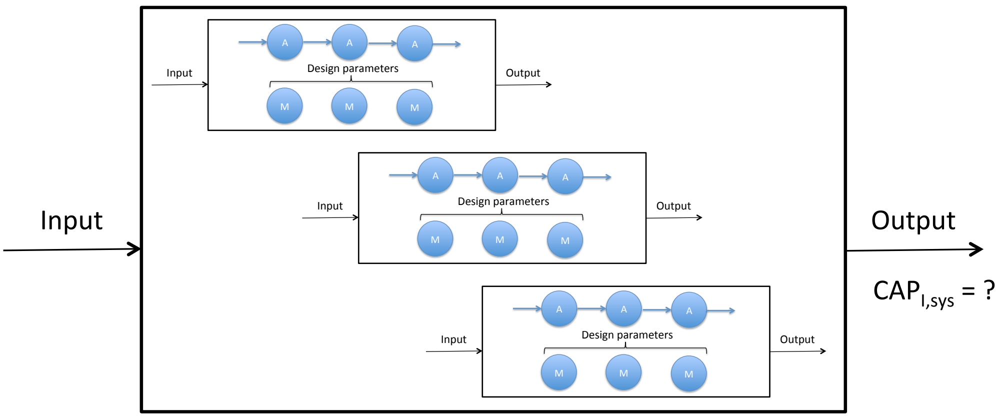

Figure 44: A system's ideal capacity (CAPI, sys) is determined by its set of single processes' ideal capacities ($CAP_{I1, I2, I3}$).

However, in reality the production system's resources (humans, equipment, and supporting IT systems etc.) will randomly fail to conform to each process' ideal capacity and thus to the system's ideal capacity. For instance, equipment always experiences random breakdowns, labour induces variations in the production system, input material is of random quality etc. These variations together lead to the complex phenomenon termed *perturbation propagation* (Li and Meerkov, 2009). This phenomenon describes how throughput is lost through starvation or blockage of production processes and how these propagate upstream or downstream in the production system. This type of problem is referred to as a queuing problem and is a key element in discrete event simulation (DES) models. Discrete event models focus on modelling production systems in detail and demand input distributions based on collected or measured data (Siebers et al., 2010).

The RPF theory enables an alternative approach for analysing problems related to production system design. Instead of analysing the system's ideal capacity and how its configuration affects the production system's performance, the suggestion is to explain how the production system's real capacity is affected by the production system design. As previously described, the only measurable losses at a system abstraction level are utilization losses (U_S, U_D and U_N), since performance losses can be measured only if the production system's ideal capacity is known. From a system perspective, it is thus that resource capacity be analysed instead of process capacity, which consequently neglects performance issues and thus limits the analysis.

A system perspective is adopted when production processes' resources are regarded as *shared*. A shared resource implies that two or more production processes can affect each other, depending on their resource consumption rates. For instance, a shared resource may be occupied with problem-solving activities related to one production process, when it is actually scheduled for performing activities that correspond to a second production process. Naturally, this affects the second process' output negatively.

A resource capacity analysis from a system perspective can be carried out with two options (see Chapter 5.3.1). Option one considers a set of production processes by analysing the average utilized capacity corresponding to each of the system's single production processes (*production process-based resource analysis*). The second option considers a set of production processes by analysing the average utilized capacity corresponding to a specific facility view, e.g. the workstation view or the subsystem view (*facility view-based resource analysis*). Figure 45 depicts a production system consisting of three production processes that pass through three defined subsystems.

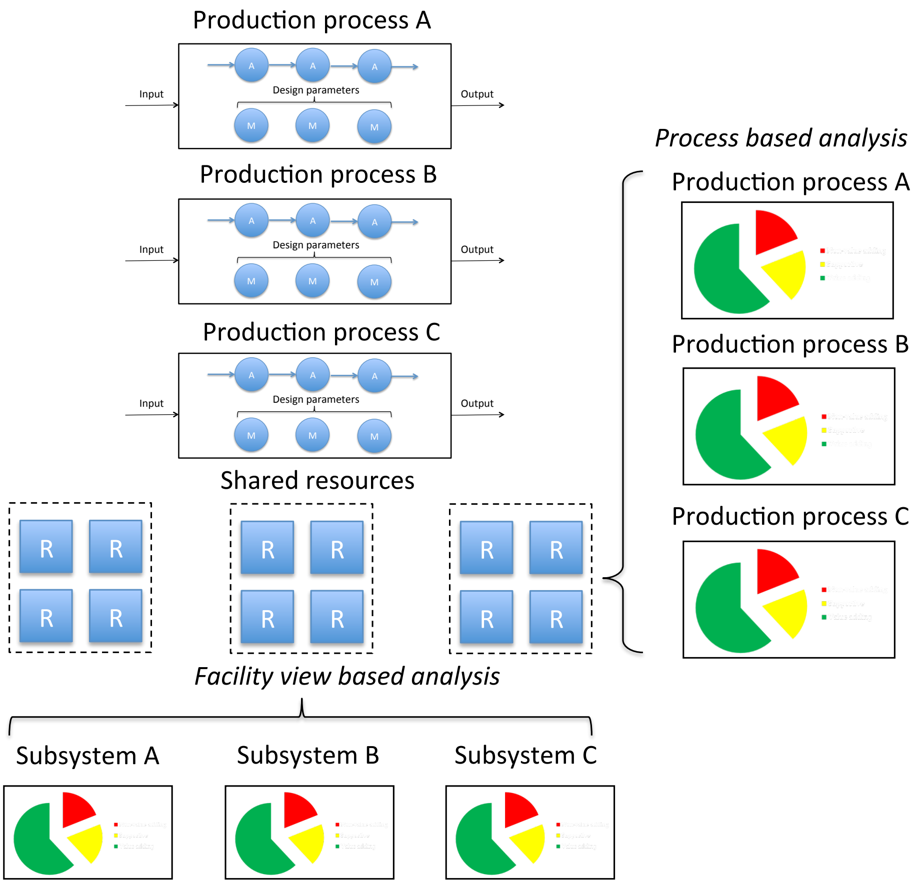

Figure 45: Utilized capacity can be analysed with two options from a system perspective: production process based or facility view based. The circle diagrams are the utilization analysis' results

The first option is equivalent to analysing the utilized capacity that corresponds to a single production process. The analysis can be repeated for each of the system's set of production processes (A, B and C). Each production process corresponds to a product or product family that in turn corresponds to a progress curve as described in Figure 41. The production process may be performed through several facility views, e.g. several workstations or several subsystems, as determined by the production system design. This analysis thus provides information on how the system design influences utilized capacity for a certain production process in terms of alignment of several workstations. This analytical approach also enables different products or product families to be mapped in the same figure (Fig. 46).

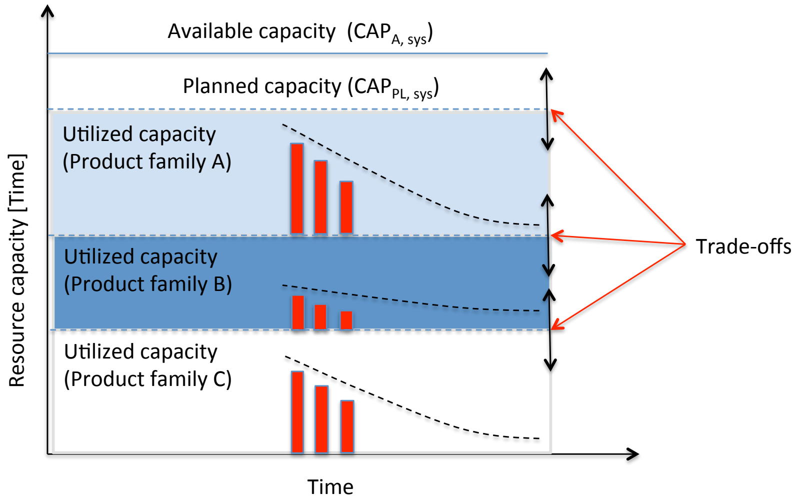

Figure 46: A utilized capacity analysis of multiple production processes

From a system perspective, system design utilization rates (U_S) refer to either balancing losses between the system's production processes or idling due to disturbances caused by the surrounding production processes. Need-based and disturbance-based utilization rates are difficult to consider from a system perspective, since surrounding processes' influence is unknown. The root cause of a utilization loss caused by its surrounding processes is difficult to determine due to the fact that there might be several reasons for it to occur. For instance, an evident U_S loss in production process A might be disturbance-related, need-based related, performance related, or related to system losses that have propagated either upstream or downstream the value chain from production process B or C. This is thus a critical limitation of the process-based capacity analysis option. Accordingly, the process-based resource capacity analysis provides results of how the production process itself contributes to system utilization losses through disturbances, alternatively to what extent the system design contributes losses that affect the production process. The results are important for product design considerations. For instance, a single production process may cause significant disturbance-affected utilization rates, while surrounding processes that share the same resources do not cause similar losses, indicating a product design problem.

Figure 46 also presents valuable information regarding long-range planning issues. Depending on the time frame, the figure presents the planned resource capacity for a certain product family or a single product. Planned resource capacity can thus be compared with current and future requirements. A production process improvement or a production policy improvement that leads to reduced resource consumption rates can be used to cover increased requirements. The most important consideration refers perhaps to how production policy changes affects utilized capacity. At the system level, this is difficult to answer. From a process perspective, it is clear that there is a relationship between real capacity improvements and utilized capacity improvements, i.e. as real capacity increases, utilized capacity increases. However, production policy trade-offs may affect utilized capacity both negatively and positively. Striving for reduced lead-times by means of production policy changes will most likely initially affect utilized capacity negatively, since it focuses on the product instead of the resources producing it. Advantages and disadvantages of the production process-based analysis option are listed in Table 27.

Table 27: A production process-based resource capacity analysis

Advantages	Disadvantages
• **The analysis provides insights into the production system design in terms of alignment of various factory views (e.g., workstations or subsystems)** • **Problematic production processes are highlighted.** • **Each product/product family can be thoroughly analysed, providing detailed feedback to R&D functions regarding product design considerations** • **Economic considerations can examined in reference to each product.**	• Difficult to derive the source or the root cause of system design utilization losses. • No clear relationship between utilized capacity progress curves and production policy changes (trade-offs)

The second option is equivalent to analysing the utilized capacity that corresponds to a defined facility view (Fig. 47). In contrast to the production process-based capacity analysis option, the facility view-based option provides insights into how the aggregation of production process (i.e. product mixes and production policy considerations) contributes to utilization losses within a defined facility view. There are two advantages of the facility view-based option over the process-based option. First, the effect of the employed production policy will be analysed for each facility view, i.e. how well the employed production policies enable the production system resources to be used efficiently. The second advantage is that improvements made within a subsystem, etc., may affect all production processes within the subsystem. In comparison, a specific process improvement may not affect other production processes. The disadvantage of this option is that a single production process' contribution to system utilization losses is not considered.

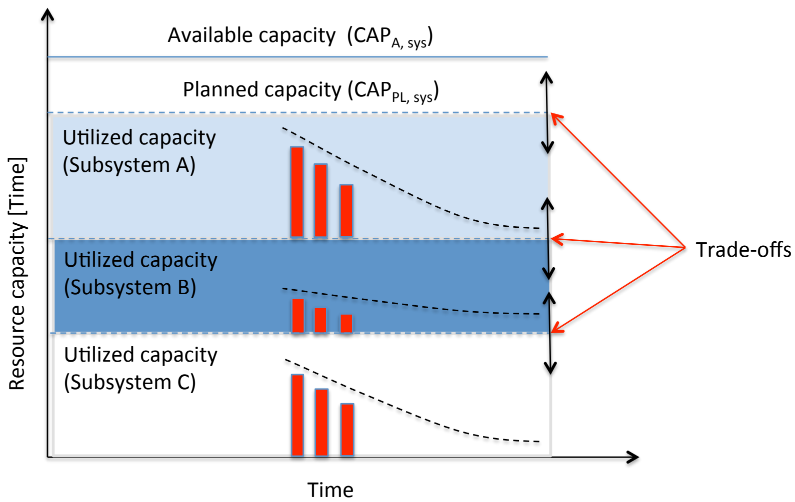

Figure 47: A utilized capacity analysis of three subsystems

The second option is, however, more suitable for analysis of higher abstraction levels (e.g., from a system perspective). The main reason is that the option includes consideration of the production policies that affect all production processes, not only a single process as in the process-based option. Advantages and disadvantages of the facility view-based option are listed in Table 28.

Table 28: A facility view-based resource capacity analysis

Advantages	Disadvantages
• **Provides insights into the production system configuration's (CAPI, SYS) effect on the defined facility view. System design errors can be identified.** • **Resource focus – The average waste distribution is discovered by analysis. Parts of the system that are underutilized will be highlighted.** • **An improvement affects all production processes within the defined factory view.** • **Economic considerations can be made with reference to each facility view.**	• Reduced process focus. • Difficult to calculate investments, since each product must carry expenses associated with these improvements. The economic improvement is most likely unevenly distributed among the product that the limited production is producing.

5.4.2 Decision support

The RPF theory is an aggregate framework of production laws, relying foremost on the *law of bottlenecks*, the *law of diminishing returns* and the *law of diminishing synergy*. The RPF theory is thus a theoretical construct based on laws equivalent to those of the OPF theory. The difference between these theories is how the underlying laws are presented in the capacity-time diagram to provide useful information for decision makers. The framework that has been presented in this chapter uses the productivity dimension concept to assess a production system's limitations and abilities. The analysis framework concerns how productivity improvements affect a production system's capacity through the use of progress curves. The capacity assessment can be performed with two options. Option one is an assessment of a defined production process' capacity. Option two is an assessment of a defined facility view's capacity (factory, subsystem or workstation). The framework reveals the productivity potential by using a set of industrial engineering tools and techniques with the purpose of measuring the production process' or the facility view's real capacity. The real capacity analysis presents productivity losses in terms of resource utilization from a production system perspective. From a production process perspective, it is possible to additionally analyse performance losses. Aggregation is, however, a necessity in decision-making processes that consequently lead to a trade-off between the detail level of the capacity analysis and the abstraction level of production system. A high level of production system abstraction results in less detailed results and a low level of production system abstraction results in more detailed results.

Sarmiento et al. (2008) discuss three problems related to the OPF theory: difficulty in making fair assessments internally and externally, as well as how phenomena taking place inside the frontier's boundaries should be measured. The analysis framework presented here solves these problems. The strength of this analysis framework is its usage of well-known industrial engineering techniques to define a production process' operating frontier and to assess the current state situation for a production system. The analysis framework can be used to continuously follow production investments over time, and predictions can be based on progress curves relying on *learning curve theory*.

The RPF has implications for the asset frontier that subsequently affects the prospect of performing external assessments, i.e. comparison with competitors. From a system perspective, utilized capacity can be measured and compared with competitors. Utilized capacity is, however, one performance measure among several that provide limited information. As described earlier, a firm's employed production policies affect utilized capacity and must therefore be considered when comparisons are made. It is, however, argued that this analytical framework provides valuable information about the processes or facility views that need to be improved, alternatively how production policy changes affect resource utilization.

5.5 Cash conversion cycle

A firm's survival depends on the profits the business generates, and "*decisions that are made today decide tomorrow's results*" (Drucker, 1954). Making wise and economically sound decisions is essential no matter what strategic path a firm follows. Excessive capital or operating expenditures are never desirable, since all improvement efforts are made for creating and sustaining future wealth for the firm's owners, employees and surrounding society. Costs are always a central issue independent of strategic choices, and productivity improvements must address this issue by evaluating the relationship between expenditures on human and physical assets and the related result, i.e. the capacity increase. So far this thesis has been concerned about production system productivity by explaining how it can be analysed and improved with industrial engineering tools and techniques. From an investor (or owner) perspective, it is essential that a proposed productivity improvement is actually beneficial from a financial point of view.

This and the following sections provide a framework for explaining the financial effects of movements within the capacity-time diagram. This section explains how a firm's capital takes different forms and the cost of converting capital between these forms. The subsequent sections describe how productivity improvement actions contribute to financial benefits derived from this section.

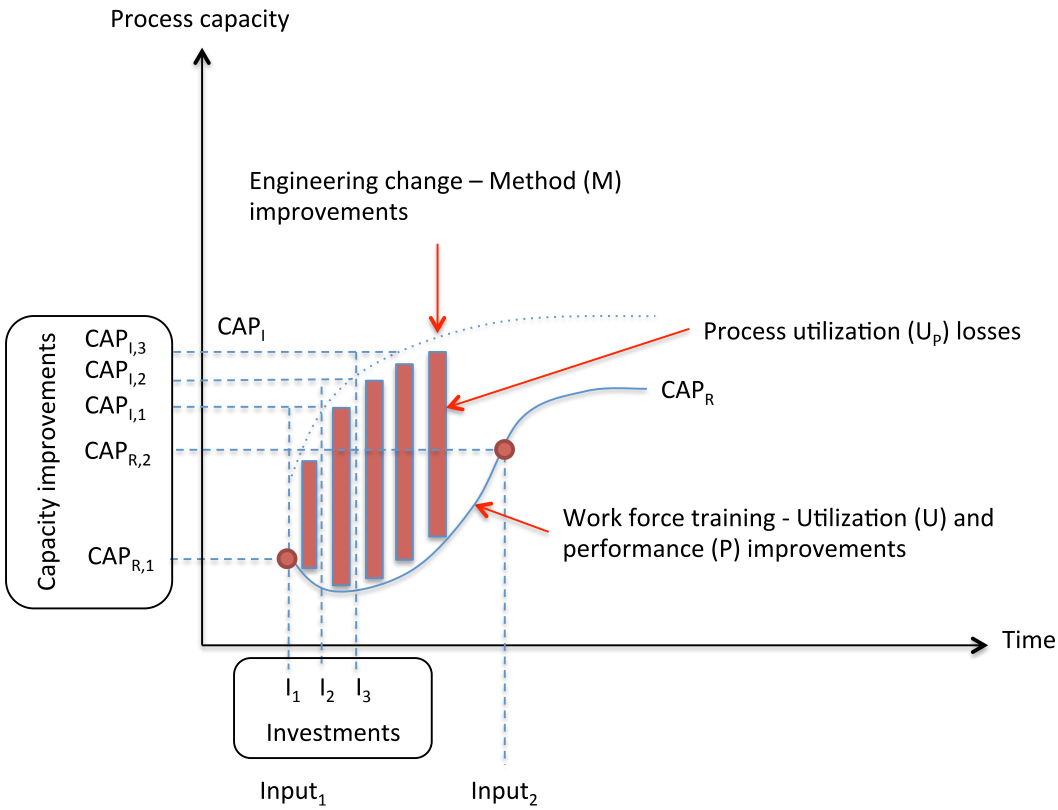

Figure 48: The real capacity improvement must cover corresponding expenses for engineering changes and work force training

Figure 48 depicts a production process' capacity-time diagram. The diagram indicates that there are significant productivity losses in the current production process ($CAP_{R,1}$). Consequently, investments are needed to improve the current state. The future state scenario is expected to provide an increased output rate ($CAP_{R,2}$). A relevant consideration is thus how $CAP_{R,2}$ is achieved and what the financial impact of reaching $CAP_{R,2}$ is.

The movement towards the operating frontier and the alteration of the operating frontier is infrastructurally restricted. That is, it concerns the capital necessary to run the firm. Capital that is necessary for continuing a firm's on-going operations is termed working capital. Historically, businesses have focused on raising and using debt and equity capital, selecting manufacturing technology for running operations, i.e. capital budgeting for structural investments (Sagner, 2010). However, increased competitiveness in most available business segments (global and domestic) have forced firms to consider alternative approaches, such as improving working capital efficiency. This approach is usually referred to as *working capital management* (Sagner, 2010).

5.5.1 Financial effects of working capital improvements

Working capital efficiency can be evaluated with the cash conversion cycle, abbreviated cash-to-cash (C2C) cycle (White, 2006). The C2C cycle explains how many days working capital is tied up in different forms on its way towards value creation. A short C2C cycle indicates high working capital efficiency. Lifland (2010) describes working capital efficiency as a vital component of a firm's long-term survival.

Figure 49 depicts a simplified C2C cycle. The first step (step 1) is cash. Cash is introduced in the C2C cycle to generate returns. This cash is used to buy materials and to pay salaries and other inputs that are required to run the business, i.e. cash inputs (step 2). The next step is business-dependent. A manufacturing firm buys materials to refine or assemble them into products and consequently transform inputs into work-in-process capital. A retailer does not refine materials. Instead, it distributes materials to customers and adds value through services that the business provides. The fourth step in the C2C cycle describes how long refined and assembled products are stored in finished goods. Step 5 is the point in time at which the product or service is sold. However, customers usually have a certain number days of credit, typically 30-90 days, which means that the cash from step 1 does not generate returns until the value of sales has been realized.

A short C2C cycle indicates efficient operations and cash management (White, 2006). Furthermore, the length of the C2C cycle is reduced by the extent to which a firm uses supplier credits. For instance, if a firm's C2C cycle is 100 days and its supplier credits are 30 days, the net cash cycle will be 70 days. A short C2C cycle consequently results in a good supply of short-term cash (liquidity) that reduces the risk of dependency on external and more expensive sources of capital. In accounting, liquidity reflects a firm's ability to cover obligations with cash flows (Farris Ii and Hutchison, 2002).

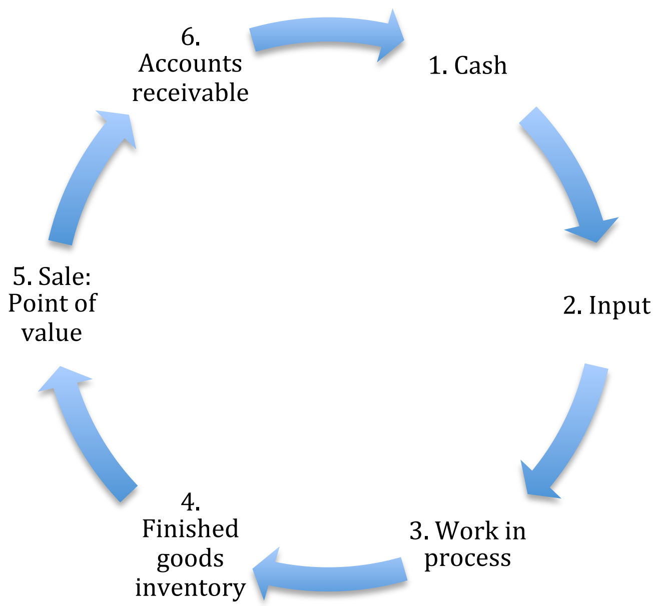

Figure 49: Cash-to-cash (C2C) cycle

Steps 1-6 in Fig. 49 are presented below with the objective of clarifying financial effects of changes to the cash cycle.

Step 1 – Cash

Capital exists in many forms, for instance natural resources, human resources and buildings. Cash is the simplest form of capital due to its tangible value. Cash is furthermore needed to fund any operations. The cost of using cash (capital) is associated with a firm's capital structure and is for that reason not primarily an issue for this thesis. Nevertheless, knowledge of how capital is funded is essential since it is necessary to apply for economic means for initiating investments of any kind.

Cost of capital can be defined in several ways, but cash-flow derivatives are generally used (Groth and Anderson, 1997). There are two main sources of capital: debt and bonds. Debt capital refers to loans from creditors and bonds refer to capital provided by shareholders (equity capital). Debt capital is usually less expensive, since interest payments on debt are tax deductible. Also, creditors claim cash flows from operations before equity holders. Consequently, equity holders are subject to greater risks than creditors. Equity capital is obtained by internally generated profits or issuance of new common stock. Issuance of new stock is more expensive than internally generated funds since it is a subject to legal fees, double taxation and underpricing of stocks (Groth and Anderson, 1997).

The cost of capital can be explained as, "*the minimum rate of return, given the risk, for investing and flowing capital through the business cycle*" (White, 2006). That is, bond and equity holders expect returns from net operating income (earnings before interest and taxes). These holders are owners, banks and other institutions that finance the business. Cost of capital will be expensive if these bond and equity holders expect large returns. The cost of capital will also be high if bond and equity holders believe that the business is associated with high risks. In contrast, high credit ratings and high market values reduce the cost of capital due to improved borrowing abilities (Groth and Anderson, 1997).

Obviously capital providers are exposed to different risks and thus subject to different costs. It is common to calculate the weighted average cost of capital (WACC) when more than one source of capital is used to finance an investment. The purpose of calculating WACC when making investment decisions is to evaluate whether the investment project earnings may cover, or sufficiently reward, all capital suppliers (debt and equity). Consequently, these funds need to be recovered by means of a positive cash flow raised from the specific investment.

A productivity investment is subjected to those requirements as well. The main difference is that a typical infrastructure investment requires less financing than a structural investment that consequently reduces the associated risks. Since this thesis generally suggests small investments, most probably financed by internally generated funds, considerations pursuant to WACC can be disregarded. The same valuation principles are, however, valid for smaller investments financed by internal funds.

The next step in the cash conversion cycle is inputs. The decision to convert capital from cash to another form, for instance materials and labour, is based on risks and expected returns. Capital held on the factory floor is subject to greater risks than holding cash. From a financing perspective, it is advantageous to reduce the time that capital is spent on forms other than cash and thus reduce associated risks of losing returns, for instance through obsolete stock, damaged goods, quality problems, etc.

Step 2 – Inputs

To maintain a business it is necessary to employ capital for workforce salaries and material supplies, i.e. *cash inputs* or resources needed in the production system for producing goods and services. From a risk perspective, it is preferable to reduce the amount of capital tied up in these assets, for instance by reducing the quantity of raw material inventory. In contrast, from a profitability perspective it might be preferable to increase investments in the working capital cycle to facilitate sales (García-Teruel and Martínez-Solano, 2007). Working capital management applies especially to planning and control of materials and labour to reduce time and associated risks for converting capital to forms other than cash. Previous research has found that managers can increase corporate profitability by reducing the number of days of account receivables and inventory to a reasonable minimum (Deloof, 2003). Reduced inventories without consideration of sub-sequent production processes may cause a sub-optimized future scenario. For instance, a quantitative reduction of raw material inventory may result in stock-outs and consequently idle operations if requested production processes have fluctuating demands.

Step 3 – Work-in-process (WIP)

Work-in-process (WIP) levels depend on several factors both within and outside the walls of a manufacturing plant, for instance market requirements, production processes and product design. The rationale for keeping WIP at higher levels is variability. Variability exists in every production system and may have an enormous impact on its performance (Hopp and Spearman, 2008). A WIP reduction may frequently be portrayed as an ideal objective, even though achieving it may have results opposite to those originally intended, e.g. increased material handling costs, loss of quantity discounts, increased distribution costs, etc. (Primrose, 1992, Meade et al., 2009). Increased WIP levels result in increased cash outlays, since more material is needed. Reduced WIP levels correspond to reduced material outlays, since re-orders are avoided for a period of time, given a continuous outflow of products or services. The lean production literature places great emphasis on reducing WIP in order to increase service levels, avoid overproduction, eliminate waste, etc. (Schonberger, 2008, Dettmer, 1997). However, empirical findings also indicate that increased WIP levels correspond to increased profitability (Deloof, 2003, García-Teruel and Martínez-Solano, 2007, Thomas and Zhang, 2002). It is explained by those firms' improved ability to meet increased requested capacity. Accordingly, when demand trends shift from rising to falling, profitability follows suit.

Step 4 to 6 – Finished goods inventory (IFG), sales and accounts receivables

Distribution channels and sales operations are outside the scope of this thesis. However, the last step of the cash conversion cycle explains that cash transactions from the customer's account to the seller's account do not occur immediately. This step is called *accounts receivables*, which means that a sold product is regarded as a current asset as long as the transaction has not been recognized as earnings.

A manufacturing firm's cash conversion cycle must consider three stages: raw material, work-in-process and finished goods. The first stage considers the time from purchasing to beginning of production. The second stage considers the production cycle, and the last stage from completion to sold product. Each stage can be estimated with turnover ratios, such as equation 13.

$$Number\ of\ days\ in\ inventory = \frac{Inventory}{COGS} \times 365 \qquad (13)$$

From a production system perspective it is clear that fixed assets have a major impact on the production part of C2C cycle. The next section presents the cash flow issues that emerge from fixed asset investments.

5.5.2 Structural investments and their effect on working capital

Increased investment levels in fixed assets, e.g. investments in more productive and capital-intense machines, aiming to speed up the flow of capital within the manufacturing process are referred to as inclined operational leverage (OLE). Operational leverage is equal to the ratio of fixed operating costs to variable costs. OLE is increasingly not directly subject to an increased risk. Risk is a function of both OLE and the variance in sales. Volatile sales figures will increase risks when more capital is employed in fixed assets that physically deteriorate with time.

Structural investments in new technology are made to increase a production system's ideal capacity, alternatively align it towards requested requirements. In addition to the fact that fixed asset investments will change the system's throughput rate ($CAP_{I,\,sys}$), two other parameters must be considered: depreciation and capitalization. "*Capitalized projects represents investments in assets for which the expected benefits extend beyond the current year*" that levels the firm's net income, since expenses are spread over the assets useful life (Byers et al., 1997). The decision of whether to capitalize or expense will affect financial ratios such as return on assets, debt to equity ratios and debt to solvency ratios due to resulting differences in the balance sheet. For instance, an expensing decision will lead to fewer assets (debts) recognized in the balance sheet and consequently improve the return-on-assets (ROA) ratio. Another important issue is that profits are overstated if no allowance is made for the replacement of the asset (White, 2006), i.e. the underlying principle of economic depreciation.

Investments in new fixed assets differ significantly from investing in existing assets. The difference is uncertainty concerning the new asset's future behaviour. Even though equipment suppliers present the asset's ideal capacity, real capacity (CAP_R) will be unknown prior to the ramp-up phase of production. A thorough fixed assets investment requires an analysis of all major parts of the cash conversion cycle. For instance, how soon will funds be recovered, i.e. how will the investment improve cash flows and working capital cycles? This type of analysis needs to consider content and variation in sales, personnel demand and inventory changes due to the asset investment. Secondly, the asset's service life must be evaluated along with impacts of maintenance operations. Other areas to consider are alternative investments by comparing the minimum alternative, i.e. the least expensive alternative, residual value, tax effects and leasing versus buying decisions. However, as previously explained, firms usually have resource utilization problems (Almström and Kinnander, 2008) and are thus operating far below the operating frontier. Accordingly, it is strongly advocated to consider whether and why current available capacity is inappropriate for further development before investing in new assets.

5.6 Shop floor improvements

The cash conversion cycle can be used for analysis purposes to understand how a firm's financial performance can be improved. This is accomplished by analysing how shop floor improvements affect production-related parts of the cycle. This chapter explains the importance of manufacturing processes' ability to process materials with high throughput rates and short throughput times. As the cash conversion cycle explains, all cash inputs are allocated to products produced in the production system. These products' book value is determined by the cost allocation process and will be present in a firm's balance sheet as work-in-process capital.

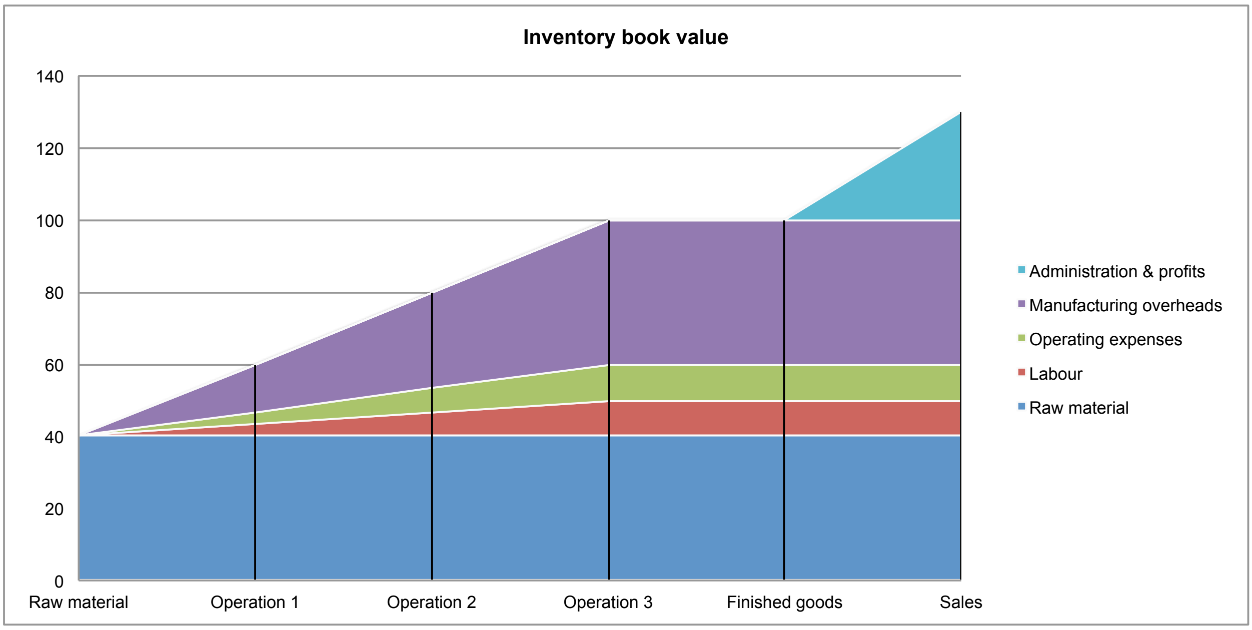

Figure 50: Book value creation

Figure 50 visualizes how book value is added to a single product in six stages. The raw material process includes activities for received goods and transport to the production area. Three different production processes have been defined that add book value to the product. The finished goods process includes activities related to the distribution of products. The cash flow elements in Fig. 50 are raw material, labour and operating expenses, such as maintenance and repairs, utilities, insurances and other expenses that relate to the business' costs of turning inventory into throughput.

The relationship between these cash flow elements and factory floor activities is derived from Little's law (eq. 14). Little's law explains relationships between a production system's work-in-process (WIP), throughput rate (T_R) and throughput time (T_T) (Little, 2011). The equation can be mathematically proved for special cases, for instance when time goes to infinity (Hopp and Spearman, 2008). Nonetheless, the equation is valid as a real-life approximation as long as the three quantities are measured in consistent units.

$$WIP = T_R \times T_T = CAP_R \times T_T \quad (14)$$

The throughput rate (T_R) is equal to a defined process' real capacity (CAP_R). The throughput rate can be determined within a limited factory view, e.g. a workstation, a subsystem or a complete production system. The process' throughput rate is restricted by its operating frontier according to the RPF theory.

The second variable, throughput time (T_T), is defined as the average time for a product or service to travel a specific route within the defined system – for instance, from one inventory point, e.g. raw material, to another inventory point, e.g. finished goods. Furthermore, T_T is the sum of time consumed by the specific route's direct activities (T_D), e.g. material processing and assembly, and indirect activities (T_{ID}), e.g. waiting for batch, waiting to match and queuing (eq. 15).

$$T_T = T_D + T_{ID} \quad (15)$$

Throughput time is thus related flow efficiency, "*the sum of value-adding activities in relation to the throughput time*" (Modig and Åhlström, 2012). In contrast, throughput rate is related to resource efficiency. With the terminology used in this thesis, value-adding activities correspond to direct activities, i.e. activities that facilitate material flow. The quantity of indirect activities is related to the production policy employed in the production system. A productivity improvement that increases real capacity will simultaneously affect a process' throughput time. A process' throughput time depends on employed production policies (e.g. the size of an inventory buffer) given a fix throughput rate of production process. A throughput time reduction can thus be reached by a single decision, e.g. to reduce the size of a buffer, while a throughput rate increase requires efficiency improvements. Three improvement scenarios can be employed to affect the amount and valuation of WIP:

1. *Real capacity (CAP_R) improvements*: A real capacity improvement is defined as an increased throughput rate enabled by productivity improvements. This option will result in a constant or reduced WIP and increased throughput rate.
2. *Production policy improvements*: A production policy improvement is defined as a reduced throughput time enabled by production policy trade-offs. This option will affect the process' real capacity while the WIP will be reduced.
3. *Inventory policy improvements*. An inventory policy improvement is defined as reduced inventory enabled by an inventory reduction decision. This option may affect a process' throughput rate and it will affect its lead-time.

5.6.1 Real capacity improvements

A real capacity improvement is based on the assumption that work-in-process (WIP) levels are management decision rather than results. Accordingly, WIP levels will typically remain constant independent of the real capacity increase. A real capacity increase will, according to equation 14, result in a throughput time reduction. For example, a manufacturing process has 10 units in WIP. The current state real capacity is 10 units per hour and the improved future state real capacity is 20 units per hour.

$T_{T,CS} = WIP_{CS} [units] / CAP_{R,CS} [units/h] = 10 /10 = 1 [h]$

$T_{T,FS} = WIP_{FS} [units] / CAP_{R,FS} [units/h] = 10/20 = 0.5 [h]$

The above example illustrates the fact that the throughput rate improvement doubles the process capacity reduces the process lead-time by 50%.

5.6.2 Production policy improvements

In contrast to real capacity improvements, production policy is based on the assumption that throughput rates are productivity-related and will typically change depending on the production policy change. As a consequence it is difficult to analyse a production policy change in comparison to a real capacity change since its effect on real capacity is difficult to predict.

Production policies concern how products are produced in the production system. That is, in what sequence, in what batch size and how the firm's fixed assets are organized (layouts and flow). The main concern of production policy is the production system's throughput time, which indicates how requested capacity (CAP_R) is met. Equation 15 explains that the throughput time is determined by the sum of direct and indirect activities. Decoupling indirect activities from the production flow can reduce its lead-time. These indirect activities must, however, still be performed in order to facilitate material flow. In comparison to real capacity improvements, production policy improvements are made at higher abstraction levels. Real capacity improvements are thus process-oriented while production policy improvements are system and resource-oriented.

For example, a manufacturing system produces 10 units per hour. The current production policy sets the throughput time at 1 hour. As a consequence, the system's WIP is 10 units. The improved production policy, given unchanged real capacity, has a lead-time of 30 minutes, reducing the system's WIP by 50%.

$WIP_{CS}\ [units] = T_{T,CS}\ [h] * CAP_{R,CS}\ [units/h] = 1*10 = 10\ [units]$

$WIP_{FS}\ [units] = T_{T,FS}\ [h] * CAP_{R,FS}\ [units/h] = 0.5*10 = 5\ [units]$

5.6.3 Inventory policy improvements

The third and last category is inventory policy improvements. This option is solely a management decision. Production policy improvements are, as previously explained, based on the assumption that throughput rates are independent of inventory levels. Production policy improvements are made to improve lead-times and thus affect inventory. Inventory policy improvements are made the other way around. That is, by reducing inventory, lead-times will be reduced.

$T_{T,CS}\ [h] = WIP_{CS}\ [units] / CAP_{R,CS}\ [units/h] = 10/10 = 1\ [h]$

$T_{T,FS}\ [h] = WIP_{FS}\ [units] / CAP_{R,FS}\ [units/h] = 5/10 = 0.5\ [h]$

In contrast to production policy improvements that focus on re-arranging the flow of indirect and direct activities, inventory policy improvements concern only the level of inventory.

5.7 Cash flow effects from shop floor improvements

The previous chapter derived three types of production improvements: *Inventory policy improvements*, *real capacity improvements* and *production policy improvements* (Fig. 51).

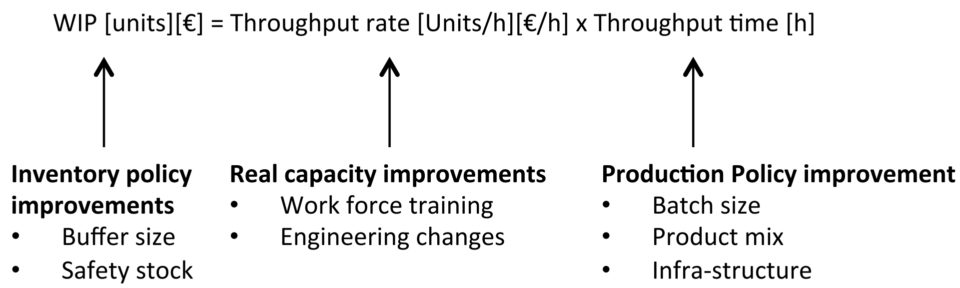

Figure 51: Little's Law is used to classify improvements.

This chapter explains the cash flow effect of adopting these improvements. *Cash flows from operations* (CFO) measure the amount of cash generated or used by a firm for production and sales of goods. Positive cash flows are essential for firm's long-term survival. Internally generated funds by a positive cash flow are used to pay dividends or repurchase equity, repay loans, replace existing capacity, or invest in acquisitions and growth (White, 2006). It is thus essential to explain how CFO can be increased through improvements of a firm's operating activities. This chapter focuses on the production system's contribution to CFO through analysis of the cash used by a firm. Chapter 5.5.1 describes how cash flows within a manufacturing firm. In practice, adopting the improvement practices presented in Figure 51 reduces time consumption at the various stages of the cash conversion cycle.

Two types of cash flow effects exist: *one-off* cash savings or expenses, and *on-going* cash savings or expenses. One-off savings and expenses are events that happen once. For instance, a production process' work-in-process is reduced once, which results in a one-off cash effect. On-going cash savings or expenses will result in a continuous change. For instance, employing staff will increase expenses related to wages and the change will continue to affect expenses in the future. The cash effects of improvements are discussed below.

5.7.1 Cash effects of real capacity improvements

Real capacity improvements increase a process' throughput rate and consequently reduce its throughput time. The financial effect that emerges from CAP_R improvements is twofold:

(1) The value of the capacity increase.
(2) The value of the throughput reduction.

The value of the capacity increase can be seen from both an input and output perspective. The output perspective concerns the fact that the firm in the future state scenario has an increased capacity available to meet customer demands with additionally increased service levels, since the lead-time is reduced. The lead-time reduction also implies that the cash conversion cycle has been reduced and thus also expenses related to interests will be reduced. The input perspective is that utilization and performance losses reduce the cost of capacity per time unit, which consequently reduces the book value of inventory while the cost of rework and quality-related expenses is also reduced. Quality improvements such as reduced needs for additional materials are also an effect of a real capacity increase. The cash effects of real capacity improvements are listed in Table 29.

Table 29: Cash effects of real capacity improvements

	One-off	**On-going**
Savings	Taxes • Tax savings due to assets reduction Interest • Interest saving due to lead time reduction	Sales (output oriented) • Volume • Value COGS (input oriented) • Labour • Materials
Expenses	COGS • Improvement expenses	N/A

5.7.2 Cash effects of production policy improvements

Production policy improvements reduce a process' throughput time and consequently its WIP. The financial effect emerging from CAP_R improvements is twofold:

(1) The value of the throughput time reduction.
(2) The value of the WIP (volume) reduction.

The production policy improvement is expected to increase service levels if the production system's throughput time is reduced. Customers will receive their requested goods or services earlier and the firm can respond to changed requirements faster. However, the difficulty lies in the fact that a production policy change will affect a system's ideal capacity and thus also its real capacity. The throughput time reduction's financial benefit is explained by the cash conversion cycle that is discussed in the following chapter. The result is a one-off cash savings due to the financing cost reduction.

Work-in-process inventory will be reduced at the same rate as the throughput time, assuming that real capacity rates remain unchanged. However, the cash effect of production policy change is a minor issue. The benefits of introducing swift-even flows has been one of the most hotly debated topics in operations management research since the 1980's and onwards. Related expenses are loss of quantity discounts, increased material handling and distribution expenses. However, this improvement is aligned with the JIT and Lean concept that argues for improved service levels, avoiding overproduction and visualization of waste. The cash effects of production policy improvements are listed in Table 30.

Table 30: Cash effects of production policy improvements

	One-off	On-going
Savings	Taxes • Tax savings due to asset reduction Interest • Interest saving due to lead-time reduction	Sales (output-oriented) • Value
Expenses	COGS • Improvement expenses	Sales (output-oriented) • Capacity decrease COGS (input-oriented) • Labour efficiency decrease

5.7.3 Inventory policy improvements

An inventory policy improvement affects only the WIP inventory levels, independent of real capacity and throughput time. An inventory reduction can be made that generates a temporary cash flow improvement. The decision is typically to drain a firm's safety stock. During this period all material inputs are restricted, including the outflow of cash. All cash flow elements will thus be restricted for a limited period of time and will instead be added to the cash and bank item in the balance sheet. Moreover, since the inventory level will be reduced, the value of the firm's assets is also reduced. As a consequence, this asset value reduction will be recorded as a profit reduction in the income statement, which leads to a tax saving. The total saving of an inventory reduction is the cash saving due to restricted material supply plus the tax saving due to the profit loss. Table 31 lists the cash effects of inventory policy improvements.

Table 31: Cash effects of inventory policy improvements

	One-off	On-going
Savings	COGS • Material supply restriction Taxes • Tax savings due to assets reduction	N/A
Expenses	N/A	N/A

5.8 Calculating cash flow effects

The previous chapter describes the cash flow effects that emerge from three improvement practices. This chapter explains how these effects can be calculated and incorporated into investment proposals.

5.8.1 Lead-time effects

Lead-time improvements are based on the cost of capital. Cost of capital is based in turn on investors' required rate of return. Various methods for calculating cost of capital exist, for instance the weighted average cost of capital (WACC) method as explained in Chapter 5.5.1. The bottom line is that reduced cash conversion cycles are exposed to reduced risks and thus subject to lower financing costs. From a production point of view, lead-time refers to the time capital is spent in forms of raw materials, work-in-process materials and finished goods. Table 32 presents a manufacturing firm that has a cash conversion cycle of approximately 100 days. The firm's operations thus require 100 days to transform cash to required returns and accordingly 100 days of financing. Table 32 illustrates that reducing WIP lead-times from 50 to 25 days generates a one-off cash savings of approximately EUR 500 thousand. The amount of savings depends on the cost of capital. Table 32 shows the importance from a financing perspective of having short cash conversion cycles.

Table 32: Cash cycle reduction example

Sales	270 000 €/day
Cost of goods sold (COGS)	191 000 €/day
Net cash conversion cycle	100 days
Financing requirements	100 days *191 000 € = 19,1 M€
Cost of capital	10%
Financing cost	• 10%*19,1M€ = 1,91M€ (100 days) • 19 100 €/day
Cost for 50 days WIP lead-time	19 100 €/day * 50 days = 955 000
Cost for 25 days WIP lead-time	19 100 €/day * 25 days = 477 500€
Savings	**477 500€**

5.8.2 Inventory effects

The second cash flow effect originating from shop floor productivity improvements relates to the value of inventory and the quantity (volume) of inventory. In order to understand how inventory changes affects financial reports, the costing allocation method must be understood. The value of inventory consists of cash flow elements and non-cash flow elements. The underlying assumption is that shop floor productivity improvements refer only to cash flow elements. In practice, shop floor improvements may lead to reduction of other activities such as various overheads.

The first effect originating from the inventory quantity change is discussed below. The second effect, originating from book value changes, requires in-depth knowledge of costing methods and is discussed in a separate chapter (5.8.3).

Figure 50 depicts a product with a book value of EUR 100, EUR 60 of which consists of cash flow elements and EUR 40 consists of non-cash flow elements. Instead of continuously re-ordering materials as usual, a decision is made to restrict the supply process and thus reduce the safety stock. Since sales are continuing, cash is flowing into the company. However, no cash is flowing out since the supply chain is restricted. Instead this portion of cash accumulates in the firm's cash and bank account. Meanwhile, the firm's assets are shrinking with the same value as the products' non-cash flow elements, i.e. EUR 40. That is, normally, overheads are allocated to these products. But, since no materials and labour are required, the overheads related to this product also disappear. This asset value reduction corresponds to a profit loss. The size of the loss is equal to the quantity of products that are restricted multiplied by the non-cash flow elements. The profit reduction leads to a tax savings equivalent to the corporate tax rate (e.g. 20-30 percent) times the profit reduction. The total savings from an inventory reduction is presented in eq. 16.

$$Cash\ savings = 60€ + 40€ \times 30\% = 72€ \qquad (16)$$

The cash effect of WIP variations will, based on this reasoning, serve as a profitability counterbalance. Hence, when demand is declining, WIP levels will be reduced to create a positive cash effect. The positive cash effects of reducing WIP levels are thus evident only when the change actually occurs (excluding the risk aspect), i.e. it is a one-off cash effect. Nevertheless, prior research also indicates that increased inventory performance, such as reduced throughput times and increased delivery precision, correlates with significant value creation and thus financial performance (Capkun et al., 2009). Vastag and Whybark (1993) examined the relationship between inventory levels and manufacturing lead-times and concluded that increased WIP inventories led to increased manufacturing throughput times. The inventory levels of the raw material storage had little effect on manufacturing throughput times and the finished goods storage had no effect at all. The results suggest that improvements should primarily focused on the production process, i.e. the WIP materials.

The second positive cash effect arising from inventory changes is book value reduction. Book value reductions emerge when production process improvements result in on-going cash flow savings. An additional one-off cash flow saving is achieved due to the resulting inventory value reduction. When quantifying a WIP reduction's cash effect, certain assumptions need to be made. The following bullet list is based on Primrose (1992) article on inventory valuation:

- Asset value and inventory holding costs are not proportional, e.g. holding costs may increase due to book value reductions.
- Various types of inventories are subject to different valuations: In-house finished goods (IFG) should be assigned large portions of overhead costs and bought-in products should be assigned small portions of overhead costs.
- Inventory book value is equal to production cost (obsolete stock is an exception)
- Stock reductions are made by means of restricted supply processes, not increased sales.
- Operating savings are recorded in the income statement: Profits and taxes increase.
- Cash flow savings are not recorded in the income statement: No tax liability due to unchanged profits.
- Stock value changes (or revaluation) can occur only by changing cost contributions from the manufacturing system itself.
- Assets reduction corresponds to profit reduction.

Accordingly, an easy-to-understand relationship between WIP variations and cash flow effects is missing. One source of confusion is the relationship between inventory holding costs and the re-evaluation effect emerging from process improvements. Also, standard costing method processes for cost allocation have the effect of deferring the expenses of producing a product until the revenue is recognized, i.e. when lowering inventories; thus costs from prior production periods will show up in the income statement (Meade et al., 2009). However, one conclusion can be drawn. If an inventory reduction earns less than it costs, other options must be considered. Cash-wise, it is preferable to focus production development investments on labour and machine utilization improvements, since capital up tied in raw material inventory can be reduced through extended supplier credits (White, 2006). Chapter 5.8.3 presents a method that is able to calculate book value changes based on productivity improvements.

5.8.3 Time-driven activity-based costing (TDABC)

A prerequisite for analysing how improvements affect cash flows from operations is to understand how inventory book value is affected by productivity improvements. Time-driven activity-based costing (TDABC) is used to estimate book value in this framework. The benefit of using TDABC is that it can be incorporated into the productivity dimension framework and thus determine how single production processes contribute to book value creation. Time-driven activity-based costing requires the estimate of two parameters:

1. The cost per time unit of supplied resource capacity [cost/time unit].
2. The unit time required to perform an activity by the supplied resource capacity [time unit].

Consequently, the costing method requires two analysis approaches, a resource analysis to calculate the cost of supplied capacity and a process analysis to estimate the time consumption to perform related production activities. Each analysis approach is discussed below.

The resource analysis covers capacity measured as time, i.e. CAP_A, CAP_{PL} and CAP_U. The resource analysis is carried out in five steps:

- Step 1: Identify resource groups.
- Step 2: Estimate the total cost of each resource group divided into cash flow elements and non-cash flow elements.

- Step 3: Estimate planned capacity of each resource group.
- Step 4: Measure utilized capacity for each resource group.
- Step 5: Calculate cost rate for each resource group.

The first step is to identify all resources that the analysis covers. An appropriate approach for this purpose is to construct a value stream map. The essential part of step 1 is to understand the resources that perform activities necessary for facilitating material flow. This analysis is aligned with the production system model's definition of production processes (see chapter 5.1). How many resources are they, to what extent are they allocated for performing these activities, is equipment involved, etc.?

The second step is to calculate the total cost of the resources that facilitate material flow and separate cash-flow elements from non-cash flow elements. Kaplan and Anderson (2007) suggest that a production department's costs include consideration of *direct labour* including fringe benefits, *supervision* and *indirect labour* including fringe benefits, *equipment and technology* costs, *occupancy* costs and other *indirect and support labour* costs. In this context, resource costs are suggested to be separated between cash flow elements and non-cash flow elements, as explained in the inventory reduction calculation example. Depreciation can be a non-cash flow element and will not affect CFO changes. This analysis should emphasize direct labour and material costs since the focus is on shop floor activities. As previously explained, cash flow elements are restricted to outward flows from the firm following a material supply restriction decision. The profit reduction, however, corresponds to non-cash flow elements (i.e. overheads that are allocated to direct labour according to standard costing methods). A subsequent effect of an inventory reduction is an inventory lead-time reduction that considers both non-cash flow elements and cash flow elements since both need financing. As a result, both cash flow elements and non-cash flow elements must be determined to provide accurate data for both inventory book value changes and inventory quantity changes.

The third step is to analyse planned capacity (CAP_{PL}) and available capacity (CAP_A) for each resource group. Planned capacity is calculated as the time that production resources are allocated for performing production activities. That is, CAP_A less time for training, meetings, workshops, breaks, etc.

The forth step is to analyse utilized capacity (CAP_U). This analysis is carried out during planned production time. As previously explained, CAP_U is determined by the distribution of direct activities, indirect activities and waste activities. Operator utilization is measured by means of work sampling studies, and equipment utilization is measured by means of the equipment's internal measurement system. Equipment utilization rates can also be measured manually if measurement systems do not exist.

The last step of the resource analysis is to calculate cost rates for each resource group included in the analysis. The result of the resource analysis provides the data presented in Table 33.

Table 33: TDABC resource analysis results

TDABC – Cost rate calculation		
Available capacity (CAP_A)		
Week	40h x 10 FTEs	400h
Per year	400h x 48w	19 200h
Planned Capacity (CAP_{PL})		
Week	35h x 10 FTEs	350 h
Per year	350h x 48w	16 800h
Utilized capacity (CAP_U)		
U	75%	12 600h
Cost of capacity		
Per year	10 FTEs	300 000 €
Per hour	300 000 /12 600	23,8 €/h

The resource capacity analysis provides an aggregate view of a firm's resource utilization rate and present insights into possible problem areas (utilization and availability problems). The resulting hourly cost rate is valid only if the mix of resources supplied is about the same for each activity and transaction performed within the analysed factory view. Otherwise, two or more cost rates are necessary. For instance, a subsystem consists of an assembly line and a machining line. The products that are produced within this facility view sometimes only go through the machining line, sometimes just through the assembly line and sometimes through both lines. In this case two cost rates must be calculated, one for the machining line and one for the assembly line.

The next step in estimating book value is to analyse time consumption rates and the corresponding cost analysis. The time consumption and cost analysis is performed in additional five steps:

- Step 6: Identify and characterize production activities.
- Step 7: Establish time drivers.
- Step 8: Establish time equations.
- Step 9: Calculate time consumption rates.
- Step 10: Calculate book value

First, a process' time consumption is described with a *time equation*. A time equation consists of a defined *activity time* and a defined *time driver* (eq. 17). The time equation describes a sequence of events that must be performed to fulfil a specific work task. An example is an equipment *setup* work task (eq. 18).

$$time\ equation\ [s] = activity\ time[s] \times time\ driver \tag{17}$$

$$Setup\ time\ per\ order = print\ picking\ list + get\ component \times X_1 + get\ tool \times X_2 + adjust\ machine \times X_1 \tag{18}$$

$$Setup\ time\ per\ order\ (product\ A\ ) = 300 + 15 \times 20\ components + 60 \times 3\ tools\ + 30 \times 20\ components = 300 + 300 + 180 + 600 = 1380\ s = 0{,}38h \tag{19}$$

Equation 19 presents the time required for the setup work task related to product A. The equation requires the time consumption rate of each activity defined in the work task. Predetermined time systems are suitable for setting time standards, for instance Sequenced based Activity and Method analysis (SAM). Furthermore, the time equation corresponds to the process ideal capacity (CAP_I). Ideal capacity is calculated by the inverse of the time equation (eq. 20).

$$Ideal\ capacity\ (CAP_I) = \frac{1}{Time\ equation} = \frac{1}{0{,}38} = 2{,}61\ [\frac{units}{h}] \tag{20}$$

Equation 20 uses the result yielded by eq. 19 to calculate CAP_I for the specific work task. Ideally, 2,61 setups can be performed per hour.

Step 6 in the proposed analysis procedure is to identify all activities (e.g. setups, adjustments, assembly, inspection, etc.) that are performed within the resource group. These activities must also be characterized as either direct or indirect. The characterization is necessary in order to calculate a production process' lead-time.

Step 7 is to establish time drivers. Each activity within the time equation is classified as either *homogenous* or *non-homogenous*. Homogenous activities must be performed independent of product. Consequently, homogenous activities do not require time drivers. For instance, the first activity in equation 18 must be performed independent of product and requires 300 seconds every time the work task is carried out. Non-homogenous activities are dependent on the product. Consequently, non-homogenous activities require time drivers. For instance, the activities *get component* and *get tool* in equation 18 vary according to the number of components each product has and the number of tools each product requires. The time drivers used in eq. 18 are listed below:

- X_1 = Number of components per order
- X_2 = Number of tools per order

The total time of a time equation thus consists of the total time needed for homogenous activities and the total time needed for each non-homogenous activity multiplied by the related time driver.

The next step (8) is to establish time equations for all work tasks carried out within the analysed facility view. Time equations for manual labour are always calculated in sequence, as in eq. 18. However, calculating time equations for work tasks performed by equipment is a special case (eq. 21). A typical example is when several workstations process a product in a line. The line consists of three workstations: workstation 1, workstation 2 and workstation 3. All direct activities in this line are carried out by equipment. The cycle time of each station varies between five and seven minutes. Station 2 is the bottleneck of the machining line with a cycle time of 7 minutes. The lead-time for a single product passing through this line is 18 minutes. However, this machine line is capable of working with products simultaneous. As a consequence, the line can be calculated as a single cost unit. The cost per time unit of the machine line is thus dependent on the bottleneck cycle time activity multiplied by the cost rate for the complete line.

$$Machining\ time\ per\ order = \\ setup\ time\ (bottleneck) + \ lead\ time + cycle\ time\ (bottleneck) \times batch\ size \qquad (21)$$

Time equations for equipment must thus be considered with regard to pitfalls related to bottleneck variations. That is, the bottleneck for a machine line may change depending on the product with regard to both setup and cycle time. The production process' lead time may also change depending on the product being produced. Finally, some equipment can handle several products simultaneously – for example, an oven with a capacity of 100 units. In that case, the time equation is 100 minutes, not 100 minutes multiplied by 100 units.

Step 9 is to complete the time consumption analysis using given product data to calculate time consumption rates for each product produced in the analysed area. Step 9 requires that time equations have been established and that product data are available. The product data are typically derived from the firm's bill-of-material (BOM). Table 34 present the results of the time consumption analysis.

Table 34: Time consumption calculation

Product family	**Number of components**	**Number of tools**	**Time equation**
A	20	3	300+(15*20)+(60*3)+(30*20) = 1380s
B	40	5	300+(15*40)+(60*5)+(30*40) = 2400s

The last step (10) is to calculate the book value contribution of the specific resource group. The result of the time consumption analysis is multiplied by cost rates yielded by the resource capacity analysis. Table 35 presents book value calculations based on 10 products per order. The material cost per product can be obtained from the BOM of the product. The book value that concerns cash flow elements can thus be calculated by adding the material cost per product to the resource cost per product.

Table 35: TDABC cost calculations

Product family	Time consumption analysis		Resource capacity analysis		Cost allocation		Material costs	Book value
	Seconds	Hours	Cash flow elements cost per hour [€/h]	Non-cash flow elements cost per hour [€/h]	Cost per order [€]	Cost per product [€]	Cost per product [€]	Cost per product [€]
Product A	1380	0.36	23.8	N/A	8.59	0.859	10	10.859
Product B	2400	0.66	23.8	N/A	15.87	1.587	12	13.587

The value of these losses is calculated with the TDABC method. Table 36 presents two scenarios: One scenario corresponds to utilization rates of 100% and one scenario corresponds to utilization rates of 70%. The book value reduction is thus obvious in the scenario corresponding to a 100% utilization rate.

Table 36: Utilization rates affect book value

Product family	Time consumption analysis	Resource capacity analysis		Cost allocation		Material costs	Book value	
	Hours	Cash flow elements cost per hour [€/h] U = 70%	Cash flow elements cost per hour [€/h] U = 100%	Cost per Product [€] U = 70%	Cost per product [€] U = 100%	Cost per product [€]	Cost per product [€] U = 70%	Cost per product [€] U = 100%
Product A	0.36	23.8	17.85	0.859	0.646	10	10.859	10.646
Product B	0.66	23.8	17.85	1.587	1.178	12	13.587	13.178

The use of the TDABC method in the context of the thesis is not primarily concerned with calculating book values for cost accounting purposes. Instead, the method is used to provide quantitative inputs for cash flow estimates of improvement projects.

5.9 Cash flow analysis framework

The purpose of the cash flow analysis framework is to explain how shop floor improvements affect a firm's cash flow. The previous sections presented three improvement actions based on Little's Law: *real capacity improvements*, *production policy improvements* and *inventory policy improvements*. The following sections explained the benefits of exploiting these improvement actions and how these effects could be calculated by adopting the TDABC method. This section uses the concepts and methods previously described to explain how these three improvement actions influence a firm's cash flow from operations (CFO). Table 37 depicts accounts that are included to calculate a firm's CFO (White, 2006).

Table 37: Cash flow analysis adopted from White (2006)

(€000)	Income statement	Balance sheet (Year 00)	Balance sheet (Year 01)	Balance sheet Change	Cash effect	Cash	
Cash collections							
Net sales	3000				Increase	3000	
Accounts receivable		200	400	200	(Decrease)	(200)	
Advances		0	100	100	Increase	100	2900
Cash inputs							
COGS	(2000)				(Decrease)	(2000)	
Inventory		1000	500	(500)	Increase	500	
Accounts payable		1000	500	(500)	(Decrease)	(500)	(2000)
Cash expenses							
Operating expenses	(500)				(Decrease)	(500)	
Rent expenses	(100)				(Decrease)	(100)	
Accrued liabilities		0	50	50	Increase	50	(550)
Cash taxes paid							
Tax expense	(50)				(Decrease)	(50)	
Taxes payable		-	50	50	Increase	50	-
Cash interest paid							
Interest expense	(250)				(Decrease)	(250)	
Interest payable		0	150	150	Increase	150	(100)
CFO							**200**

Cash flow from operations is calculated as the change in inflows less the changes in outflows in operations for a given period of time (e.g. yearly or quarterly). Table 37 describes cash flow changes as negative by using parentheses and positive by not using parentheses. Cash flow from operations becomes positive when the positive change in inflows is larger than the negative change in outflows. The largest cash flow accounts are usually the cash collection account and cash inputs accounts. Cash flow losses are hidden in these accounts, either as a loss of inflows or as a loss due to excessive outflows. Cash inflows depend on external factors and are thus regarded as out of scope for this thesis. Cash outflows, however, relate to controllable factors and are thus the primary target of this analysis framework.

Figure 52 depicts a capacity-time diagram integrated with a cash flow diagram. The RPF theory explains how improvement initiatives affect process capacity as measured on the right positive vertical axis. The left axis represents cash flows from operations. The left positive vertical axis represents inflows (net sales, accounts receivable and advances). The left negative vertical axis represents cash outflows (COGS, operating expenses, tax expenses and interest expenses). Figure 52 plots four bars: *Cash collection with investments*, *ideal cash outflows with investments*, *cash flow losses with investments* and *budgeted cash flows without investments*.

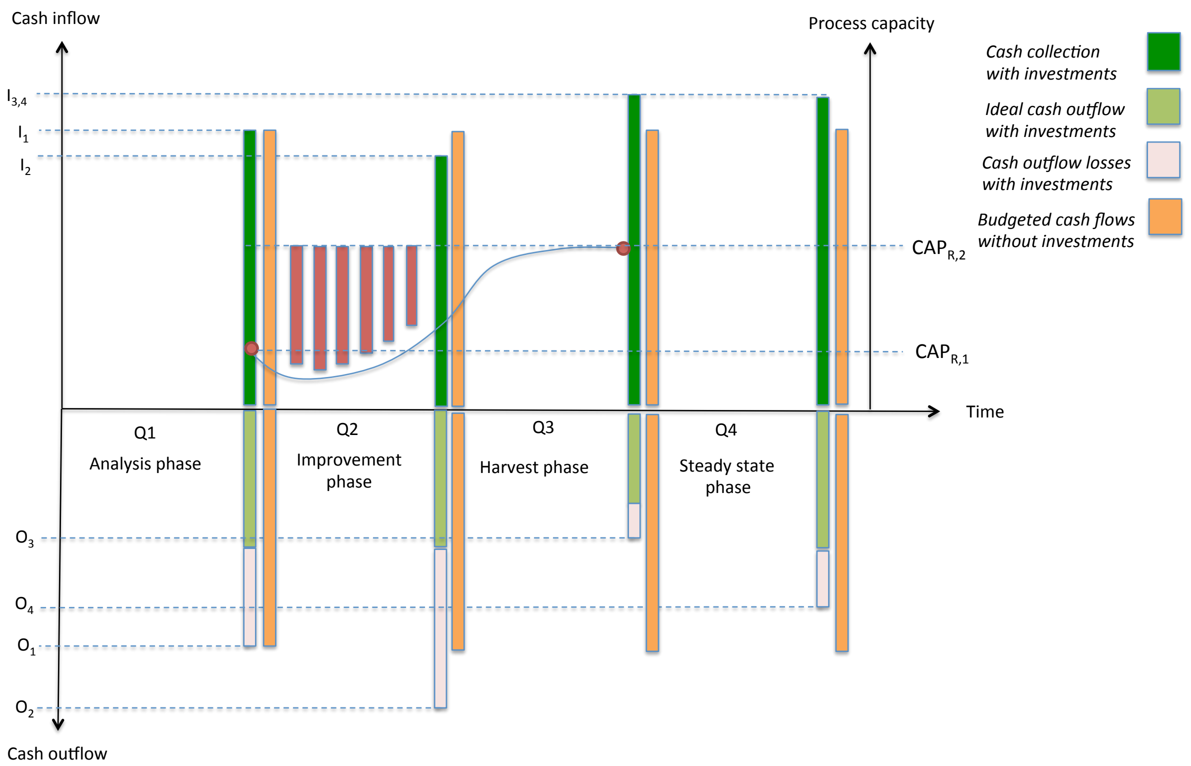

Figure 52: Cash outflows are plotted as ideal cash flow and cash flow losses

Budgeted cash flows represent cash flows as if no productivity investments will be realized. In reality, inflows and outflows always vary to some extent due to seasonal demand variations, introduction of new products, etc. The other three bars in Figure 52 represents cash flows as if productivity investments will be realized. Cash flow losses are defined as *excessive cash outflows caused by utilization and performance losses*. These losses are quantified with support from the TDABC concept explained in the previous section. Ideal cash outflows correspond with utilization and performance rates of 100%. Cash collection with investments refers to how improvements affect cash inflows. The horizontal axis in Figure 52 plots time divided into four phases: *analysis phase*, *improvement phase*, *harvest phase* and *steady state phase*. Each phase will affect cash flows to a certain extent as described below.

Analysis phase

The analysis phase corresponds to a current situation analysis. This is the starting point for the analysis and it is performed to assess where the production system or process is located in the capacity-time diagram, that is $CAP_{R,1}$. Ideal cash outflows are the outflows generated by a process' ideal capacity. That is, containing no expenses for either process utilization or performance losses. The Q1 cash outflow bar in Fig. 52 indicates the portion of ideal cash flow and cash flow losses estimated from the TDABC calculation. A real capacity improvement aims to reduce those cash flow losses. The analysis reveals whether attention should be given to engineering changes or workforce training. Small utilization and performance losses suggest that the focus should be on engineering changes. Large utilization and performance losses suggest that the improvement focus should be on workforce training, perhaps in combination with engineering changes. Since the Q1 bar represents a current state, it is equivalent to budgeted cash flows assuming that no investment will be realized.

Improvement phase

The improvement phase typically increases cash outflows due to expenses related to investments in workforce training, process alignment, method design analysis, etc. These costs are one-off expenses that are registered in the Q2 cash outflow bar. These expenses must be covered by a positive cash flow generated by process improvements in order to be advantageous. Figure 52 also depicts cash inflows, for instance net sales, and how they are altered during the productivity improvement process. The RPF theory explains that there is usually an initial drop in process capacity at the beginning of the improvement phase. Depending on inventory levels and customer requirements, this drop in capacity may affect cash inflows negatively (see I_2 in Fig. 52). Furthermore, the improvement generates a one-off cash effect due to the profit loss in the income statement that corresponds to less cost for tax liabilities.

Harvest phase

The harvest phase is the period of time when the productivity improvements are realized in the financial statement. The Q3 bar in Fig. 52 visualizes that process utilization improvements have been harvested, resulting in both on-going cash flow savings and one-off cash flow savings (i.e. reductions of outflows). Figure 53 summarizes the cash flow effects emerging from throughput rate increases and throughput time reductions.

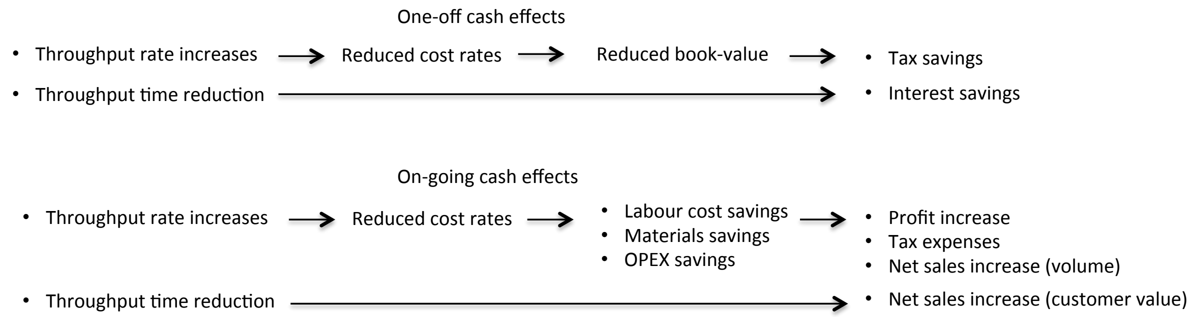

Figure 53: Cash flow effects of throughput rate increases and throughput time reductions.

Steady state phase

Steady state is achieved when all one-time effects have been harvested from the productivity improvement. The best-case scenario is depicted in Fig. 52. The proposed improvement results in both increased inflows and reduced outflows, i.e. the change in inflows and outflows will led to improved CFO.

5.9.1 Investment calculations

Understanding how shop floor improvements affect cash flows is essential for making appropriate investment decisions. The basic decision rule is that the productivity investment is profitable when the change of cash inflows covers the change of cash outflows after a given period of time. Within this period of time, cumulative inflows and outflows must be estimated and compared with a budgeted scenario.

Four time phases have been covered that concern the investment period. Each time phase is related to a set of expenses and savings that can be evaluated. Some of these activities are found in the results of the project management study (Study III). Each phase is biased by several factors. The project management study explained that factors influencing the improvement projects include the availability of improvement resources, culture and competence. These factors are difficult to anticipate in advance and depend on the organization's previous experience of improvement projects.

5.10 A model for analysing financial benefits of shop floor productivity improvements

Figure 54 presents a model that consists of a set of frameworks that are used to analyse financial benefits of shop floor productivity improvements.

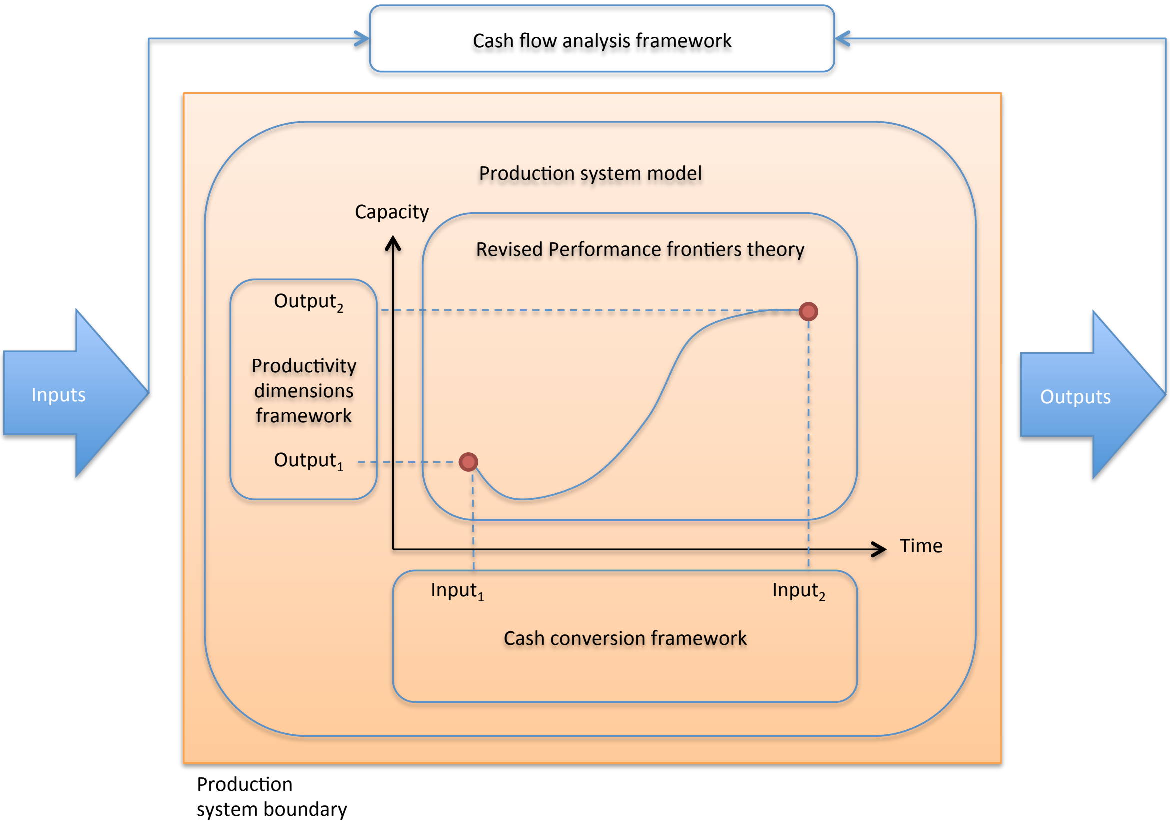

Figure 54: A productivity analysis model

The foundation of the model is the descriptive production system model presented in chapter 5.1. The production system model is able to represent production system resources and activities that are modelled as production processes. The resources in the production system model are characterized by capabilities, i.e. the activities that they can perform, and capacity, i.e. their potential workload. The activities are classified as either direct activities that facilitate material flow or indirect activities that do not facilitate material flow but are still necessary to carry out.

The productivity dimension framework is used to explain the relationship between the production system model's constituent parts and operational performance. The productivity dimension framework considers how efficiently the production system utilizes its resources, as well as the effectiveness of the current production system. The productivity dimension framework establishes the ideal capacity of a process based on predetermined time systems. All manual activities carried out in a production system can be assigned an ideal capacity based on predetermined time systems (effectiveness). The framework also serves as an analysis framework regarding real capacity (efficiency). The productivity potential is determined by comparing a production process' ideal capacity with its real capacity. The productivity dimension framework is mapped on the vertical capacity axis in Fig. 54, since it establishes ideal and real capacity. The following list summarizes what the productivity dimension framework does in the productivity analysis model:

- It establishes time standards and consequently ideal capacities (effectiveness).
- It provides tools to analyse utilization and performance losses (efficiency).
- It provides suggestions regarding system and process design, i.e. engineering changes.
- It provides suggestions regarding resource development, i.e. workforce training.

The cash conversion framework focuses instead on the inputs to the system, e.g. labour, materials and capital and is thus mapped on the horizontal axis in Fig. 54. The cash conversion framework explains the effect of productivity improvements on the cash conversion cycle's length and the financial effects of reducing it. The cash conversion framework is based on Little's Law, which explains the relationships between a process' work-in-process, throughput rate and throughput time. Based on Little's Law, three improvement actions were derived that create financial effects. Time-driven activity based costing (TDABC) was incorporated into the framework to determine the monetary value of those effects. The following list summarizes what the cash conversion framework does in the productivity analysis model:

- It explains how real capacity (CAP_R) improvements, production policy improvements, and inventory policy improvements create cash flow effects.
- The framework uses the TDABC method to incorporate the productivity dimension framework to establish the relationships between shop floor productivity and the book value of a firm's assets.
- The TDABC method as presented in this thesis also provides a structured way to calculate inventory book values. It has been a structured improvement method since its incorporation of MTM methods.
- It highlights the costs for resource utilization losses.

The revised performance frontiers (RPF) theory is the core of the model presented in Fig. 54. The theory explains how a firm's shop floor improvement actions are developed and establishes the constraints. The theory relies on the law of bottlenecks, the law of diminishing returns and the law of diminishing synergy.

- The RPF theory provides useful information for decision-makers regarding a production system's capacity and how it can be developed with support from progress curves.
- In combination with the analysis framework, it is possible to assess a production system's limitations and capabilities (the operating frontier) and to benchmark production systems (provide external comparisons). These comparisons are based on mapping each system's operating frontier and real capacity curve in a capacity-time diagram and analysing how it can be altered to increase the system's competitiveness.

The last framework of the productivity analysis model is the cash flow analysis framework .The cash flow analysis framework compares cash inflows and outflows. It can be used as an outcome-oriented framework to build knowledge, and it can be used as a predictive-oriented measure to predict the outcome of investment proposals.

- The framework explains how shop flow improvements affect economic accounts and the accounts that are affected.
- The framework can be incorporated into investment algorithms to calculate the NPV of organizational investment projects.

6. Discussion

This chapter provides a discussion of each research question and its results. The focus of the discussion is the conceptual framework that has been developed during the course of the research initiative. The subsequent discussion concerns the research methodology, its appropriateness and design for the research purpose and objectives. Finally there is a discussion of future work on the topic of interest.

6.1 Research questions and results

Three research questions were stated in the introductory chapter of this thesis. Each question and the related results are discussed below.

6.1.1 Research question 1

The first research question was formulated as *how is shop floor productivity analysed and modelled?* The question is twofold. *How is shop floor productivity analysed?* and *how is shop floor productivity modelled*? This research initiative is divided into two parts to create a decision support tool for shop floor productivity investments. This thesis has focused on *how shop floor productivity is analysed*, while the other part of the research initiative has focused on the modelling aspect of productivity (Hedman, 2013). Nevertheless, these two research areas are meant to converge. For instance, the production system model is the foundation of the explanatory framework presented in Chapter Five. However, before addressing *how* shop floor productivity is analysed, the reason *why* it should be analysed must be clarified. Why productivity should be analysed involves two aspects: the purpose of analysing and the objective of analysing.

Teague and Eilon (1973) mentioned four purposes for measuring productivity: *Strategic purposes*, *tactical purposes*, *planning purposes* and *internal management purposes*. Strategic purposes refer to comparing a firm's performance with its competitors. Tactical purposes refer to controlling the performance of a firm's functions or products. Planning purposes refer to how the firm benefits from using varying proportions of different inputs – for instance, labour, material or capital. Internal management purposes refer to collective bargaining with trade unions, etc.

The analysis methods that were covered in Study I primarily concerned strategic purposes. That is, methods that assessed internal performance or methods that assessed firms' performance vis-à-vis their competitors. The objective of Study I was to compare the PPA method with other equivalent methods. The PPA method has an expressed purpose of providing companies with both external and internal benchmarks and is thus aligned with the strategic standpoint.

The second consideration of why to analyse relates to the objective of the analysis. Some productivity analysis models are effective at the group level and are primarily improvement-oriented, while others are effective at the plant and enterprise level and are primarily control-oriented (Sink et al., 1984). Typical control-oriented measures would be what Löfsten (2000) refers to as productivity aggregates. These models concern plant or enterprise levels of productivity and typically use data retrieved from a firm's accounting system. Improvement-oriented measures would be what Löfsten (2000) refers to as component measures. Sink et al. (1984) use the term surrogate models for equivalent models. Surrogate models are described as any measurement, evaluation or improvement technique correlated with productivity (Sink et al., 1984). This thesis merely advocates surrogate models, such as work sampling, predetermined time systems, checklists and audits.

Productivity aggregates have traditionally been looked on as providing inadequate information to plant managers (Hayes and Clark, 1986, Armitage and Atkinson, 1990). Instead, plant managers prefer operational data such as quality, throughput rates and throughput times, since profit and loss statements do not provide up-to-date information regarding factory performance. This standpoint has been widely discussed in performance measurement literature. For instance, Johnson and Kaplan (1991) suggest that short term financial measures have been undermined due to rapidly changing technology, shortened product life cycles and operational innovations. This view is shared by several prominent researchers in the area of performance measurement (Bourne et al., 2013, Bourne et al., 2002, Ghalayini and Noble, 1996). As a consequence, this thesis emphasizes productivity measures that provide managers with information that is closely related to work tasks and activities that can be observed and subsequently improved.

It is thus suggested to measure shop floor productivity with the productivity dimension framework adapted from the work of Saito (2001), Helmrich (2003) and Sakamoto (2010). The original concept has been developed to a framework that decomposes the productivity dimensions into utilization and performance variables, e.g. need-based utilization rates, system design utilization rates and disturbance-affected utilization rates. This decomposition was first presented by Almström (2013), and it has been further developed and described in this thesis. The productivity dimension framework can be used to analyse both labour productivity and equipment productivity.

Overall equipment efficiency (OEE) is the most widely recognized and used performance measure regarding equipment efficiency (Muchiri and Pintelon, 2008). The main difference between OEE and the productivity dimension framework is that OEE regards the output of a machining process as a single entity, i.e. equipment and human, while the decomposition of productivity into M, P and U factors distinguishes between the output that is provided by the equipment and how the human resource handles the equipment, i.e. the output of the operator.

The OEE measure decomposes equipment productivity into six big losses: equipment failure, set-up and adjustment, idling and minor stoppages, reduced speed, defects in the process and reduced yield. This type of decomposition facilitates the prioritizing process of improvement actions, since the measure supplies data regarding what causes the biggest loss and should accordingly be dealt with as a first priority. The M, P and U decomposition provides a slightly different approach. First, it involves a mind-set that concerns both method design and resource utilization. Secondly, it focuses on improvements while simultaneously pinpointing utilization losses. In that sense, M, P and U is a wider concept than OEE. Third, in processes that use equipment, it is clear that the productivity dimension framework considers the activities that need to be performed by the operator as well.

A comparison can be made between the productivity dimension equation and the OEE equation. In order to differentiate the performance factor in the equation, the following variables are used concerning OEE. Overall equipment efficiency can be calculated by multiplying availability (A), which is the planned production time minus larger stoppages and break-downs, the operation efficiency (O) (including both small stops and speed reductions), and the quality yield (Q) presented in equation 22.

$$OEE = A \times O \times Q \qquad (22)$$

The OEE figure is not a productivity measure – there is no M factor. The A factor plus the small stops of the O factor are the same as U losses, and the speed reduction component of O is the same as P losses. That yields the following relationships:

$$M \times OEE = M \times P \times U \times Q \quad (23)$$

$$OEE = P \times U \times Q \quad (24)$$

The objective of RQ1 was to find modelling alternatives and analysis methods that converge and could be incorporated into a single framework for analysing shop floor productivity. It is argued that the productivity dimension framework does this successfully. The framework is generic and can be applied to any situation containing manual work as well as work performed by equipment.

6.1.2 Research question 2

The second research question was formulated as *how can shop floor productivity be improved?* Productivity is defined as the ratio between outputs and inputs. The straightforward answer to RQ2 is that productivity can be improved by using less input to provide constant or increased levels of output. This is of course not a satisfactory answer.

Instead, productivity improvements must be related to aspects such as what type of improvement should be implemented, when should it be implemented and why should it be implemented? Sink et al. (1984) suggest that any improvement action must consider the preference of possible outcomes. That is, an improvement proposal must clarify what a firm's resources should devote their attention to. Second, there must be a belief about cause and effect. That is, the suggested improvement proposal must explain the methods and techniques that should be used in order to successfully attain goals and objectives. Finally, the improvement proposal must suggest a desirable standard. This element refers to whether, and how well, goals and objectives are accomplished.

It is argued that the theory of performance frontier can be used to guide managers concerning strategic directions for such improvement proposals. However, Sarmiento et al. (2008) assert that the illustrations and statements made by Schmenner and Swink (1998) are valuable and insightful but also have some limitations:

1. They do not state that any manufacturing firm can, at any point in time, make fair assessments of its performance compared to the industry and competitors, while also comparing its own internal performance over a period of time.
2. It has not been clarified that organisations are able to make these two types of assessments (internal and external) for each individual area of manufacturing.
3. They do not clarify whether the performance frontiers and the phenomena that take place inside their boundaries should be measured, and if so, how they should be measured.

The revised performance frontier theory (RPF) resolves these limitations by expanding to involve lower level measurement provided by the productivity dimension framework. The RPF theory explains how shop floor productivity can be assessed in a capacity-time diagram. The frontiers serve as constraints and goals simultaneously. The original performance frontier theory proposed that performance can be measured according, for example, to the competitive priorities formulated by Skinner (1969), e.g. quality or flexibility against a relevant input measure, such as cost (Clark, 1996). Vastag (2000) pointed out that cost is also regarded as a performance measure, i.e. a determinant of the overall performance of the firm. Instead Vastag (2000) suggests that performance should be measured by means of a performance index such as the practice-performance index used by Voss et al. (1995). An equivalent index is the level of production engineering used in the PPA method (Almström and Kinnander, 2011).

Using indices as comparative measures has inherent pitfalls. It can be argued that there is little or no causality between a firm's performance in terms of financial measures, for instance profitability, and production practices. Moreover, Lapré and Scudder (2004) assert that the key question is whether improvements should be attempted on one dimension at a time (e.g. quality or speed) or whether a company should attempt to improve several dimensions simultaneously. This question adds to the discussion, since the one dimension at a time approach would suggest that a performance index is unnecessary given that only one dimension needs to measured, for instance quality. The simultaneous approach would instead suggest that several improvement programmes could be launched and thus affect a performance index positively.

This thesis provides an alternative approach by measuring performance as capacity provided by one or a set of defined production processes. How this capacity is provided can subsequently be evaluated with performance measures, for instance throughput time, quality yield and resource utilization. The rationale for this approach is that capacity ultimately matters. Real capacity is determined by several factors such as quality yields, set-up times and processing times. The targeted capacity is referred to as ideal capacity and is set by predetermined time systems. The objectives of each specific production process are accordingly set by management decisions, i.e. the desired state. Non-financial performance measures such as quality and inventory turnover thus reveal opportunities for improvements and provide guidelines as to where to initiate improvements in each process.

In the short term, the relative position of the operating frontier has the greatest influence on the competitive position of a firm (Vastag, 2000). This relative position can be improved through alteration (production policy improvements) or cumulative capability improvements (real capacity improvements), which include both engineering changes and workforce training. A current state analysis of a defined production process will indicate the potentials by revealing utilization and performance losses that can be used for improving the process' real capacity. The alteration of the operating frontier is related to customer requirements, i.e. the capacity that the customer is requesting and when. Cumulative process improvements will serve to enable policy changes. The improvement strategy for achieving cumulative improvements is suggested to follow the results of previous research by starting with quality considerations and thereafter dependability considerations, striving to reduce internal production process variations (Schroeder et al., 2010, Flynn and Flynn, 2004, Ferdows and De Meyer, 1990).

Alteration of the operating frontier is determined by policy decisions. According to Modig and Åhlström (2012), optimal labour utilization and performance is a trade-off between the production system's variance handling capability and cost. Based on the RPF theory presented in this thesis, this trade-off is similar to the cost of planned production capacity and the production system's variance handling capability, i.e. the evident gap between CAP_{PL} and CAP_{U}. However, every improvement that increases the throughput rate of a defined process is advantageous. In that sense, such improvement increases flexibility since the gap between planned capacity and available capacity will increase. This time can be used for several purposes – for instance, new product introduction, greater opportunities to handle emergency orders, greater opportunities to change production schedules, etc.

The last improvements presented in this thesis are inventory policy improvements. This type of improvement action is actually a decision rather than an improvement. The decision is to restrain material inflows, which has both operational and economic consequences. These are also discussed under research question 3.

6.1.3 Research question 3

The third research question was formulated as *what is the financial benefit of shop floor productivity improvements?* This question is this thesis' ultimate concern. As described in the introductory chapter, any firm's paramount business objective is to create wealth for the its owners, employees and surrounding society. Research within operations management has traditionally focused on either operational or economic concerns. Productivity is a performance measure that fits well into this category. Since the 1950s, an abundance of productivity models concerning firms' productivity and price recovery ability have emerged. Their pitfall is, as previously discussed, their inability to provide managers with information that actually supports productivity improvement actions. On the other hand, non-financial surrogate productivity models have emerged from the 1980s and onwards that provide managers with information regarding production process deficiencies, such as availability losses, quality losses and speed losses. However, the bridge between those two extremes has not been sufficiently investigated. An exception, which has been very influential in practice, is the balanced scorecard presented by Kaplan and Norton (1996). The balanced scorecard links strategic objectives for customers, financial, internal and learning with a set of strategic measures. However, the balanced scorecard does not explain the relations between these measures in a direct fashion.

The strength of the productivity analysis model depicted in Chapter 5.10 is its bottom-up approach that collects shop floor data, which can be translated, to financial benefits in a direct fashion. What distinguishes this approach from those previously mentioned is that the relative capacity improvement can be appraised in monetary terms and thus constitute the underlying rationale for all improvements.

The primary objective of traditional improvement projects has often been to complete projects at the earliest possible time (Baroum and Patterson, 1996). As a consequence, management of cash flows are usually assigned secondary importance in comparison to other project objectives. This is especially true in projects for which a deadline must be met to avoid economic penalties. However, several authors argue that the proper objective of improvement projects should be to optimize net present values (Etgar et al., 1997). The rationale for optimizing net present values is that shorter project durations may not yield the highest return on investments.

The cash flow analysis framework suggests that certain outflows and inflows of cash correspond to specific phases of the proposed improvement project. Traditional project scheduling algorithms have been based on two fundamental assumptions (Elmaghraby and Herroelen, 1990):

1. Net cash flows magnitudes are independent of the time of their occurrence.
2. Net cash flows are known *a priori*.

In practice, these assumptions have made managers attempt to improve present values of projects by overprice tasks that are performed in early phases and under-price tasks that are completed later (Elmaghraby and Herroelen, 1990). A cash flow analysis requires estimates of several parameters – for instance, the number of activities and events, duration of activities, time of occurrence of events, discount factors, net cash flows associated with events, etc. Additionally, they are subject to constraints such as precedence constraints, budget constraints, and resource availability constraints. The cash flow analysis framework does not address these issues. However, it provides additional financial effects that can be used in project investment algorithms, etc. Additionally, it covers how cash flow changes emerge from real capacity improvements, production policy improvements and inventory policy improvements.

6.2 Research methodology concerns

The purpose of this research initiative has been related both to theory building and to theory extension. The research questions have been formulated to explain key variables of a certain phenomenon (shop floor productivity) and the linkages between these variables. According to Voss et al. (2002), case study research typically suits this type of research concern. The result is an explanatory framework that bears on existing theory. The research initiative is thus of a cumulative nature. It is based primarily on previous research conducted by Almström and Kinnander (2011) and on the theory presented by Schmenner and Swink (1998).

6.2.1 Reliability

The replicability of this research project is considered to be high. The foundation of this research initiative is the well-standardized PPA method. The method is publicly available and well-documented. These documents are also presented in Appendix A. All cases in Study II have been subjected to the PPA standard analysis procedure and data have been saved to the PPA database. The complete data collection procedure is also described in Chapter Three, ensuring the transparency of the research study. The interview questions that relate to Study I and Study III are found in Appendix B and Appendix C.

The repeatability, i.e. the consistency of the measurement parameters, is also high. For instance, the work sampling technique that is widely used within this research project has been statistically evaluated (Niebel and Freivalds, 2003). Overall, the data-collection techniques that have been used in this research project are regarded as well-established industrial engineering techniques designed to ensure little variation as an effect of the analyst's previous experience and knowledge. The predetermined time system SAM has been specifically designed to minimize user errors by reducing the number of decisions the user faces. The overall research design and the case study design are congruent with respect to reliability and replicability concerns.

6.2.2 Validity

Validity can be decomposed into construct validity (measurement validity), internal validity and external validity (see Chapter 3.6.2).

Construct validity concerns the measurements used in this research initiative. As previously explained, these are well-established performance measures explicitly stated to measure the performance of production processes in various manners. The strength of this research project is the primary use of first-order data collection methods employed directly for shop floors. Also, by avoiding scales that need to be interpreted, it strengthens the construct validity of the collected data.

The internal validity of this research project is its weakest link. However, the focus has been on theory building rather than theory testing. This implies that internal validity is currently a minor concern. Furthermore, the explanatory framework bears upon existing laws and theories. For instance, Little's Law has been used to derive the shop floor improvement framework and the RPF theory is an extension of work by Schmenner and Swink (1998) and Vastag (2000). Also, the use of research techniques such as iterative triangulation (explanatory framework) and investigator triangulation (study III) adds to the establishment of internal validity (Yin, 2009).

External validity concerns generalizability of the study, i.e. whether conclusions can be extended beyond the specific research context. Since a theory has been developed but not tested, generalizability remains to be tested.

6.3 Future work

This thesis is as previously discussed, of a theory-generating nature. The future work is consequently related to testing and validating the proposed theory and associated frameworks. There are several aspects of this testing phase that need to be considered. First, the set of frameworks that have been presented is intended for practical use. It is thus of interest to investigate how this analysis is performed in practice. This concerns issues such as the production areas to be analysed, time consumption for analysis, availability of data, opportunities for simulating future scenarios, opportunities for visualizing results, etc.

From an academic perspective, consideration must be paid to how the theory and related frameworks should be tested. There are also several question marks regarding the content of the proposed improvement actions. Three improvements actions have been proposed that provides financial benefits: real capacity improvements, production policy improvements and inventory policy improvements. However, this thesis does not cover the actions and activities that need to be performed for reaching desired states. In practice, this could be examined by following a set of improvement projects and recording all activities and actions related to the project, continuously monitoring cash transactions, establishing and following capacity measures, establishing and following M, P and U variables, etc. The inquiry is thus to test causality between each improvement action and suggested financial effects.

Finally, the research group's aggregate objective is to establish an IT-based decision support tool able that incorporates the explanatory framework into the production system model. This task involves difficulties related to any product development, that is, required skills, knowledge, resources, time, etc.

7. Conclusions

Previous research has revealed that firms' resource utilization figures are surprisingly low. Many of these utilization losses are unnecessary and correspond to significant economic losses and thus competitive disadvantages. Meanwhile, productive time is lost for resolving quality issues, repairing equipment breakdowns and looking for tools and utilities to perform setups and adjustments. The contemporary investment climate in more productive and failsafe equipment seems to be declining or at least lingering at historically low levels. Uncertainty and volatility characterise predictions of the global economy development. The aggregate picture that can be drawn from these observations regarding production investments is that future investment decisions in both fixed and current assets require an increased level of certainty based on investment calculation methods that look beyond traditional investment concerns, such as residual value, lifetime, interest rates and initial investment costs.

This thesis presents a refined theory to explain how investments affect organizational efficiency and effectiveness. It is argued that the capacity of a production system is the ultimate investment concern. This thesis provides a framework that explains how productivity potentials can be exploited to improve the capacity of production processes that can subsequently be translated into monetary terms. The explanatory framework also identifies improvement actions that provide economic benefits to capture financial benefits of current accounting concepts and rules.

The framework is intended for use as a decision support tool for industry practitioners. The explanatory framework provides a productivity analysis model that consists of a set of frameworks incorporated into a production system model. The constituent parts of the model are:

- A productivity analysis framework that uses standardized industrial engineering tools and techniques to collect shop floor productivity data.
- A shop floor improvement framework that suggests three improvement actions: real capacity improvements, production policy improvements and inventory policy improvements. All of these improvements provide financial benefits.
- A refined theory that explains how production capacity can be evaluated and improved.
- A cash flow analysis framework that can be incorporated into traditional investment methods to calculate the value of productivity improvements.

8. References

Accenture 2013. Accenture 2013 global manufacturing study - How leading manufacturers thrive in a world of ongoing volatility and uncertainty.

Adam, E. E., Corbett, L. M., Flores, B. E., Harrison, N. J., Lee, T. S., Rho, B.-H., Ribera, J., Samson, D. & Westbrook, R. 1997. An international study of quality improvement approach and firm performance. *International Journal of Operations & Production Management,* 17**,** 842-873.

Adler, P. S., Benner, M., Brunner, D. J., Macduffie, J. P., Osono, E., Staats, B. R., Takeuchi, H., Tushman, M. L. & Winter, S. G. 2009. Perspectives on the productivity dilemma. *Journal of Operations Management,* 27**,** 99-113.

Adler, P. S. & Clark, K. B. 1991. Behind the Learning Curve: A Sketch of the Learning Process. *Management Science,* 37**,** 267-281.

Ahire, S. L. & Dreyfus, P. 2000. The impact of design management and process management on quality: an empirical investigation. *Journal of Operations Management,* 18**,** 549-575.

Ahlstrom, P. & Karlsson, C. 1996. Change processes towards lean production The role of the management accounting system. *International Journal of Operations & Production Management,* 16**,** 42-56.

Almström, P. Performance and utilization factors for manual and semi-automated work. In the proceedings of the EurOMA 2013 conference, Dublin, 2013.

Almström, P. & Kinnander, A. Results and conclusions from the productivity potential assessment studies. Proceedings of the 2nd Swedish Production Symposium, 2008.

Almström, P. & Kinnander, A. 2011. The productivity potential assessment method: Assessing and benchmarking the improvement potential in manufacturing systems at shop-floor level. *International Journal of Productivity and Performance Management,* 60**,** 758-770.

Anzanello, M. J. & Fogliatto, F. S. 2011. Learning curve models and applications: Literature review and research directions. *International Journal of Industrial Ergonomics,* 41**,** 573-583.

Armitage, H. M. & Atkinson, A. A. 1990. The choice of productivity measures in organizations. *Measures for Manufacturing Excellence***,** 91-126.

Auerbach, C. F. & Silverstein, L. B. 2003. *Qualitative data: An introduction to coding and analysis*, NYU press.

Banker, R. D., Chang, H.-H. & Majumdar, S. K. 1993. Analyzing the Underlying Dimensions of Firm Profitability. *Managerial and Decision Economics,* 14**,** 25-36.

Barney, J., Wright, M. & Ketchen, D. J. 2001. The resource-based view of the firm: Ten years after 1991. *Journal of management,* 27**,** 625-641.

Barney, J. B., Ketchen, D. J. & Wright, M. 2011. The future of resource-based theory revitalization or decline? *Journal of Management,* 37**,** 1299-1315.

Baroum, S. M. & Patterson, J. H. 1996. The development of cash flow weight procedures for maximizing the net present value of a project. *Journal of Operations Management,* 14**,** 209-227.

Bauer, A., Bowden, R., Brown, J., Duggan, J. & Lyons, G. 1994. *Shoop Floor Control Systems: From Design to Implementation,* Ipswich Book Company, Sufflok, GB, Chapman & Hall.

Beer, S. 1985. Diagnosing the System for Organisations Wiley. London.

Bellgran, M. & Säfsten, K. 2010. *Production development: design and operation of production systems*, Springer.

Benbasat, I., Goldstein, D. K. & Mead, M. 1987. The case research strategy in studies of information systems. *MIS quarterly*, 369-386.

Benjaafar, S. & Ramakrishnan, R. 1996. Modelling, measurement and evaluation of sequencing flexibility in manufacturing systems. *International Journal of Production Research,* 34, 1195.

Bernolak, I. 1997. Effective measurement and successful elements of company productivity: The basis of competitiveness and world prosperity. *International Journal of Production Economics,* 52, 203-213.

Bicheno, J. 2004. *The new lean toolbox: towards fast, flexible flow*, Picsie Books Buckingham.

Blair, J., Czaja, R. F. & Blair, E. A. 2013. *Designing surveys: A guide to decisions and procedures*, SAGE Publications, Incorporated.

Blanchard, B. S. & Fabrycky, W. J. 1998. *Systems engineering and analysis*, Prentice Hall Englewood Cliffs, New Jersey.

Bourne, M., Neely, A., Platts, K. & Mills, J. 2002. The success and failure of performance measurement initiatives: perceptions of participating managers. *International journal of operations & production management,* 22, 1288-1310.

Bourne, M., Pavlov, A., Franco-Santos, M., Lucianetti, L. & Mura, M. 2013. Generating organisational performance: The contributing effects of performance measurement and human resource management practices. *International Journal of Operations & Production Management,* 33, 1599-1622.

Breyfogle Iii, F. W. 2003. *Implementing Six Sigma: smarter solutions using statistical methods*, Wiley. com.

Brox, J. A. & Fader, C. 2002. The set of just-in-time management strategies: An assessment of their impact on plant-level productivity and input-factor substitutability using variable cost function estimates. *International Journal of Production Research,* 40, 2705-2720.

Bryman, A. & Bell, E. 2011. *Business research methods*, Oxford university press.

Byers, S. S., Groth, J. C., Richards, R. M. & Wiley, M. K. 1997. Capital investment analysis for managers. *Management decision,* 35, 250-257.

Cakmakci, M. & Karasu, M. 2007. Set-up time reduction process and integrated predetermined time system MTM-UAS: A study of application in a large size company of automobile industry. *The International Journal of Advanced Manufacturing Technology,* 33, 334-344.

Capkun, V., Hameri, A.-P. & Weiss, L. A. 2009. On the relationship between inventory and financial performance in manufacturing companies. *International Journal of Operations & Production Management,* 29, 789-806.

Chenhall, R. H. & Langfield-Smith, K. 2007. Multiple perspectives of performance measures. *European Management Journal,* 25, 266-282.

Choong, K. K. 2013. Has this large number of performance measurement publications contributed to its better understanding? A systematic review for research and applications. *International Journal of Production Research*, 1-24.

Clark, K. B. 1996. Competing through manufacturing and the new manufacturing paradigm: is manufacturing strategy passé? *Production and Operations Management,* 5, 42-58.

Clegg, B., Macbryde, J. & Dey, P. 2013. Trends in modern operations management. *International Journal of Operations & Production Management,* 33.

Coelli, T., Grifell-Tatjé, E. & Perelman, S. 2002. Capacity utilisation and profitability: A decomposition of short-run profit efficiency. *International Journal of Production Economics,* 79**,** 261-278.
Combs, J., Liu, Y., Hall, A. & Ketchen, D. 2006. How much do high-performance work practices matter? A meta-analysis of their effects on organizational performance. *Personnel Psychology,* 59**,** 501-528.
Craig, C. E. & Harris, R. C. 1973. Total Productivity Measurement at the Firm Level. *Sloan Management Review (pre-1986),* 14**,** 13-13.
Dal, B., Tugwell, P. & Greatbanks, R. 2000. Overall equipment effectiveness as a measure of operational improvement–a practical analysis. *International Journal of Operations & Production Management,* 20**,** 1488-1502.
Dangayach, G. & Deshmukh, S. 2001. Manufacturing strategy: literature review and some issues. *International Journal of Operations & Production Management,* 21**,** 884-932.
De Meyer, A., Nakane, J., Miller, J. G. & Ferdows, K. 1989. Flexibility: the next competitive battle the manufacturing futures survey. *Strategic Management Journal,* 10**,** 135-144.
De Ron, A. & Rooda, J. 2005. Equipment effectiveness: OEE revisited. *Semiconductor Manufacturing, IEEE Transactions on,* 18**,** 190-196.
De Toni, A. & Tonchia, S. 2001. Performance measurement systems - Models, characteristics and measures. *International Journal of Operations & Production Management,* 21**,** 46-71.
Deloof, M. 2003. Does working capital management affect profitability of Belgian firms? *Journal of Business Finance & Accounting,* 30**,** 573-588.
Dettmer, H. W. 1997. *Goldratt's theory of constraints: a systems approach to continuous improvement*, ASQ Quality Press.
Drake, P. P. & Fabozzi, F. J. 2012. *Analysis of Financial Statements*, John Wiley & Sons.
Drucker, P. 1954. The principles of management. *New York*.
Dutton, J. M. & Thomas, A. 1984. Treating Progress Functions as a Managerial Opportunity. *The Academy of Management Review,* 9**,** 235-247.
Elmaghraby, S. E. & Herroelen, W. S. 1990. The scheduling of activities to maximize the net present value of projects. *European Journal of Operational Research,* 49**,** 35-49.
Ernst Eder, W. 2010. Engineering design science and theory of technical systems: legacy of Vladimir Hubka. *Journal of Engineering Design,* 22**,** 361-385.
Eroglu, C. & Hofer, C. 2011. Lean, leaner, too lean? The inventory-performance link revisited. *Journal of Operations Management,* 29**,** 356-369.
Etgar, R., Shtub, A. & Leblanc, L. J. 1997. Scheduling projects to maximize net present value — the case of time-dependent, contingent cash flows. *European Journal of Operational Research,* 96**,** 90-96.
Fare, R., Grosskopf, S. & Kokkelenberg, E. C. 1989. Measuring Plant Capacity, Utilization and Technical Change: A Nonparametric Approach. *International Economic Review,* 30**,** 655-666.
Farris Ii, M. T. & Hutchison, P. D. 2002. Cash-to-cash: the new supply chain management metric. *International Journal of Physical Distribution & Logistics Management,* 32**,** 288-298.
Feder, G. 1983. On exports and economic growth. *Journal of Development Economics,* 12**,** 59-73.

Ferdows, K. & De Meyer, A. 1990. Lasting improvements in manufacturing performance: In search of a new theory. *Journal of Operations Management,* 9**,** 168-184.
Fioretti, G. 2007. The organizational learning curve. *European Journal of Operational Research,* 177**,** 1375-1384.
Fitzgerald, L., Brignall, S., Silvestro, R., Voss, C. & Robert, J. 1991. *Performance measurement in service businesses*, Chartered Institute of Management Accountants London.
Flood, R. L. 1993. *Dealing with complexity: an introduction to the theory and application of systems science*, Springer.
Flynn, B. B. & Flynn, E. J. 2004. An exploratory study of the nature of cumulative capabilities. *Journal of Operations Management,* 22**,** 439-457.
Friedlob, G. T. & Plewa Jr, F. J. 1996. *Understanding return on investment*, John Wiley & Sons.
García-Teruel, P. J. & Martínez-Solano, P. 2007. Effects of working capital management on SME profitability. *International Journal of Managerial Finance,* 3**,** 164-177.
Ghalayini, A. M. & Noble, J. S. 1996. The changing basis of performance measurement. *International Journal of Operations & Production Management,* 16**,** 63-80.
Gold, B. 1955. *Foundations of productivity analysis*, University of Pittsburgh Press.
Goodson, R. E. 2002. Read a plant-Fast. *Harvard Business Review,* 80**,** 105-113.
Groth, J. C. & Anderson, R. C. 1997. The cost of capital: perspectives for managers. *Management Decision,* 35**,** 474-482.
Hahn, G. J. & Kuhn, H. 2011. Optimising a value-based performance indicator in mid-term sales and operations planning. *The Journal of the Operational Research Society,* 62**,** 515-525.
Harlin, U., L, M. A., L., M., B., S., C., W., Gullander, P., M., H. & P-Å., S. 2009. LeanNavigatorn - Ett dialogverktyg för utveckling av konkurrenskraftiga
produktionssystem inspirerat av Lean.
Hayes, R. H. & Clark, K. B. 1986. Why some factories are more productive than others. *Harvard Business Review,* 64**,** 66-73.
Hayes, R. H. & Pisano, G. P. 1996. Manufacturing strategy: at the intersection of two paradigm shifts. *Production and operations management,* 5**,** 25-41.
Hayes, R. H. & Wheelwright, S. G. 1979. The dynamics of process-product life cycles. *Harvard Business Review,* 57**,** 127-136.
Hedman, R. 2013. *Manufacturing Resource Modelling for Productivity Management.* Licentiate thesis, Chalmers tekniska högskola.
Helmrich, K. 2003. Productivity process: Methods and experiences of measuring and improving. *International MTM Directorate, Stockholm, Sweden*.
Hendricks, K. B. & Singhal, V. R. 2001. Firm characteristics, total quality management, and financial performance. *Journal of Operations Management,* 19**,** 269-285.
Herron, C. & Braiden, P. M. 2006. A methodology for developing sustainable quantifiable productivity improvement in manufacturing companies. *International Journal of Production Economics,* 104**,** 143-153.
Hicks, B. J. 2007. Lean information management: Understanding and eliminating waste. *International Journal of Information Management,* 27**,** 233-249.
Holmes, A. W. & Overmyer, W. S. 1972. *Basic auditing principles*, RD Irwin.
Hopp, W. J. & Spearman, M. L. 2008. *Factory physics*, McGraw-Hill/Irwin New York.
Imd 2004. SAM - Sequential Activity – and Methods Analysis - System description. International MTM Directorate.

Iso10303-1 Industrial automation systems and integration - Product data representation and exchange.

Iso15531-1 Industrial automation systems and integration - Industrial manufacturing management data.

Iso15531-32 Industrial automation systems and integration – Industrial manufacturing management data – Resource usage management data: Conceptual model for resources usage management data. Geneva, Switzerland.

Johansen, L. 1968. *Production functions and the concept of capacity*, University of Oslo, Institute of Economics.

Johnson, H. T. 1991. *Relevance lost: The rise and fall of management accounting*, Harvard Business Press.

Johnson, H. T. & Kaplan, S. R. 1991. *Relevance lost: the rise and fall of management accounting*, Harvard Business Press.

Jonsson, P. & Lesshammar, M. 1999. Evaluation and improvement of manufacturing performance measurement systems - the role of OEE. *International Journal of Operations & Production Management,* 19**,** 55-78.

Kaplan, R. S. 1983. Measuring Manufacturing Performance: A New Challenge for Managerial Accounting Research. *The Accounting Review,* 58**,** 686-705.

Kaplan, R. S. 1998. *Cost & effect: Using integrated cost systems to drive profitability and performance*, Harvard Business Press.

Kaplan, R. S. & Anderson, S. R. 2007. *Time-driven activity-based costing: a simpler and more powerful path to higher profits*, Harvard business press.

Kaplan, R. S. & Norton, D. P. 1996. *The balanced scorecard: translating strategy into action*, Harvard Business Press.

Karlsson, C. 2009. *Researching Operations Management*, Taylor & Francis.

Kaynak, H. 2003. The relationship between total quality management practices and their effects on firm performance. *Journal of Operations Management,* 21**,** 405-435.

Kennerley, M. & Neely, A. 2002. Performance measurement frameworks: a review. *Business performance measurement: Theory and practice***,** 145-154.

Klenow, P. J. 1998. Learning Curves and the Cyclical Behavior of Manufacturing Industries. *Review of Economic Dynamics,* 1**,** 531-550.

Kraaijenbrink, J., Spender, J.-C. & Groen, A. J. 2010. The resource-based view: a review and assessment of its critiques. *Journal of Management,* 36**,** 349-372.

Kuhlang, P., Edtmayr, T. & Sihn, W. 2011. Methodical approach to increase productivity and reduce lead time in assembly and production-logistic processes. *CIRP Journal of Manufacturing Science and Technology,* 4**,** 24-32.

Lapré, M. A. & Scudder, G. D. 2004. Performance Improvement Paths in the U.S. Airline Industry:Linking Trade-offs to Asset Frontiers. *Production and Operations Management,* 13**,** 123-134.

Leong, G. K., Snyder, D. L. & Ward, P. T. 1990. Research in the process and content of manufacturing strategy. *Omega,* 18**,** 109-122.

Letmathe, P., Schweitzer, M. & Zielinski, M. 2012. How to learn new tasks: Shop floor performance effects of knowledge transfer and performance feedback. *Journal of Operations Management,* 30**,** 221-236.

Lewis, M. W. 1998. Iterative triangulation: a theory development process using existing case studies. *Journal of Operations Management,* 16**,** 455-469.

Li, J. & Meerkov, S. M. 2009. *Production systems engineering*, Springer.

Lifland, S. A. 2010. The Corporate Soap-Opera “As the Cash Turns”: Management of Working Capital and Potential External Financing Needs. *The Peter J. Tobin College of Business*, 35.
Little, J. D. 2011. OR FORUM—Little's Law as Viewed on Its 50th Anniversary. *Operations Research,* 59, 536-549.
Ljungberg, Õ. 1998. Measurement of overall equipment effectiveness as a basis for TPM activities. *International Journal of Operations & Production Management,* 18, 495-507.
Long, J. B. D. & Summers, L. H. 1991. Equipment Investment and Economic Growth. *The Quarterly Journal of Economics,* 106, 445-502.
Löfsten, H. 2000. Measuring maintenance performance – in search for a maintenance productivity index. *International Journal of Production Economics,* 63, 47-58.
Mccreery, J. K., Krajewski, L. J., Leong, G. K. & Ward, P. T. 2004. Performance implications of assembly work teams. *Journal of Operations Management,* 22, 387-412.
Mckinsey Global Institute, M. 2012. Manufacturing the future: The next era of global growth and innovation. McKinsey Operations Practice.
Meade, D., Kumar, S. & White, B. 2009. Analysing the impact of the implementation of lean manufacturing strategies on profitability. *Journal of the Operational Research Society,* 61, 858-871.
Melnyk, S. A., Stewart, D. M. & Swink, M. 2004. Metrics and performance measurement in operations management: dealing with the metrics maze. *Journal of Operations Management,* 22, 209-218.
Meredith, J. 1993. Theory building through conceptual methods. *International Journal of Operations & Production Management,* 13, 3-11.
Meredith, J. 1998. Building operations management theory through case and field research. *Journal of operations management,* 16, 441-454.
Meredith, J. R., Raturi, A., Amoako-Gyampah, K. & Kaplan, B. 1989. Alternative research paradigms in operations. *Journal of operations management,* 8, 297-326.
Miller, D. M. 1984. Profitability=productivity + price recovery. *Harvard Business Review,* 62, 145-153.
Miltenburg, J. 2005. *Manufacturing strategy: how to formulate and implement a winning plan*, Productivity Press.
Modi, S. B. & Mishra, S. 2011. What drives financial performance,Äìresource efficiency or resource slack?: Evidence from U.S. Based Manufacturing Firms from 1991 to 2006. *Journal of Operations Management,* 29, 254-273.
Modig, N. & Åhlström, P. 2012. *This is Lean: Resolving the Efficiency Paradox*, Rheologica.
Morrison, C. J. 1985. Primal and Dual Capacity Utilization: An Application to Productivity Measurement in the U.S. Automobile Industry. *Journal of Business & Economic Statistics,* 3, 312-324.
Muchiri, P. & Pintelon, L. 2008. Performance measurement using overall equipment effectiveness (OEE): literature review and practical application discussion. *International Journal of Production Research,* 46, 3517-3535.
Nakajima, S. 1988. *Introduction to TPM: Total Productive Maintenance,* Cambridge, MA, Productivity Press.
Nakayama, S. I., Nakayama, K. I. & Nakayama, H. 2002. A study on setting standard time using work achievement quotient. *International journal of production research,* 40, 3945-3953.

Neely, A., Gregory, M. & Platts, K. 1995. Performance measurement system design: a literature review and research agenda. *International journal of operations & production management,* 15**,** 80-116.

Neely, A., Gregory, M. & Platts, K. 2005. Performance measurement system design: a literature review and research agenda. *International Journal of Operations & Production Management,* 25**,** 1228-1263.

Nembhard, D. A. & Uzumeri, M. V. 2000. An individual-based description of learning within an organization. *Engineering Management, IEEE Transactions on,* 47**,** 370-378.

Niebel, B. & Freivalds, A. 2003. *Methods, standards, and work design*, McGraw-Hill Boston, MA.

Ohno, T. 1988. *Toyota production system: beyond large-scale production*, Productivity press.

Olhager, J., Rudberg, M. & Wikner, J. 2001. Long-term capacity management: Linking the perspectives from manufacturing strategy and sales and operations planning. *International Journal of Production Economics,* 69**,** 215-225.

Paranko, J. 1996. Cost of free capacity. *International Journal of Production Economics,* 46–47**,** 469-476.

Petrin, A. & Levinsohn, J. 2012. Measuring aggregate productivity growth using plant‐level data. *The RAND Journal of Economics,* 43**,** 705-725.

Porter, M. E. 1980. Competitive strategy: Techniques for analyzing industry and competitors. *Competitive strategy: techniques for analyzing industry and competitors*.

Primrose, P. 1992. The value of inventory savings. *International Journal of Operations & Production Management,* 12**,** 79-92.

Prokopenko, J. 1992. *Productivity management: a practical handbook*, International Labour Organization.

Radhakrishnan, S. & Srinidhi, B. 1994. Should Quality Be Designed In or Inspected In? A Cost-Of-Quality Framework. *Quality Management Journal,* 2.

Radnor, Z. J. & Barnes, D. 2007. Historical analysis of performance measurement and management in operations management. *International Journal of Productivity and Performance Management,* 56**,** 384-396.

Reinhart, C. M. & Rogoff, K. S. 2009. The aftermath of financial crises. National Bureau of Economic Research.

Rosenzweig, E. D. & Easton, G. S. 2010. Tradeoffs in Manufacturing? A Meta-Analysis and Critique of the Literature. *Production and Operations Management,* 19**,** 127-141.

Sagner, J. 2010. *Essentials of Working Capital Management,* Hoboken, NJ, USA, Wiley.

Saito, S. 2001. Reducing labor costs using industrial engineering techniques. *Maynard's industrial engineering handbook***,** 2151-64.

Sakamoto, S. 2010. *Beyond World-class Productivity: Industrial Engineering Practice and Theory*, Springer.

Sarmiento, R., Sarkis, J. & Byrne, M. 2008. Manufacturing capabilities and performance: a critical analysis and review. *International Journal of Production Research,* 48**,** 1267-1286.

Sawhney, R. 2013. Implementing labor flexibility: A missing link between acquired labor flexibility and plant performance. *Journal of Operations Management,* 31**,** 98-108.

Schmenner, R. W. & Swink, M. L. 1998. On theory in operations management. *Journal of Operations Management,* 17**,** 97-113.

Schonberger, R. J. 1982. *Japanese manufacturing techniques: Nine hidden lessons in simplicity*, SimonandSchuster. com.

Schonberger, R. J. 2007. Japanese production management: An evolution—With mixed success. *Journal of Operations Management,* 25, 403-419.

Schonberger, R. J. 2008. *World class manufacturing*, The Free Press.

Schroeder, R. G., Bates, K. A. & Junttila, M. A. 2002. A resource ‐ based view of manufacturing strategy and the relationship to manufacturing performance. *Strategic management journal,* 23, 105-117.

Schroeder, R. G., Shah, R. & Xiaosong Peng, D. 2010. The cumulative capability 'sand cone' model revisited: a new perspective for manufacturing strategy. *International Journal of Production Research,* 49, 4879-4901.

Seliger, G., Viehweger, B. & Wieneke, B. 1987. Decision support in design and optimization of flexible automated manufacturing and assembly. *Robotics and Computer-Integrated Manufacturing,* 3, 221-227.

Seuring, S. 2009. The product-relationship-matrix as framework for strategic supply chain design based on operations theory. *International Journal of Production Economics,* 120, 221-232.

Shah, R. & Ward, P. T. 2003. Lean manufacturing: context, practice bundles, and performance. *Journal of Operations Management,* 21, 129-149.

Siebers, P. O., Macal, C. M., Garnett, J., Buxton, D. & Pidd, M. 2010. Discrete-event simulation is dead, long live agent-based simulation! *Journal of Simulation,* 4, 204-210.

Singh, H., Motwani, J. & Kumar, A. 2000. A review and analysis of the state-of-the-art research on productivity measurement. *Industrial Management & Data Systems,* 100, 234-241.

Sink, D. S., Tuttle, T. C. & Devries, S. J. 1984. Productivity measurement and evaluation: what is available? *National Productivity Review,* 3, 265-287.

Skinner, W. 1966. PRODUCTION Under Pressure. *Harvard Business Review,* 44, 139.

Skinner, W. 1969. *Manufacturing-missing link in corporate strategy*, Harvard Business Review.

Skinner, W. 2007. Manufacturing strategy: The story of its evolution. *Journal of Operations Management,* 25, 328-335.

Slack, N., Chambers, S. & Johnston, P. R. 2007. *Operations management*, Prentice Hall/Financial Times.

Slack, N. & Lewis, M. 2002. *Operations strategy*, Pearson Education.

Suito, K. 1998. Total productivity management. *Work Study,* 47, 117-127.

Sundkvist, R., Almström, P., Hedman, R. & Kinnander, A. 2013. The effect of factory floor productivity improvements on operational performance measures. *EurOMA 2013 7th-12th June.* Dublin, Ireland.

Sundkvist, R., Almström, P. & Kinnander, A. 2009. Manufacturing system analysis methods review. *In the proceedings of the international 3rd Swedish production symposium.*

Sundkvist, R., Hedman, R., Almström, P. & Kinnander, A. Improvement potentials in Swedish electronics manufacturing industry – Analysis of five case studies. The 45th CIRP Conference on Manufacturing Systems, 2012 Athens, Greece. 126-131.

Swamidass, P. M. & Newell, W. T. 1987. Manufacturing Strategy, Environmental Uncertainty and Performance: A Path Analytic Model. *Management Science,* 33, 509-524.

Tangen, S. 2003. An overview of frequently used performance measures. *Work study,* 52**,** 347-354.
Tangen, S. 2005. Demystifying productivity and performance. *International Journal of Productivity and Performance Management,* 54**,** 34-46.
Taylor, F. W. 1914. *The principles of scientific management*, Harper.
Teague, J. & Eilon, S. 1973. Productivity measurement: a brief survey. *Applied Economics,* 5**,** 133.
Thomas, J. & Zhang, H. 2002. Inventory Changes and Future Returns. *Review of Accounting Studies,* 7**,** 163-187.
Van Mieghem, J. A. 2003. Capacity Management,Investment, and Hedging:Review and Recent Developments. *Manufacturing & Service Operations Management,* 5**,** 269-302.
Vastag, G. 2000. The theory of performance frontiers. *Journal of Operations Management,* 18**,** 353-360.
Vastag, G. & Whybark, D. C. 1993. Global relations between inventory, manufacturing lead time and delivery date promises. *International Journal of Production Economics,* 30–31**,** 563-569.
Voss, C., Blackmon, K., Hanson, P. & Oak, B. 1995. The Competitiveness of European Manufacturing--A Four Country Study. *Business Strategy Review,* 6**,** 1.
Voss, C., Tsikriktsis, N. & Frohlich, M. 2002. Case research in operations management. *International journal of operations & production management,* 22**,** 195-219.
Wernerfelt, B. 1984. A Resource-Based View of the Firm. *Strategic Management Journal,* 5**,** 171-180.
Wheelwright, S. C. 1984. Manufacturing Strategy: Defining the Missing Link. *Strategic Management Journal (pre-1986),* 5**,** 77.
White, G. 2006. *THE ANALYSIS AND USE OF FINANCIAL STATEMENTS, (With CD)*, Wiley. com.
Wilcox, M. & Bourne, M. 2003. Predicting performance. *Management Decision,* 41**,** 806-816.
Williamson, K. & Bow, A. 2002. *Research methods for students, academics and professionals: Information management and systems*, Centre for Information Studies, Charles Sturt University.
Womack, J. P., Jones, D. T. & Roos, D. 2007. *The machine that changed the world: The story of lean production--Toyota's secret weapon in the global car wars that is now revolutionizing world industry*, SimonandSchuster. com.
Wren, D. A. 1987. Management History: Issues and Ideas for Teaching and Research. *Journal of Management,* 13**,** 339.
Wu, B. 1994. *Manufacturing systems design and analysis*, Springer.
Yin, R. K. 2009. *Case Study Research: Design and Methods*, SAGE Publications.
Youndt, M. A., Snell, S. A., Dean, J. J. W. & Lepak, D. P. 1996. HUMAN RESOURCE MANAGEMENT, MANUFACTURING STRATEGY, AND FIRM PERFORMANCE. *Academy of Management Journal,* 39**,** 836-866.
Zequeira, R. I., Valdes, J. E. & Berenguer, C. 2008. Optimal buffer inventory and opportunistic preventive maintenance under random production capacity availability. *International Journal of Production Economics,* 111**,** 686-696.
Zijm, W. H. M. & Buitenhek, R. 1996. Capacity planning and lead time management. *International Journal of Production Economics,* 46–47**,** 165-179.

Appendix A – Productivity Potential Assessment (PPA) documents

Table A1: Company facts

Turnover		
Operating results		
Investments		
Number of employees		
Type of products		
Type of production		
SNI code		
Owner		Family company
		Private (not listed)
		Public (listed)
Company structure		Part of a group
		Independent company
Number of customers		Few
		Many
Size of customers		Large
		Small
Number of suppliers		Few
		Many
Size of suppliers		Large
		Small
Number of products		Few
		Many
Product development		Company's own products
		Development responsibility for subsystems
		Participation in customers' product development
		None

Wage system		Fixed wage
		Fixed wage + any bonus
		Partly flexible wage
		Completely flexible wage
Qualifying and order-winning criteria (Mark qualifying with a Q and rank order-winning with 1,2,3 etc.)		Quality
		Price (cost)
		Cost-reducing ability
		Delivery ability, capacity
		Delivery accuracy
		Flexibility
		Product: characteristics, performance or design
		Service (post-market)
		Marketing
		Geographic proximity to customer
		Organisational proximity
		Product development competence
		Risk inclination
Production cost		Material cost, per cent
		Cost for operators, per cent
		Other personnel cost, per cent
		Machine cost, per cent
		Energy cost, per cent
		Other, per cent
Level of automation in the unit studied		Process industry
		Completed automatic production
		Semi-automatic production
		Manual production

Table A2: PPA parameters - Level 1

Efficiency: Labour		
	Value	Unit
Value-adding		%
Supporting		%
Disturbance		%
Efficiency: Machines		
	Value	Unit
OEE		%

Table A3: PPA parameters - Level 2

Speediness		
	Value	Unit
Inventory turnover rate		times
Reliability		
	Value	Unit
Delivery precision		%
Quality		
	Value	Unit
Scrap rate		%
Customer reject rate		%

Table A4: PPA parameters - Level 3 (aggregate)

Level of production engineering		
Number of affirmative responses		Scale from 1 to 40
Work environment		
	Value	Unit
Short absenteeism (<2 weeks)		%
Total absenteeism		%

Personnel turnover		%
Physical workload		Scale from 1 to 5
Physical work environment		Scale from 1 to 5
Psychosocial work environment		Scale from 1 to 5

Table A5: Level of production engineering

Area	**Question**	Yes	No
Strategy-goals	1. Can the management present a clear production strategy, based on qualifying and order-winning criteria?		
	2. Has the strategy been converted into measurable goals for production?		
	3. Are the goals followed up regularly and is the follow-up available to production personnel?		
	4. Is the outcome of the goal fulfilment connected to any kind of reward?		
Work method	5. Is a standardized work method used and is it documented?		
	6. Is the standardized work method changed if the operator finds a better work method?		
	7. Are more than one machine run at a time?		
Maintenance	8. Are stop times measured and are causes of stops documented?		
	9. Are stop times measured by an automatic system?		
	10. Are causes of short stops followed up and remedied?		
	11. Is preventive maintenance performed?		
	12. Is condition-based maintenance performed?		
Competence	13. Is there anyone who has the responsibility and competence to measure manual labour?		
	14. Is the work manager able to perform all work tasks?		
	15. Is there a competence development plan?		
Cleanliness and order	16. Do all materials, all tools and so on have their own places and are they always there?		

	17. Is there enough room around the workplace so that materials can be moved as planned?		
	18. Are floors and other surfaces free of material spill, scrapped pieces, lubricants, etc.?		
Material handling	19. Are load carriers adapted to the components?		
	20. Are suitable volumes used in relation to the way in which components are used?		
	21. Is the same load carrier used for a product as far as possible?		
	22. Are materials stored closed to the place where they are used?		
	23. Are workers independent of overhead cranes, trucks or forklifts for moving materials?		
Changeovers	24. Are changeover times measured?		
	25. Is there an active effort to decrease the changeover time in the bottleneck?		
	26. Are tools, fixtures and so on placed close to the area in which they are used?		
Continuous improvement	27. Is improvement work performed on a regular basis and in a systematic way, and is the work visualized?		
	28. Are the operators involved in improvement work?		
	29. Does the management have an understanding of the productivity potential?		
	30. Is the experience of previous improvement and development work used in a systematic way?		
Calculations	31. Does the company follow up on investment calculations?		
	32. Does the company follow up on product calculations?		
Planning	33. Is the ideal cycle time known and is it based on facts?		
	34. Are true operation times reported in the system?		
	35. Are operation times updated continuously in the planning system on the basis of the actual production outcome?		
	36. Is production planned according to pull principles if this is possible in practice?		
	37. Are lead-times or throughput times measured for the purpose of decreasing them?		

Quality	38. Is an established quality system used (for example, ISO 9000)?		
	39. Is the individual operator responsible for measuring the quality of his or her work?		
	40. Are systematic methods used to eliminate the occurrence of errors?		

PPA Psychosocial work environment

Task variation

1. To what extent does the work offer *variation*?

1-------------------2------------------3------------------4------------------5

Not at all | To a certain extent | To a very great extent

Task identity

2. To what extent does the work mean that an operator performs a *"whole and identifiable part of a piece of work"*?

1-------------------2------------------3------------------4------------------5

Not at all | To a certain extent | To a very great extent

Significance of the work to others

3. How significant are an operator's work efforts to the customer or the end-user?

1-------------------2------------------3------------------4------------------5

Not at all significant | Relatively significant | Very significant

4. How significant are an operator's work efforts to the following work or unit?

1-------------------2------------------3------------------4------------------5

Not at all significant | Relatively significant | Very significant

5. Is the operator aware of the significance of his or her own work to the next work to be done?

1-------------------2------------------3------------------4------------------5

Not at all | To a certain extent | To a very great extent

Autonomy in the work

6. To what extent is there *autonomy* with respect to the *technical* system?

1-------------------2------------------3------------------4------------------5

Not at all | To a certain extent | To a very great extent

7. To what extent is there *autonomy* with respect to the *administrative* system?

1-------------------2------------------3------------------4------------------5

Not at all | To a certain extent | To a very great extent

Opportunities for development

8. What opportunities do operators have to obtain, when necessary, a greater number of work tasks that require *similar* skills?

1-------------------2------------------3------------------4------------------5

None | Certain opportunities | Very great opportunities

9. What opportunities do operators have to obtain, when necessary, a greater number of work tasks that require *different* skills?

1-------------------2------------------3------------------4------------------5

None | Certain opportunities | Very great opportunities

Feedback

10. To what extent are operators given information concerning the results of their work?

1-------------------2------------------3------------------4------------------5

To a fairly small extent | To a certain extent | To a very great extent

11. To what extent does the *work in itself* give operators information about their work?

1-------------------2------------------3------------------4------------------5

To a fairly small extent | To a certain extent | To a very great extent

Work management

12. What is contact and cooperation between operators and their immediate supervisor like?

1-------------------2------------------3------------------4------------------5

Very unsatisfactory | Acceptable | Very satisfactory

13. To what extent does the immediate supervisor discuss various actions with operators when problems arise?

1-------------------2------------------3------------------4------------------5

Not at all | To a certain extent | To a very great extent

14. To what extent is it possible for an operator to be given the support of the immediate supervisor when needed?

1-------------------2------------------3------------------4------------------5

To a very little extent | To a certain extent | To a very great extent

15. Do the operators receive enough information about the work from their immediate supervisor?

1-------------------2------------------3------------------4------------------5

Very dissatisfied | Neither satisfied nor dissatisfied | Very satisfied

Work fellowship

16. To what extent does the work require operators to work close to others?

1-------------------2------------------3------------------4------------------5

To a very little extent | To a certain extent | To a very great extent

17. How suitable is the size of the team in relation to the work situation?

1-------------------2------------------3------------------4------------------5

Not at all | To a certain extent | To a very great extent

18. How dependent are operators on one another for performing the group's task?

1-------------------2------------------3------------------4------------------5

Not at all | Some cooperation is necessary | Everyone must cooperate

19. To what extent can operators obtain support from co-workers when necessary?

1-------------------2------------------3------------------4------------------5

To a very little extent | To a certain extent | To a very great extent

20. To what extent is it possible to talk with co-workers on the job about things that are not related to work?

1-------------------2------------------3------------------4------------------5

To a very little extent | To a certain extent | To a very great extent

21. How often do operators take breaks together?

1-------------------2------------------3------------------4------------------5

Never | Sometimes | Very often

Psychological workload

22. To what extent must work be performed under constant time pressure because of a high workload?

1-------------------2------------------3------------------4------------------5

To a very great extent | To a certain extent | To a very small extent

23. Does the work usually require overtime and cancellation of breaks?

1-------------------2------------------3------------------4------------------5

Yes, often | Sometimes | No, not all

Analysis of the psychosocial work environment

Mean value for each category:

Work contents: _____

Work management: _____

Work fellowship: _____

Work load: _____

Total mean value: _______

Is there any single parameter that is particularly noticeable and that should be paid particular attention?

Value	Assessment criteria (scale 1-5)
1	There are *very great* weaknesses in the psychosocial work environment and thus *very great* potential for improvement in this area.
2	There are *great* weaknesses in the psychosocial work environment and thus *great* potential for improvement in this area.
3	There are *certain* weaknesses in the psychosocial work environment and thus *relatively little* potential for improvement in this area.
4	There are *few* weaknesses in the psychosocial work environment and thus *little* potential for improvement in this area.
5	There are *in principle no* weaknesses in the psychosocial work environment and thus *very little* potential for improvement in this area.

PPA Physical work environment and physical workloads

Table A6: Assessment criteria

	Value	Assessment criteria (scale 1-5)
Physical workload		1: Many yes answers. Lack of awareness, obvious risks. 2: Several yes answers. Great weaknesses, large risks of injuries. 3: Few yes answers. Sporadic work with the physical workload, weaknesses exist. 4: Few yes answers. Active work with the physical workload, weaknesses remain. 5: One or two yes answers. Active work with the physical workload, proactive.
Physical work environment		1: Many yes answers. Terrible environment, I could never handle being there myself. 2: Several yes answers. Poor environment, limited actions taken. 3: Few yes answers. A few factors are not very good, otherwise okay. 4: Few yes answers. Everything is okay; actions have been taken as far as possible at a reasonable cost. 5: No yes answers. Everything is good, clean and attractive, good premises.

Table A7: Questions about load factors

1. Are work tools and other devices unsuitably formed or poorly adjusted?	Yes	No
2. Is the work chair poorly designed or poorly adjusted?		
3. Is the work height poorly adapted to the work task and body size?		
4. Is visibility poorly adapted to the visibility requirements of the task so that it leads to stressful work positions?		
5. Is lengthy or repetitious work performed when the back is:		
a) leaning forward, backward or to the side?		
b) twisted?		
c) turned and twisted at the same time?		
6. Is the neck repeatedly or for long time periods:		
a) leaning forward, backward or to the side?		
b) twisted?		
c) turned and twisted at the same time?		
7. Is there lengthy or repeated work with a forward or outwardly held unsupported arm or an arm held above shoulder height?		

8. Is there repeated work with the forearm and hand with:		
a) turning motions?		
b) strong grips?		
c) uncomfortable hand grips?		
d) keys on a keyboard or buttons?		
e) great demands for accuracy?		
9. Manual lifting:		
a) takes place often		
b) is heavy		
10. Is there repeated, lengthy or uncomfortable carrying, pushing or dragging of loads?		
11. Is lengthy or repetitious work performed:		
a) with repetition of the same work movements?		
b) with repetition of the same work movement outside a comfortable distance? Consider factors such as weight and ability to grip the work objects and tools.		
Consider also these factors:		
a) Are there time factors, such as the length of the shift, distribution of breaks and pauses, work cycle times, etc., that aggravate the impact of any of risk factors 1-11?		
b) Are opportunities for influencing the design and performance of the operators' own work too small?		
c) Is the work performed under time pressure or does it cause negative stress?		
d) Does the work cause unusual or unexpected situations?		
e) Do cold, heat, drafts, noise or the like have an impact on any of risk factors 1-11?		
f) Is there a negative impact of jolts, shaking or vibrations?		
g) Does the worker lack a sufficient amount of knowledge that is important in the context?		

Appendix B – Study I interview questions

Part I - Method identification

Contextual background information.

1.1 Personal information
1.2 Company information
1.3 Other information

Method identification.

1.4 Describe the purpose and objectives of the analysis method.
1.5 Describe the analysis method in general terms.
1.6 Describe how the data collection is carried out. For example, who is doing the analysis, how is it done and time consumption necessary to fulfil the analysis etc.
1.7 Describe how the method addresses production-related problems.
1.8 Describe how the method provides problem-solving suggestions.
1.9 Describe whether and how the method indicates the problem that is of most importance and needed to be solved at first.

Part II – Method mapping

1.10 *Market and Strategy* - Describe whether and what market and strategy factors are analysed? What parameters are examined? How are they examined?
- 1.10.1 *Physical structure (structural aspects)* – Describe whether and how the method considers a plant's physical structure (buildings, machinery, equipment layout, etc.).
- 1.10.2 *Infrastructural aspects* – Describe whether and how the method identifies production processes (such as routings and production flows). Does the method describe the other processes such as information flows and how?

1.11 *Performance measurement* – Describe whether and which performance measures are analysed (cost, quality, speed, etc.). *If too detailed or classified by the company, try to make a short summary*
- 1.11.1 Describe whether and how data are collected and analysed.

1.12 Production development
- 1.12.1 Describe whether and what industrial engineering issues are analysed.
- 1.12.2 Describe whether and how manufacturing development options are identified.
- 1.12.3 Describe whether and how the method considers the product produced (product life cycle, volume/capacity, batch sizes, etc.) in order to support the manufacturing development process.

1.13 Work organization
- 1.13.1 Describe the part of the organization that is analysed (e.g. the shop floor, logistics, office environments, etc.).
- 1.13.2 Describe whether and how the method analyses work tasks and work content?
- 1.13.3 Describe whether and how the method considers decision-making processes, authority and responsibilities
- 1.13.4 Describe whether and how the method analyses workforce composition (gender, demographics) and working hours

1.14 *Work environment* – Describe whether and how the method analyses the work environment? Any other specific concerns

Appendix C – Study III interview questions

Part I – Introduction

Contextualising the interview

1 Presentation of interview study

1.1 Brief the respondent with the background, purpose, aim, schedule and content of the interview (e.g., estimated time consumption)

1.2 Introductory questions to the respondent (nomothetic character)

- 1.2.1 Age?
- 1.2.2 Education?
- 1.2.3 Position at work and typical work content?
- 1.2.4 Number of years at position?
- 1.2.5 Other positions during career?
- 1.2.6 What branches or industries have been represented?

Part II – Questions regarding improvement project (semi-structural questions)

1.1 Introduction to improvement project

Describe a defined and specific improvement project (e.g. a flow implementation, setup time reduction, equipment investment, etc.)

- 1.1.1 Describe the background and problem.
- 1.1.2 Describe the improvement project's purpose and objectives.
- 1.1.3 Describe the improvement organization (team composition, characteristics of members and other stakeholders, size, etc.)
- 1.1.4 Describe work procedures and how work tasks were distributed within the improvement organisation (responsibilities, authorities, deadlines, etc.)
- 1.1.5 Reasons for the improvement project

Describe how the improvement project was initiated (what was the motive for this improvement?)

- Proposal from the shop floor
- Audits or similar follow-ups that included employees
- Performance measures that indicated improvement potentials
- New requirements or objectives from the management team
- Others?

1.2 Action plans

Describe the improvement programme for the specific problem

- 1.2.1 How were goals and objectives stated?
- 1.2.2 What means or aids were available to visualize or clarify the problem? (For instance, standards, requirements or others)?
- 1.2.3 What improvement alternatives were presented?
- 1.2.4 What were these proposals based on?
- 1.2.5 How was the final solution selected?
- 1.2.6 What activities can be related to the project (For instance, planning, procurement, consultation, data collection, etc.)?
- 1.2.7 When did these activities occur (sketch a timeline)?
- 1.2.8 What was the time consumption for these activities?

1.2.9 What was the resource consumption for these activities? (who executed these activities

1.3 Results

Describe the result of the improvement project

What

1.4 Effects of action programme

Describe the long-term impact of the action programme

1.4.1 Describe the actual long-term impact in relation to goals and objectives.
1.4.2 What visible (physical) effects did the improvement programme yield? (For instance, reduction of surface, visualized flows, improved information flows, etc.)
1.4.3 Performance measures?
1.4.3.1 Non-financial – What was used? How were they used?
1.4.3.2 Financial – What was used? What were the economic consequences of the improvement? What did it cost , what did you save on it?
1.4.4 Other impacts that occurred but were not directly related to the target image (e.g., renewed requirements for education and skills)

1.5 Follow-up

Describe how the project was followed up

1.5.1 How was the improvement project followed up?
1.5.2 Lessons learned?
1.5.3 How are data from this improvement project reused in upcoming projects?
1.5.4 In retrospect, would you or the team have been able to do anything differently?

Part III – About general improvement in the organization (open/unstructured)

Describe the improvement organization

1.6 The individuals in the improvement organization

1.6.1 What tasks or activities did you perform that did not contributes to an improved organization? (Perceived opinion)
1.6.2 What are the perceived benefits of working with improvements in comparison to others of an administrative nature?
1.6.3 What tasks or activities did you perform that are of vital importance for attaining successful project results?
1.6.4 What personal qualities do you think are important for the success of improvement projects?
1.6.5 To what extent did you influence the outcome of the project?
1.6.6 What resources (or support tools) did you use most to reach a successful outcome in your improvement projects?
1.6.7 What do you perceive as the biggest obstacle to a successful improvement project?

1.7 The improvement organization in general terms

1.7.1 Identify the organization’s improvement drivers (Individuals and managements, Decision models, time and money, competitors, others)

1.7.2 What is the best incentive for pushing through improvements? For instance, communication, present the economic benefits or impacts, present other benefits such as environmental or health improvements.

1.7.3 Do you think that the company has an efficient improvement organization? If not, what would you like to change or improve?

1.7.4 Do you think that your organization lacks tools or resources to process improvements?

1.8 Other opinions or remarks you would like to add