Industrialization and mass production created a culture of manufacturing, consumption and disposal without consideration for the rapid increases in virgin raw material extraction, the introduction of excess products into the market, the rapid obsolescence of old products, increased volumes of industrial waste and other concerns related to global sustainability, emission generation, resource capacity and waste generation. Assuming that the current resource supply can satisfy the demand for materials in the short term, it may not be sufficient to satisfy demand in the long term, given constantly increasing production rates and development. In addition to possible material shortages in the long term, total energy demand and the consumption, extraction and processing of virgin raw materials must be considered. Therefore, population and economic growth suggest higher demand not only for raw materials, but also for energy to support extraction and manufacturing, both of which directly contribute to global warming and climate change.

This doctoral thesis contributes to existing knowledge on management and improvement of material efficiency in manufacturing, focusing on barriers, tools and methods, and performance measurements. Material efficiency in manufacturing implies any activities to (1) reduce the amount of material used for manufacturing a product in a factory, (2) generate less waste per product, and (3) achieve better waste segregation and management. These three aspects of material efficiency lead to prevention and reduction in extraction and consumption of virgin raw materials, cost and energy savings in fabrication, transformation, transportation and disposal, reduction of industrial waste volumes, increased recycling and reusing in waste management as well as reduced energy demands, carbon emissions and overall environmental impact of the global economy in a broader perspective. Therefore, improvements to material efficiency are imperative to improving the circular economy and capturing value in industry, even if annual production remains at its current level.

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SUSTAINABLE MANUFACTURING THROUGH MATERIAL EFFICIENCY MANAGEMENT

Sasha Shahbazi

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School of Innovation, Design and Engineering
SUSTAINABLE MANUFACTURING THROUGH
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Akademisk avhandling

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Akademin för innovation, design och teknik
Abstract

Material efficiency contributes to reduced industrial waste volumes, reduced extraction and consumption of virgin raw materials, increased waste segregation, decreased energy demand, and reduced carbon emissions, thereby generally mitigating the environmental impact of the manufacturing industry. However, the area of material efficiency in manufacturing is under-researched, and related knowledge is limited particularly at individual manufacturing sites and lower levels. These levels are crucial to achieve improved material efficiency, as a great amount of material is consumed and waste flows are generated on manufacturing shop floors. There are still gaps in both literature and industrial practice regarding material efficiency in manufacturing, where materials are consumed to make products and great volumes of waste are generated simultaneously.

The research objective of this dissertation is to contribute to existing knowledge on management and improvement of material efficiency in manufacturing. To achieve this objective, three research questions were formulated to investigate material efficiency barriers, material efficiency tools and strategies, and material efficiency performance measurement. The results are supported by four structured and extensive literature reviews and also by five empirical case studies conducted at a total of fourteen Swedish global manufacturing companies. These empirical studies entail observations, interviews, waste stream mapping, waste sorting analyses, environmental report reviews, and company walkthroughs.

A number of material efficiency barriers in manufacturing were identified, categorized and clustered to facilitate an understanding of material efficiency to effectively mitigate the barriers. The clustered barriers cited most often in the literature are budgetary, information, technology, management, vision and culture, uncertainty, engineering, and employees. In the empirical studies, vision and culture, technology, and uncertainty were replaced by communication. Most of the material efficiency barriers identified appear to be internal and are dependent on the manufacturing company’s characteristics.

A number of tools and strategies were identified and some were used to assess, manage, and improve material efficiency in the manufacturing companies studied. Empirical studies indicated that certain criteria are necessary to select and use operational tools. These criteria include being hands-on, time efficient, based on lean principles, easy to use and learn, visualized, promoting engagement, and being connected to a predetermined goal. These criteria are essential for mutual understanding, intra-organizational communication, performance improvement, and becoming a learning organization.

A model for a material efficiency performance measurement system was proposed that included the most common material efficiency-related key performance indicators from literature and empirical findings. The model divides material and waste flows into four main categories: productive input materials, auxiliary input materials, products, and residual output materials. The four main categories should be measured equally to realize material efficiency performance improvements in an operation.

This research contributes to the research area of material efficiency and sheds light on different interconnected aspects, which affect one another and contribute to assess, manage and improve material efficiency in a manufacturing context. The studied conducted and the results are presented in five appended papers.
Abstract

Material efficiency contributes to reduced industrial waste volumes, reduced extraction and consumption of virgin raw materials, increased waste segregation, decreased energy demand, and reduced carbon emissions, thereby generally mitigating the environmental impact of the manufacturing industry. However, the area of material efficiency in manufacturing is under-researched, and related knowledge is limited particularly at individual manufacturing sites and lower levels. These levels are crucial to achieve improved material efficiency, as a great amount of material is consumed and waste flows are generated on manufacturing shop floors. There are still gaps in both literature and industrial practice regarding material efficiency in manufacturing, where materials are consumed to make products and great volumes of waste are generated simultaneously.

The research objective of this dissertation is to contribute to existing knowledge on management and improvement of material efficiency in manufacturing. To achieve this objective, three research questions were formulated to investigate material efficiency barriers, material efficiency tools and strategies, and material efficiency performance measurement. The results are supported by four structured and extensive literature reviews and also by five empirical case studies conducted at a total of fourteen Swedish global manufacturing companies. These empirical studies entail observations, interviews, waste stream mapping, waste sorting analyses, environmental report reviews, and company walkthroughs.

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This research contributes to the research area of material efficiency and sheds light on different inter-connected aspects, which affect one another and contribute to assess, manage and improve material efficiency in a manufacturing context. The studied conducted and the results are presented in five appended papers.
Sammanfattning

Materialeffektivitet bidrar till minskade volymer av industriavfall, minskad utvinning och förbrukning av jungfruliga råvaror, ökad avfallssortering, minskat energibehov och minskade koldioxidutsläpp och dämpar därmed tillverkningsindustrins miljöpåverkan i stort. Materialeffektivitet inom tillverkning är emellertid föga utforskad och kunskap om den är begränsad, särskilt gällande enskilda tillverkningsställen och operativa nivåer. Dessa nivåer har stor betydelse när det gäller att uppnå förbättrad materialeffektivitet, eftersom en stor mängd material förbrukas och avfallsflöden skapas på tillverkningsindustrins verkstadsgolv. Fortfarande finns det luckor både i litteraturen och i industriell praxis när det gäller materialeffektivitet inom tillverkning, där material förbrukas för att tillverka produkter samtidigt som stora volymer avfall genereras.

Forskningsmålet för denna avhandling är att bidra till kunskapen om styrning och förbättring av materialeffektivitet inom tillverkning. För att nå detta mål har tre forskningsfrågor formulerats för att undersöka hinder för materialeffektivitet, verktyg och strategier för materialeffektivitet samt prestandamätning av materialeffektivitet. Resultaten stöds av fyra strukturerade och omfattande litteraturgenomgångar samt fem empiriska fallstudier som genomförts vid sammanlagt 14 svenska globala tillverkningsföretag. Dessa empiriska studier omfattar observationer, intervjuer, kartläggning av avfallsströmmar, analys av avfallssortering, genomgångar av miljörapporter samt industribesök.

Flera hinder för materialeffektivitet har identifierats, klassificerats och grupperats för att underlätta förståelsen för materialeffektivitet för att kraftigt reducera hinder. Dessa grupperade hinder som oftast nämns i litteraturen rör budget, information, teknik, ledning, vision och kultur, osäkerhet, maskinteknik och personal. Ett antal hinder för materialeffektivitet har identifierats; några av dem har använts för att bedöma, styra och förbättra materialeffektivitet i de undersökta tillverkningsföretagen. Empiriska studier har visat att vissa kriterier är nödvändiga för att välja och använda operativa verktyg. Dessa kriterier innefattar att vara praktiska, tidskritiska, grundade på resurssnål (lean) tillverkning, lätta att använda och lära sig, visualiserade, engagerande och kopplade till ett förutbestämt mål. Kriterierna är av stor betydelse för ömsesidig förståelse, omorganisatorisk kommunikation och resultatomtäthet samt för att stärka en lärande organisation.

Ett antal verktyg och strategier har identifierats; några av dem har använts för att bedöma, styra och förbättra materialeffektivitet i de undersökta tillverkningsföretagen. Empiriska studier har visat att vissa kriterier är nödvändiga för att välja och använda operativa verktyg. Dessa kriterier innefattar att vara praktiska, tidskritiska, grundade på resurssnål (lean) tillverkning, lätta att använda och lära sig, visualiserade, engagerande och kopplade till ett förutbestämt mål. Kriterierna är av stor betydelse för ömsesidig förståelse, omorganisatorisk kommunikation och resultatomtäthet samt för att stärka en lärande organisation.

Ett förslag till modell för ett system att mäta materialeffektivitet presenteras som innefattar de vanligaste nyckelindikatorerna för materialeffektivitet från litteraturen och de empiriska slutsatserna. Modellen delar in material- och avfallsflöden i fyra huvudkategorier: produktmaterial, processmaterial, produkter och produktionsrester. Dessa fyra huvudkategorier bör mätas på samma sätt för att uppnå resultatförbättring av materialeffektivitet i en tillverkningsprocess.

Denna forskning bidrar till forskningsområdet materialeffektivitet och belyser olika sammanhängande aspekter som påverkar varandra och bidrar till att bedöma, styra och förbättra materialeffektivitet inom tillverkning. De genomförda studierna och resultaten presenteras i fem bifogade artiklar.
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January 2018, The House of Culture, Stockholm

Sasha Shahbazi
Publications

Appended Papers


A draft version of this paper was presented at a conference: Shahbazi, S., Kurdve, M. (2014). Material efficiency in manufacturing, the 6th Swedish Production Symposium (SPS14), 16–18 September 2014, Gothenburg, Sweden.


Shahbazi contributed to the literature review and theoretical analysis of existing methods. Shahbazi also participated in the data analysis, writing process, and review of the paper.


A draft version of this paper was presented at a conference: Shahbazi, S., Wiktorsson, M. (2016). Using the Green Performance, Map: towards material efficiency measurement, the 23rd EurOMA Conference, 17–22 June 2016, Trondheim, Norway.


A draft version of this paper was presented at a conference: Shahbazi, S., Amprazis, P. (2017), Improve material efficiency through an assessment and mapping tool, *the 23rd Annual Conference of International Sustainable Development Research Society (ISDRS)*, 14–16 June 2017, Bogotá, Colombia.


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Introductory Definitions

**Absolute KPIs:** Key performance indicators that reflect the difference between measurements in a specific area of interest over two periods in time.

**Auxiliary material:** Any type of material or product that is used in the production of the main product but is not a part of the main product and does not add value to the final product. In this dissertation, the term is synonymous with non-value added material, non-productive material and process material.

**Direct KPIs:** Key performance indicators related to values that can be measured or changed within the manufacturing phase of a product life cycle.

**Frequency of KPIs:** Refers to the number of key performance indicators mentioned by different scholars that have the same meaning and goals, although they could be formulated differently.

**Go to Gemba:** going to the manufacturing shop floor where the problems happen.

**Homogeneous (quality of) waste:** A uniform content or composition of waste in terms of its natural properties, i.e., the materials are all of the same type and have the same properties. In this dissertation, the term is synonymous with homogeneity of waste.

**Indirect KPIs:** Key performance indicators related to values that cannot be measured or changed within the manufacturing phase of a product life cycle. These KPIs could be related to the design phase, the use phase, or the end-of-life phase and are thus out of control of the manufacturing unit.

**Lagging KPIs:** Key performance indicators that are typically input-oriented and difficult to measure but easy to influence. The main focus of these KPIs is to measure activities undertaken by operators to achieve a given goal.

**Leading KPIs:** Key performance indicators that are typically output-oriented, i.e., backward-focused to measure actual results. They are easy to measure but difficult to improve.

**Manufacturing:** In this dissertation, the term *manufacturing* is limited to processes within a plant in which the operations necessary to make a product are performed.

**Material efficiency:** "The ratio of output of products to input of raw materials" (Abdul Rashid, 2009) or "to continue to provide the services delivered by materials, with a reduction in total production of new material" (Allwood et al., 2013).

**Material efficiency strategies:** In this dissertation, this term refers to environmental sustainability strategies that support material efficiency at different levels, e.g., national, supply chain, industry, consortium, individual plant, management, operation, process and shop floor. However, strategies at lower levels than an individual plant are called material efficiency tools.

**Residual material:** Excluding the main product, any remnant or leftover material or product derived from a manufacturing process. Residual material can be derived from productive material or process material. It is not part of the primary product and does not add value to the final product. In this dissertation, the term is synonymous with waste, rest material or by-products.
Relative KPIs: Refers to the change in scale (ratio) of a value in one area when correlated to performance in another area, primarily the number of products made. The relative KPI allows comparison of the ratios of two numbers.

Reuse: Any operation in which material is used again for a purpose that is the same as or different from the purpose for which it was intended. Checking, cleaning and/or small modifications might be necessary. In this dissertation, repairs, refurbishments and remanufacturing are subsets of reuse.

Strategy: In this dissertation, strategy refers to any type of approach, principle, method, strategy, tool, policy, vision or concept that aims to achieve a goal.

Sustainability strategy: A series of maneuvers to “help society to design and implement short- and long-term approaches to achieve the transition to truly sustainable societal development” (Almeida et al., 2015).

Virgin raw material: Resources extracted from nature in their raw form that have not been previously processed, consumed, used or subjected to processing (mainly recycling) other than for original production.

Waste: Waste is any substance or object that the holder discards or decides or is required to dispose, but it is not a product of the operations (European Commission, 2008).

Waste fractions: The segregation of industrial waste segments into different types of materials. For instance, metal waste can be segregated into aluminum, copper, steel and cast iron, and combustible waste can be separated into paper, cardboard, biodegradables, wood and plastics.

Waste management: Waste management implies monitoring and fully controlling all stages of the production, collection, storage, transportation, sorting, container handling and disposal or local treatment of waste material, whether it is liquid, solid or gaseous and whether it is hazardous or non-hazardous, to ensure that it is harmless to humans, animals and the environment (Hogland and Stenis, 2000; Taiwo, 2008).

Waste segments: The segregation of industrial waste into the most common categories of waste, including metals, combustibles, inert materials, fluids and hazardous waste.

Waste segregation: In this dissertation, the term is synonymous with waste sorting and waste separation, referring to the separation of waste into different waste segments and fractions.
1. Introduction

This chapter introduces the research by presenting the background and a problem statement concerning material efficiency, followed by the research objective and research questions. The chapter concludes with research delimitations and project contexts.

1.1 Background

One of the most crucial issues for the future is resource consumption. Total global material consumption has dramatically increased and is now approximately 60 billion tons per year for a population of more than 7 billion people. Assuming that the current resource supply can sustain the demand for materials in the short term, it may not be sufficient to satisfy demand in the long term, given constantly increasing production rates and development. Industrialization and mass production created a culture of manufacturing, consumption and disposal without consideration for the rapid increases in virgin raw material extraction, the introduction of excess products into the market, the rapid obsolescence of old products, increased volumes of industrial waste and other concerns related to global sustainability, emission generation, resource capacity and waste generation. In light of increasing wealth and production, and an anticipated population growth to 9 billion people by 2050, demand for material is likely to be at least doubled by 2050 (The International Energy Agency IEA, 2012); the UN estimates that 140 billion tons of key resources are expected to be consumed annually by 2050. In addition to possible material shortages in the long term, total energy demand and the consumption, extraction and processing of virgin raw materials must be considered. The industrial sector drives approximately one-third of total energy demand, most of which is used to produce bulk materials (Allwood et al., 2013). Therefore, population and economic growth suggest higher demand not only for raw materials, but also for energy to support extraction and manufacturing, both of which directly contribute to global warming and climate change.

Generation of industrial waste is also a critical concern given its impact on both sustainability and the environment (Ellen MacArthur Foundation, 2012). Most extracted resources and materials and the majority of products eventually become waste, a journey known as the cradle-to-grave process. Furthermore, the majority of waste ends up in landfills and incinerators, thus contaminating land, water and air. In Europe, waste generation is expected to increase by 10–20% by 2020 in comparison to 2005 (Frostell, 2006). In 2014, the total waste generated by households and economic activities in Europe amounted to 2.5 billion tons, 10% of which (255 million tons) were contributed by the manufacturing sector. The total amount of waste generated by households and economic activities in Sweden in 2014 amounted to 167 million tons; the manufacturing industry contributed 5.7 million tons, or approximately 3.5%, of Sweden’s total generated waste (European Commission, 2017; Naturvårdsverket, 2017), as shown in Figure 1. In the same period, economic activity in manufacturing has remained constant. Despite the successful reduction of industrial waste volume in Sweden since 2008, the challenge of end-of-life scenarios (i.e., reusing, recycling, etc.), to reduce virgin material consumption and maintain the high homogeneity of material in the industrial system has remained. Ideally, industrial waste could be utilized directly in another process or be reused within its own loop, thereby reducing demand for virgin material.

Material efficiency is defined as “the ratio of output of products to input of raw materials” (Abdul Rashid, 2009) or “to continue to provide the services delivered by materials, with a reduction in total production of new material” (Allwood et al., 2013). Material efficiency contributes to reduced industrial waste volumes, reduced extraction and consumption of
resources, increased waste segregation and decreased energy demand, carbon emissions and overall environmental impact of the global economy, all in line with European long-term visions for 60% carbon dioxide reduction and 80% greenhouse gas reduction by 2050 (European Commission, 2011a). Material efficiency in manufacturing directly results in cost and energy savings in fabrication, transformation, transportation and disposal as well as reduced greenhouse gas emissions through better waste segregation and a higher recycling rate, and increases the success rate of waste management initiatives (Allwood et al., 2012). Therefore, improvements to material efficiency are imperative even if annual production remains at its current level. The European Commission (2011a), the World Economic Forum (2012) and Mistra (2011) also emphasized that a circular economy and resource efficiency (material efficiency being a part of these) are the most important strategic options to capture value in industry because these strategies will provide great economic opportunities, improve productivity, drive down costs and boost competitiveness.

Figure 1 – Economic activity in manufacturing and total waste generated in manufacturing in Sweden (Naturvårdsverket, 2017; European Commission, 2017), presented in Paper I.

1.2 Problem Statement
Knowledge related to reverse logistics, closed loop, and circular economy and infrastructures for waste management and recycling, along with technologies and capacities for returning material flows to their environmental origins or introducing them into new cycles, is not as developed as traditional manufacturing flows of consuming materials and making products. Consequently, the area of material efficiency is under-researched (Allwood et al., 2013). Additionally, many factors contribute to the difficulties surrounding material efficiency, including the presence of numerous external and internal actors, low levels of information and knowledge, little correlation among the different actors’ business models, the method of allocating gains and costs in the system, and the relationships between legal and regulatory systems and environmental and economic benefits (Allwood et al., 2011; Abdul Rashid, 2009; Mittal and Sangwan, 2014). Recent studies have mainly focused on eco-design and product sustainability rather than on manufacturing sustainability. Additionally, metal processing and manufacturing management have already improved significantly (Allwood et al., 2013), whereas other manufacturing materials are not managed as promisingly as the metal segment due to different barriers, such as lack of economic incentive, lower value, more limited
knowledge, and absence of a performance measurement system. Academic publications 
have drawn attention to the area of material efficiency in a broad sense, i.e., at global, 
national, and sectoral levels (see Chapter 3 for what has been published), although less has 
been published addressing the area of material efficiency in an operation or at a 
manufacturing site through less waste generation, less material consumption, and higher 
waste segregation. There are still gaps in both literature and industrial practice regarding 
material efficiency barriers to overcome, tools and strategies for improvement, and 
performance indicators and measurements to retain.

This gap mainly relates to a delusive historical fact that productivity and efficiency, 
quality, cost and delivery are generally considered more important than sustainability to 
run a business and fulfill customer needs. Material efficiency has even lower priority at 
manufacturing companies; it is not considered as important as other sustainability aspects 
such as energy efficiency, renewable energy sources or CO₂ neutralization, which could 
be because of lack of enforcement, legislation and regulations regarding material 
consumption and waste generation.

1.3 Research Objective and Questions

The overall purpose of the research presented in this dissertation is to increase 
sustainability, profitability and competitiveness of the manufacturing industry while 
simultaneously maintaining quality and manufacturing functionality and productivity. The 
research objective of this dissertation is to contribute to existing knowledge on 
management and improvement of material efficiency in manufacturing. Note that the 
results and discussions presented in this dissertation aim to provide a foundation for better 
understanding of material efficiency in manufacturing and further development of theories 
and frameworks in future studies. Hence, in line with the objective, the result and 
discussion level of this dissertation deliberately has a system perspective. Bearing the gap 
and research objective presented in mind, the following research questions have been 
formulated. The research questions are not derived from one another and are not in 
sequence, i.e., they are independent but interrelated.

**RQ1: What barriers hinder increased material efficiency in manufacturing?**

To manage and improve material efficiency in manufacturing, companies must identify 
barriers that hinder them from going up in the waste hierarchy to prevent waste generation, 
consume less material, increase waste segregation, and eventually recycle and reuse more 
of the generated waste. Therefore, based on literature reviews and empirical studies, this 
research question focuses on barriers to improved material efficiency.

**RQ2: What tools and strategies help to assess and improve material efficiency in 
manufacturing?**

To manage and improve material efficiency in manufacturing, companies require practical 
tools and strategies to assess their operation, identify improvement potentials, learn about 
material and waste flows, engage in environmental improvements and maintain the 
improvement actions. Therefore, based on literature reviews and empirical studies, this 
research question focuses on practical tools and strategies that help manufacturing 
companies to improve material efficiency.

**RQ3: How can material efficiency performance measurement be developed and integrated 
in manufacturing?**

To manage and improve material efficiency in manufacturing, companies need a 
performance measurement system to support systematic strategic development and
monitor the existing situation and improvement actions with respect to material consumption and waste generation. Therefore, based on literature reviews and empirical studies, this research question focuses on material efficiency performance measurement.

1.4 Delimitations
This dissertation addresses material efficiency in the manufacturing phase of the product life cycle, in which productive material and auxiliary material are used to make products (see Introductory Definitions for terms used in this dissertation). Thus, this research excludes the obsolescence, disposal and treatment of products through remanufacturing, recycling and reuse during their use and end-of-life phases. Waste generation in the resource-acquisition phase is also excluded.

The majority of the empirical data in this research was collected at large global automotive manufacturing companies in Sweden. Metal is their primary product material, and they generate common types of residual material including metal scraps, cardboard, wood, hazardous waste, plastics and combustible waste. Therefore, the results might not be generalized to all manufacturing companies. Generalizability, justification of the selection of companies and quality of research are discussed later in the method chapter.

1.5 Project Context
This research has been conducted in the context of different projects including

- INNOFACTURE – Production innovation as a strategic solution to the future challenges of the manufacturing industry; financed by the Knowledge Foundation (2012–2018)
- LGPN – Lean and Green Production Navigator; financed by Vinnova (2011–2013)
- MEMIMAN – Material Efficiency Management in Manufacturing; financed by Mistra (2012–2015)

The research area of each project directly contributed to different aspects of this dissertation. INNOFACTURE was an industrial graduate school for PhD education addressing challenges to the future of the manufacturing industry in Sweden including material efficiency; the LGPN project correlated with integration of environmental aspects (green) and development and improvement of production systems (lean) on operational level; the MEMIMAN project assessed the industrial barriers to increased material efficiency, recycling as well as waste management in the manufacturing industry; SuRE BPMS focused on developing a sustainable performance measurement system to support manufacturing companies in development and redesign of performance measurement systems considering sustainability; finally the CiMMRec project addressed LCC and LCA models for recycling loops, focusing on material and process information systems, life cycle cost structures and collaboration between different partners in waste management systems.

In addition, this research has contributed to MITC (Mälardalen Industrial Technology Centre). The main empirical studies and the contribution in later stages, however, are connected to Volvo Group. The core research group is also connected to the strategic initiative X PRES – the Initiative for Excellence in Production Research, which is a joint initiative of KTH, Mälardalen University, Swerea IVF and Swerea Kimab.
2. Method

This chapter aims to describe the research path taken and to explain the design of the research. First, research approach and strategy are presented, followed by research process and data collection method. This chapter then is concluded with measures to ensure research quality.

2.1 Research Approach and Strategy

Research approach implies conscious scientific reasoning. It is divided into three main categories, deductive, inductive and abductive. Differences between these three approaches relate to the research process, purpose, premises, and relevance of hypotheses to the study. The deductive approach tests and confirms the validity of theories, hypotheses, or assumptions, while the inductive approach is used to create new theories and generalizations. However, the abductive approach was chosen for this dissertation because this approach aims to understand an existing phenomenon – material efficiency – using a new framework and perspective (Kovács and Spens, 2005) by capturing and utilizing both theory and empiricism (Dubois and Gadde, 2002). Figure 2 illustrates this research approach. In practice, the abductive approach is used for a great deal of qualitative research (Saunders et al., 2009). Abductive reasoning searches for suitable theories to explain empirical observations, which leads to an iterative process between theory and empiricism. This continuous back-and-forth process between theory and empirical study is called "systematic combining" or "theory matching" (Dubois and Gadde, 2002); it entails literature study, empirical data collection, and simultaneous case analysis that evolve in a learning loop (Spens and Kovács, 2006). In the research presented in this dissertation, established (prior) knowledge in the research area was gathered through a pilot study (see section 2.2.3). Next, the collection of real-life observations and empirical data was commenced by investigating material efficiency management and improvement at large global manufacturing companies in Sweden. Literature reviews and empirical studies were then conducted simultaneously via a continuous back-and-forth process, leading to an iterative process between theoretical findings and empirical results.

Throughout the research process, different types of qualitative methods such as cross-case analysis, color coding, categorization and clustering as well as a few quantitative methods, such as data matrix, diagrams and charts were utilized to collect, analyze and interpret data. This approach overcame the weaknesses of the mono method by providing a broader scope of data collection techniques and analytical procedure, a contextual background, and a better understanding of the research problem (which is in line with the abductive approach).

Figure 2 – The abductive approach adapted from Spens and Kovács (2006).
approach), facilitating the research formulation and follow-ups, redrafting of research questions, generalizability of the study (in line with the abductive approach), and credibility of the study to produce more complete knowledge (Saunders et al., 2009).

Research strategy represents the manner in which the researcher plans to answer the research questions and can be influenced by the research objective, the types of research questions, research approach, the nature of the research, existing knowledge, available resources, and the time available to conduct the research (Saunders et al., 2009). The main strategy used to collect empirical data was the multiple case study with analytic generalization (Yin, 2003). In essence, the case study strategy uses in-depth inspection of empirical phenomena and their context both to develop theory (Dubois and Gadde, 2002) and to enhance understanding of phenomena without the use of experimental controls and manipulation (Meredith, 1998). Case studies use one or more cases both to build theoretical constructs and propositions (Eisenhardt and Graebner, 2007) and to provide empirical descriptions of a phenomenon based on a variety of data sources (Yin, 2014). This strategy can use quantitative methods, qualitative methods or a combination thereof to collect and analyze data. Bearing in mind the objective of this dissertation and the questions formulated, the case study approach was selected as the primary strategy to fulfill the research objective and to answer the research questions. In addition, because material efficiency is influenced by various factors, it was essential to study multiple cases to minimize the risks and drawbacks inherent in single-case studies, including misinterpretation, observation biases, and most importantly, a limited ability to generalize the results (Yin, 2014). A multiple case study strategy is appropriate when there is some knowledge about the phenomenon but much remains unknown (Meredith, 1998). In addition, a multiple case study not only enables replications, comparisons and extensions of theory based on varied empirical investigations (Yin, 2014), but also allows wider exploration of the research questions and theoretical elaboration (Eisenhardt and Graebner, 2007). For instance, it was crucial to use multiple case studies in empirical studies on barriers, strategies and performance measurement because a single case study would not provide sufficient data for replication and comparison to analyze and draw conclusions. In addition, all of these subjects had been touched upon in other contexts such as manufacturing productivity, which provided basic knowledge for this research (Yin, 2014).

2.2 Research Process

Figure 3 depicts the research process in terms of literature and empirical studies in a timeline. The connection of each study to the research questions has been also indicated.
2.2.1 Data Collection

Literature studies were essential parts of this research. Theoretical data were collected not only from scientific papers and reports, but also from non-academic sources and gray literature. It was essential to collect data from a variety of sources to increase the validity and reliability of the research results. The literature study entailed an integrated data collection technique that was applied in parallel with empirical data collection and analysis. Literature studies were conducted using keyword searches in scientific databases and non-academic sources, along with qualitative upstream and downstream searches for references. Suggested papers in conferences and journal publications were also included. Details about the literature studies are presented in section 2.2.3.

Empirical data collection for this research included participant and direct observations, document reviews and semi-structured interviews in case studies to develop a rich understanding of the cases (Yin, 2003). Participant observation was accomplished through multiple site visits whereby the researcher participated in daily activities and revealed his purpose as a researcher (Saunders et al., 2009). Sets of focused semi-structured interviews were conducted at different times during the empirical studies. Interviews provided rich empirical data (Eisenhardt and Graebner, 2007) and led to a direct focus on the subject (Yin, 2014). In addition, archival research was conducted through a review of environmental reports and improvement project documents (both sustainable and operational projects). Archival research helps answering questions by providing information about the past and developments over time (Saunders et al., 2009). The empirical studies are presented in section 2.2.4 – 2.2.8, and details on the applied data collection methods, such as number of interviewees and their function, can be found in the appended papers indicated in Table 2.

2.2.2 Selection of Participating Companies

Fourteen global manufacturing companies located in Sweden are involved in this research, although not all of them were included in each study. Most of the case companies were industrial partners in research projects. Therefore, the selection of these companies was primarily based on close collaboration and project connections. This access to the
companies made it easier to obtain interviews, visit production facilities and monitor material efficiency activities and waste management systems. Moreover, the companies’ market leadership, international reputation, global ecological footprints, prior successful implementation of appropriate environmental management systems, and current environmental goals and visions together with significant interest in improving their current systems for achieving sustainability in their operations led to their initial selection for participation in this research. In addition, the selected companies’ products are manufactured, assembled, and sold worldwide, and their global reputation and business success have forced them to maintain tighter control of environmental issues, including material and waste flows. As the majority of participating companies are in the automotive industry, their products and manufacturing processes significantly contribute to various types of environmental pollution, large volumes of solid waste, depletion of natural resources, and a moderate recycling rate of residual material and packaging, which in turn made this industry interesting to study. The manufacturing companies typically use metal as their primary product material, and generate common types of residual material, including plastics, aluminum, steel, cardboard, wood, hazardous waste, and combustible waste. Table 1 lists the companies and their respective involvement in the research process.

Note that some companies had a major role in data collection and some had a limited role for only one research question.

Table 1 – Overview of selected companies

<table>
<thead>
<tr>
<th>Company</th>
<th>Type of industry</th>
<th>Empirical studies</th>
<th>No. of employees</th>
<th>Operation studied</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Manufacturer of drilling equipment and underground rock excavation equipment</td>
<td>A</td>
<td>1900</td>
<td>Fabrication</td>
</tr>
<tr>
<td>B</td>
<td>Manufacturer and assembler of gearboxes for trucks, marine and heavy equipment</td>
<td>A</td>
<td>1500</td>
<td>Fabrication</td>
</tr>
<tr>
<td>C</td>
<td>Manufacturer of construction equipment and industrial material handling</td>
<td>A, B</td>
<td>2400</td>
<td>Fabrication</td>
</tr>
<tr>
<td>D</td>
<td>Manufacturer of products for heat transfer, separation and fluid handling</td>
<td>A, B, C</td>
<td>1000</td>
<td>Fabrication and assembly</td>
</tr>
<tr>
<td>E</td>
<td>Manufacturer of heavy trucks and buses, gearboxes and engines</td>
<td>A, B, E</td>
<td>10000</td>
<td>Assembly¹</td>
</tr>
<tr>
<td>F</td>
<td>Remanufacturer of engines and components of trucks, buses and construction equipment</td>
<td>B</td>
<td>220</td>
<td>Disassembly and fabrication</td>
</tr>
<tr>
<td>G</td>
<td>Manufacturer and assembler of gearboxes for trucks</td>
<td>D</td>
<td>1500</td>
<td>Fabrication¹</td>
</tr>
<tr>
<td>H</td>
<td>Manufacturer of brake systems for heavy trucks, trailers and buses</td>
<td>C</td>
<td>270</td>
<td>Fabrication and assembly</td>
</tr>
<tr>
<td>I</td>
<td>Manufacturer of construction equipment and industrial material handling</td>
<td>C</td>
<td>800</td>
<td>Fabrication and assembly</td>
</tr>
<tr>
<td>J</td>
<td>Designer and manufacturer of aerospace components</td>
<td>C</td>
<td>1200</td>
<td>Fabrication and testing</td>
</tr>
<tr>
<td>K</td>
<td>Manufacturer of machines and tools for metal cutting</td>
<td>C</td>
<td>380</td>
<td>Fabrication and assembly</td>
</tr>
<tr>
<td>L</td>
<td>Manufacturer of vehicles</td>
<td>C</td>
<td>1800</td>
<td>Fabrication and assembly</td>
</tr>
<tr>
<td>M</td>
<td>Manufacturer of construction equipment and industrial material handling</td>
<td>C</td>
<td>1000</td>
<td>Fabrication and assembly</td>
</tr>
<tr>
<td>N</td>
<td>Manufacturers of large buses and coaches</td>
<td>C</td>
<td>380</td>
<td>Fabrication and assembly</td>
</tr>
</tbody>
</table>

2.2.3 Literature Studies

This research commenced in 2012 with a structured literature-based pilot study to become familiar with the subjects of material efficiency, industrial waste management and sustainable manufacturing. The pilot study comprised exploration of black holes and white spots in the area, determination of a worthwhile research objective, formulation of initial research questions and development of a research plan. The pilot study included keywords

¹ Only some parts of the operation or assembly were included, not the entire plant.
such as "material efficiency", "industrial waste", "sustainability" and "waste management strategy", along with a combination of these terms with "manufacturing" and "automotive". In addition, qualitative upstream and downstream searches of the literature were conducted for relevant references. The pilot literature study was reported in Shahbazi et al. (2013). Afterwards, four separate literature studies (A–D) were carried out using keyword searches in scientific databases and non-academic sources. Snowballing was then used to gather the most important and cited articles in relation to material efficiency, sustainable manufacturing and industrial waste management.

Literature study A focused on research question 2 and aimed to identify environmental sustainability tools and strategies that support material efficiency assessment, improvement and management. To find relevant literature, keywords including "material efficiency", "dematerialization" and "resource efficiency", combined with "strategy", "approach", "method", "model", "principle", "concept" and "tool", were utilized to search scientific databases. The selection method was based on both an abstract review and full-paper skim and scan. Qualitative upstream and downstream searches of the literature were conducted for relevant references.

Literature study B aimed to provide insight into and increase awareness about the existing state of material efficiency, raw material consumption and waste generation, with a focus on the manufacturing sector. This literature study helped to answer research questions 1 and 2. To find relevant literature, keywords including "material efficiency", "material flow", "waste flow", and "resource efficiency" combined with "manufacturing" and "improvement", were utilized to search scientific databases. The selection method was based on both an abstract review and full-paper skim and scan. Qualitative upstream and downstream searches of the literature were conducted for relevant references.

Literature study C aimed to investigate barriers toward improved material efficiency; it contributed to answering research question 1. This search incorporated keywords such as "waste", "material efficiency", "recycling" and "barrier", along with their combination with "manufacturing", "automotive" and "environment". Although the main keyword was "barrier", other synonyms including "difficulty", "hindrance", "constraint", "obstacle" and "limitation" were also deployed to find relevant literature. The selection method was based on both an abstract review and full-paper skim and scan. Qualitative upstream and downstream searches of the literature were conducted for relevant references.

Literature study D aimed to provide knowledge regarding material efficiency measurements and sustainable manufacturing performance indicators. This study contributed to answering research question 3. The literature selection method was based on a keyword search, abstract review and full-text reading of papers. The search incorporated the keywords "material efficiency", "resource efficiency", "measure", and "indicator" as well as combinations with the terms "sustainable manufacturing", "manufacturing" and "production". Qualitative upstream and downstream searches of the literature were conducted for relevant references.

### 2.2.4 Empirical Study A: Material Efficiency Barriers and Strategies

Empirical study A was a multiple case study with the objective to (a) identify barriers that impede material efficiency improvements and waste segregation (research question 1) and (b) evaluate material efficiency tools and strategies in an industrial context (research question 2). The researcher had an active executive role in the collection, documentation and analysis of data. The first objective was fulfilled via 41 semi-structured interviews at five manufacturing companies, even though not all interviews were carried out by the
The semi-structured interviews lasted between 15 and 70 minutes and comprised predefined questions regarding barriers, improvement potential, and the actors involved in improving material efficiency and waste segregation. To obtain an interdisciplinary and collaborative perspective on material efficiency barriers, informants included seven environmental managers/coordinators, two plant directors, three production group leaders, ten operators, seven production managers, three safety, quality and health managers, and nine waste management entrepreneurs. To fulfill the second objective, empirical data regarding the levels of awareness of identified tools and strategies, and their implementation (if any) were investigated through 13 semi-structured interviews at five manufacturing companies, all conducted by the author. Each interview lasted approximately 20 minutes. Informants were asked whether they recognized or applied the tools and strategies in their manufacturing company. They were also asked to relate any industrial waste management activities/projects to the applied tools and strategies in their operational area or company. To achieve a holistic understanding and broad organizational representation (as different functions influence material efficiency in manufacturing), interviewees included five environmental coordinators/managers, two operators, two plant directors and four production managers. Each interview was recorded, transcribed and transferred into an Excel document for further analysis. More specific details on the applied data collection and analysis methods of this empirical study can be found in Paper I.

2.2.5 Empirical Study B: Material and Waste Streams
The objective of empirical study B was to increase knowledge and gain a detailed understanding of the existing state of material efficiency, the waste streams and the residual material value chains among manufacturing companies. This study included different tools and strategies for assessment, improvement and management of material efficiency and waste streams. Examples of applied tools are the Green Performance Map (GPM), Waste Flow Mapping (WFM), Waste Sorting Analysis, Environmental Value Stream Mapping (EVSM), Eco-mapping and Life Cycle Assessment (LCA). Empirical data were collected through participant observation, focused semi-structured interviews, and reviews of environmental reports and operational improvement projects. This empirical study was a multiple case study conducted at four large global manufacturing companies in Sweden. Empirical study B is directly connected to research question 2, tools and strategies for material efficiency assessment and improvement, and indirectly connected to research question 1, barriers toward improved material efficiency.

The researcher had an active executive role in mapping material and waste flows and revealed his purpose as a researcher. In the focused semi-structured interviews, 44 participants in different functions were asked predefined questions. The interviews were documented through a common template, and the researcher had an active role in the analysis of all of the interviews. The interview questions were related to material efficiency, routines, the existence of any short- or long-term goals, improvements and cooperation. The interviews lasted from 10 to 30 minutes, and interviewees included environmental managers, plant directors, production leaders, machine operators and waste management entrepreneurs. More specific details on the applied data collection and analysis methods of this empirical study can be found in Papers II, III and IV.

2.2.6 Empirical Study C: Manufacturing KPIs
Empirical study C was a multiple case study at seven global manufacturing companies located in Sweden to identify current Material Efficiency-related Key Performance Indicators (ME-KPIs) at the lowest operational level. Case company N (see Table 1) also
indirectly contributed to this empirical study in later stages. This study focused on research question 3 through data collection by means of direct observations, formal and informal discussions and document reviews. Formal and informal discussions refer to project meetings with academics and practitioners from companies. The researcher had an active executive role in the documentation and analysis of data. However, the data collection was carried out together with other project members. Therefore, the researcher had access to all of the collected data.

Empirical study C identified more than 3,000 Key Performance Indicators (KPIs) from seven manufacturing companies at the shop-floor level (see Landström et al. (2016) and Zackrisson et al. (2017)). ME-KPIs were selected through an iterative process in which KPIs not linked or indirectly linked to material efficiency were excluded during each iteration. The iterative process was carried out as follows:

1. The initial set of ME-KPIs was selected based on the KPI explanations and mathematical formulas given by visualizations or descriptions provided by the boards or by KPI owners at each company. The initial set included KPIs that had any component of material efficiency (i.e., that were related to consuming material and generating or handling waste).

2. The first iteration excluded KPIs that measured time losses or delays because these are related to process productivity levels. General environmental accident measurements were also excluded because such measurements can relate to a variety of different environmental problems that might not involve waste or materials.

3. In the second iteration, quality and productivity KPIs, such as the First Time Through (FTT) and first time pass rates, were excluded. Overall Equipment Effectiveness (OEE) was also excluded in this iteration because it involves three factors: performance, availability and quality. Only the latter is arguably relevant to ME, and not all companies measure OEE in the same way.

4. In the next iteration, KPIs measuring maintenance-related activities were excluded, although they are relevant for preventing scrapping and for consumed materials such as lubricants. These KPIs can be considered indirect ME-KPIs related to auxiliary materials; examples are personal protection equipment or maintenance tools. In addition, supplier quality issues were excluded because unacceptable input components and materials are rejected prior to the manufacturing phase. With the last exclusion iteration, a set of 337 KPIs (11%) remained as direct ME-KPIs.

More specific details on the applied data collection and analysis methods of this empirical study can be found in Paper V.

2.2.7 Empirical Study D: Material Efficiency of Productive Materials

Empirical study D was a single case study at a large manufacturing company located in Sweden. The study aimed to map productive material flow, improve material efficiency and reduce scrap generation through material efficiency assessment and measurements. This study contributed to answering research questions 2 and 3. The data collection lasted for two weeks and was based on participant observation, archival review of internal environmental and operational reports and discussions with different functions including internal environmental manager at the factory level, external environmental manager at the enterprise level, operators, team manager, production manager, waste management entrepreneur, production planner and production technicians. The document reviews helped to realize a basic insight into companies, their overall strategy and environmental target and current improvement projects. The researcher had an active executive role in data collection, documentation, data analysis and project management. More specific
details on the applied data collection and analysis methods of this empirical study can be found in Paper V.

2.2.8 Empirical Study E: Material Efficiency of Auxiliary Materials

Empirical study E was a single case study at a large manufacturing company located in Sweden. The study aimed to map material flow, improve material efficiency and increase recycling of plastics through material efficiency assessment and measurements. The focus of this study was on auxiliary materials and recycling of residual material, mainly plastic and combustibles from assembly lines. This study contributed to answering research questions 2 and 3. The data collection lasted for one week and was based on participant observation, archival review of internal environmental and operational reports and discussions with the internal waste management department, environmental manager, team manager, assemblers, technicians, purchasing manager, suppliers and performance improvement experts. The researcher had an active role in data collection, documentation, and data analysis. More specific details on the applied data collection and analysis methods of this empirical study can be found in Paper V.

Table 2 presents a summary of empirical studies performed.

<table>
<thead>
<tr>
<th>Empirical study</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Related RQs</td>
<td>RQ1, RQ2</td>
<td>RQ2, RQ3</td>
<td>RQ3</td>
<td>RQ2, RQ3</td>
<td>RQ2, RQ3</td>
</tr>
<tr>
<td>Research strategy</td>
<td>Multiple case study</td>
<td>Multiple case study</td>
<td>Multiple case study</td>
<td>Single case study</td>
<td>Single case study</td>
</tr>
<tr>
<td>Unit of analysis</td>
<td>Tools and strategies, and barriers</td>
<td>Material efficiency practices in manufacturing</td>
<td>Material efficiency-related key performance indicators</td>
<td>Productive material flow</td>
<td>Auxiliary material flow</td>
</tr>
<tr>
<td>Data collection method</td>
<td>Semi-structured interviews and direct observations</td>
<td>Semi-structured interviews, direct observation, document review, on-site visits and company walkthroughs</td>
<td>On-site visits and company walkthroughs, direct observations, discussions, document reviews</td>
<td>Participant observation, discussions, document review, multiple factory visit</td>
<td>Participant observation, discussions, document review, multiple factory visit</td>
</tr>
<tr>
<td>Data analysis method</td>
<td>Cross-case analysis, categorization and clustering, data matrix</td>
<td>Pattern matching, expert opinion and discussions in workshops, data matrix, cross-case analysis</td>
<td>Cross-case analysis, data matrix, pattern matching, categorization and clustering</td>
<td>Expert opinion, discussions in workshops, data matrix, color-coding</td>
<td>Expert opinion, discussions in workshops, data matrix, color-coding</td>
</tr>
</tbody>
</table>

2.2.9 Data Analysis

As suggested by Yin (2014), a data analysis was conducted while the data were collected, which is consistent with the inductive approach of this research (Kovács and Spens, 2005) and with theory matching (Dubois and Gadde, 2002). Such a continuous iterative process allows the researcher to identify patterns, themes and relationships. Throughout the data collection and analysis, the researcher endeavored to maintain consistency from one case to another by conducting continual comparisons and reviews of the analyses of both empirical and theoretical data. The results of the empirical data analysis were then compared with the results of the literature review to draw conclusions.
A variety of techniques was deployed for data analysis depending on the study, including categorization and clustering, pattern matching, cross-case analysis, color-coding, data matrix, etc. The data analysis was performed through three activities defined by Miles and Huberman (1994), including data reduction, data display, and conclusion drawing and verification. Thus, the collected data were immediately simplified, organized (into Excel documents), and interpreted, and empirical conclusions were drawn shortly thereafter. Placing an intervening time between each interview and observation enabled the researcher to conduct an initial analysis before proceeding to subsequent interviews and/or observations.

Cross-case analysis, one of the major techniques employed in this research, not only enhances understanding and explanation, but also increases generalizability (Miles and Huberman, 1994). This research employed a variable-oriented analysis in which each variable was investigated across the different cases to build a general theory through replication and logic. In addition, the cases were analyzed individually to understand the particular dynamics of each case.

### 2.3 Quality of Research

The research conducted was quality assured through construct validity, internal validity, external validity and reliability, as recommended by Yin (2014).

#### 2.3.1 Validity

According to Saunders et al. (2009), construct validity is defined as "the extent to which your measurement questions actually measure the presence of those constructs you intended them to measure". As suggested by Voss et al. (2002), the use of multiple sources of evidence can support construct validity and ensures that the information being collected is correct (Meredith, 1998). Therefore, the sources of evidence were triangulated by collecting data from multiple sources; this triangulation included interviews, a questionnaire, observations, content analysis of documents and archival research. Construct validity was further strengthened by peer examination of collected data and results concluded from case studies in different time stages by projects members, academics and industrial supervisors and research fellows at conferences (Yin, 2014). Furthermore, the internal validity of this research was secured by pattern matching between theory and studied cases as well as explanation building for case studies D and E.

External validity relates to the generalizability of findings to other contexts (Saunders et al., 2009). As empirical studies A, B and C were multiple case studies, replication logic was employed to ensure external validity (Yin, 2014). In single case studies (D and E), however, empirical results were related to existing theory.

The main implications of this research are qualitative based on case studies with analytic generalization (Yin, 2014). Hence, the replication of results at manufacturing companies is plausible under similar circumstances. As described earlier, this research primarily describes the situation at large automotive companies located in Sweden, which use metal as their primary product material and generate common types of residual material. Thus, the results might not be generalizable to other industries, to similar manufacturing companies outside of Sweden, or to SMEs in Sweden. In addition, other invisible important aspects such as environmental legislation and regulations, environmental costs, economic and environmental incentives, organizational factors including manufacturing culture or environmental consciousness, educational levels, and societal factors vary greatly over time and across different geographical areas; market actors also vary depending on material
type, supply and geographical region. Therefore, the results might be affected by different sets of specific factors.

2.3.2 Reliability
Reliability is defined as whether consistent results would be achieved either if another researcher replicated the research or if the research was repeated using the same data collection and analysis techniques (Saunders et al., 2009). To secure the reliability of this research, case study databases were used to structurally document the procedure performed, data collected and results concluded in both hard- and soft-copy form. The case study databases also included environmental reports, photographs, written protocols, observations, personal reports and relevant scientific papers, along with all of the recorded interviews and analyses performed.

In addition to the case study databases, structured protocols were written and documented for each case study, company visit and project meeting. Interviews were conducted pursuant to developed guidelines, the study objective, study questions and study propositions to ensure consistency during each interview and data collection, and to prevent participant and researcher error and bias. During the interviews, the conversations were recorded to facilitate more precise interpretation. Most of the recorded interviews were transcribed/listened to and interpreted within one or two weeks of the interview. To enhance interview quality, a variety of interviewees from various hierarchical levels and functions at different companies were selected (Kvale, 1996). The semi-structured interview was chosen due to its flexibility, which permitted discussion and the formulation of new questions during the interview (Saunders et al., 2009) as well as maintaining control of the conversation. To ensure the quality, reliability and validity of data collection, two or three interviewers participated in each interview (Eisenhardt, 1989), notes were taken, and all of the questions were asked and answered in Swedish to prevent any misunderstanding or bias.
3. Theoretical Framework

This chapter provides a summary of the theoretical base, previous research and the theoretical findings of this dissertation. It begins by reviewing sustainable manufacturing, waste management and material efficiency. Next, material efficiency definition and options are discussed, followed by an introduction to material efficiency barriers, tools and strategies. This chapter concludes with a description of material efficiency measurements.

3.1 Sustainable Manufacturing

The most common definition of sustainable development has been given in a report titled "Our common future", which refers to "development that meets the needs of present generations while not compromising the ability of future generations to meet their needs" (World Commission on Environment and Development, 1987). Driven by this definition, Garetti and Taisch (2011) define sustainable manufacturing as "the ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviors, are able to satisfy economic, environmental and social objectives, thus preserving the environment while continuing to improve the quality of human life". A similar definition of sustainable production has been given by the Lowell Center as "the creation of goods and services using processes and systems that are: non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for workers, communities, and consumers; and, socially and creatively rewarding for all working people" (Veleva et al., 2001a). The International Institute for Sustainable Development (IISD, 1992) also has a close definition of corporate sustainability as "adopting business strategies and activities that meet the needs of the enterprise and its stakeholders today while protecting, sustaining, and enhancing the human and natural resources that will be needed in the future", which is closely associated – if not synonymous – with corporate social responsibility (Roca and Searcy, 2012). These definitions encompass not only the environmental aspect, but also economic and social aspects. Occasionally, sub-dimensions such as technology, performance management and education are also included (Arena et al., 2009; Baud, 2008; Joung et al., 2013). These definitions emphasize conserving natural resources as a need for future generations, which can be referred to as the importance of material consumption, waste management, circular economy and material efficiency. In a manufacturing context in which materials are used to produce a product and waste is generated, the given definitions relate to using less input (virgin) materials and generating less output waste.

There is no doubt about the importance of manufacturing in sustainable development. Manufacturing activities contribute up to 22% of Europe’s GDP, and 70% of jobs in Europe directly or indirectly depend on manufacturing (Garetti and Taisch, 2011). Manufacturing currently accounts for 33% of total global energy consumption and 38% of direct and indirect CO₂ emission generation; in both cases, the share of manufacturing is greater than the shares attributable to transportation, households and services (IMS, 2009). Manufacturing greatly contributes to (virgin) raw material consumption, the greenhouse effect, climate change, energy use, toxics, waste generation and water and air emissions (Esty and Winston, 2009). Although manufacturing companies accept environmental excellence as extensive benefits, the cost of complying with environmental legislation and best practice targets is found to be high by companies, at least in the short term (Smith and Ball, 2012). Conversely, recent literature reports the relationship between environmental performance and positive financial and market performance of firms in the long term (Zokaei et al., 2013; Sundin et al., 2012; Lee et al., 2010).
3.2 Industrial Waste Management
Industrial waste is a key factor to consider when assessing the sustainability of a manufacturing process or a company. Defining the term ‘waste’ is essential for improving material efficiency, controlling waste and protecting health and the environment. Defining waste facilitates the determination of whether a material constitutes waste and whether it should be managed as waste. According to the EU Waste Framework Directive, waste is any substance or object that the holder discards or intends or is required to discard but is not a product of the operations (European Commission, 2008). However, according to the Defra (2012), "whether a material is a waste or not depends on the specific factual circumstances, and that therefore the decision must be taken by the competent authority on a case by case basis". Therefore, if the given residual material has no possible use and is destined to be discarded, it would be considered waste, although retains value.

Best practice waste management includes monitoring and fully controlling all stages of waste production, collection, storage, transportation, sorting, handling and disposal or local treatment of waste material – whether it is liquid, solid or gaseous and whether it is hazardous or non-hazardous – to ensure that the waste is rendered harmless to humans, animals and the environment (Hogland and Stenis, 2000; Taiwo, 2008). Best practice waste management also includes the acquisition and dissemination of necessary information about waste disposal techniques and options, fuel handling, spillage control, pollution measurements, and related health and safety issues (Atlas, 2001). Best practice waste management contributes to the reduction of the environmental burden generated throughout a product’s life cycle, to decrease the effect of waste on health and the environment, to increase environmental friendly material consumption and avoid hazardous and toxic material, to use processes and technologies with lower emissions, to the minimization of waste and to correct waste segregation and disposal via reuse and recycling and to avoid landfill and incineration. Given the focus of this dissertation on material efficiency in manufacturing, industrial waste management is of particular interest, and the research presented contributes to efforts to move up the waste hierarchy steps, presented in Figure 5. The waste hierarchyprioritizes various waste streams and end-of-life scenarios to achieve optimal environmental and economic benefits.

![Figure 4 – Waste hierarchy.](image)

3.3 Material Efficiency Definition and Options
According to Oxford Learner’s Dictionaries, *efficiency* means “the quality of doing something well with no waste of time or money”; the Longman dictionary of Contemporary English defines it as “the quality of doing something well and effectively, without wasting time, money, or energy”. Therefore, in a simple definition, *material efficiency* would be defined as “the quality of doing something well with no waste of material”.

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The material efficiency concept was initially introduced as homologous to energy efficiency by Worrell et al. (1995). Since then, material efficiency has been addressed by different scholars, mainly in the UK, the USA and the Netherlands. Table 3 summarizes the given definitions of material efficiency. Definitions given by Abdul Rashid (2009) and Söderholm and Tilton (2012) are primarily related to factories and manufacturing entities, whereas the other definitions are more holistic and generic and relate to the entire supply chain or society as a whole. In this dissertation, material efficiency in manufacturing implies any activities to (1) reduce the amount of material used for manufacturing a product in a factory through different options such as process improvement or in-house recycling/reusing, (2) generate less waste per product regardless of end-of-life scenarios, and (3) achieve better waste segregation and management to move up the waste hierarchy steps. These three aspects of material efficiency lead to prevention and reduction in extraction and consumption of virgin raw materials, cost and energy savings in fabrication, transformation, transportation and disposal, reduction of industrial waste volumes, increased recycling and reusing in waste management as well as reduced energy demands, carbon emissions and overall environmental impact of the global economy in a broader perspective. Thus, improved material efficiency is a key to improving the circular economy and capturing value in industry (Shahbazi et al., 2016).

<table>
<thead>
<tr>
<th>Definitions</th>
<th>References</th>
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<tr>
<td>&quot;The amount of primary material that is needed to fulfill a specific function. Material efficiency improvement allows the same function to be fulfilled but with a reduced amount of material.&quot; (1995); &quot;Reducing the consumption of primary materials without substantially affecting the service or function, or – in a broader definition – without affecting the level of human activities qualitatively&quot; (1997); &quot;Material efficiency entails the pursuit of technical strategies, business models, consumer preferences, and policy instruments that would lead to a substantial reduction in the production of new materials required to deliver well-being.&quot; (2016)</td>
<td>Worrell et al. (1995, 1997, 2016)</td>
</tr>
<tr>
<td>&quot;The amount of a particular material needed to produce a particular product [...] In a slightly broader sense, taking into account the industrial production-consumption cycle, material efficiency can refer to the amount of virgin natural resources required for producing a given amount of product, with recycling of post-consumption waste material back into production&quot;</td>
<td>Peck and Chipman (2007)</td>
</tr>
<tr>
<td>&quot;The ratio of output of products to input of raw materials&quot;</td>
<td>Abdul Rashid (2009)</td>
</tr>
<tr>
<td>&quot;Material efficiency encompasses all changes that result in decreasing the amount of engineered and processed materials used to produce one unit of economic output or to fulfill human needs more broadly [...] Material efficiency in industrial production can be defined as the amount of a particular material needed to produce a particular product.&quot;</td>
<td>Söderholm and Tilton (2012)</td>
</tr>
<tr>
<td>&quot;Material efficiency means providing material services with less material production and processing.&quot; (2011); &quot;to continue to provide the services delivered by materials, with a reduction in total production of new material&quot; (2013)</td>
<td>Allwood et al. (2011, 2013)</td>
</tr>
</tbody>
</table>

Inspired by Allwood et al. (2011) and with a framework adoption from Romvall et al. (2011), Figure 5 illustrates different material efficiency options through a product’s life cycle. The focus of this dissertation, however, is on the manufacturing phase, where productive material and auxiliary material are consumed and residual material is generated. Thus, phases of product design, material acquisition, transportation of raw materials, transportation of finished products, obsolescence, post-consumer recycling as well as disposal and treatment of products after the use phase are excluded. However, the correlation and effect of these aspects on manufacturing have not been neglected. Material acquisition and supplier manufacturing phases have the same material efficiency options as the manufacturing phase, while package and transport options mainly mirror the design phase such as usage of light-weight materials. Reuse options during the end-of-life phase include the reuse of materials and components with another purpose in a new life cycle,
e.g., recycling plastic to make clothes, whereas component reuse during the use stage refers to reuse with the same purpose.

Figure 5 – Material efficiency options for different product life cycles inspired by Allwood et al. (2011).

According to literature study B, the main improvement potentials in the manufacturing phase relate to correct waste segregation (e.g., separating plastics from combustibles) for recycling and reuse, sufficient volume of specific waste fractions, process improvement (e.g., having fewer quality deviations or scraps), technology development (which is costly but vital in the long term) and correct component/material purchasing, where reused/refurbished/remanufactured/recycled components/materials could come into play (Shahbazi et al., 2016). Remanufacturing is also essential for material efficiency in manufacturing, but it is usually performed together with other plants or suppliers and is more related to product than to manufacturing. Material efficiency management and improvement is vital in the manufacturing phase to correctly segregate and use the wasted value of residual materials. Material efficiency in manufacturing is, however, much dependent on other phases too. For instance, decisions on using environmentally sound materials, precise measures, packaging with less material and lightweight components in the design phase as well as dematerialization (usually refers to digital technologies such as the paperless office) play an important role in achieving material-efficient manufacturing. Collecting products in the end-of-life phase for remanufacturing or reuse of products or components is also linked to the manufacturing phase but is not within the scope of this dissertation.

Material efficiency has been studied by various scholars on a broad and general level. For example, Lilja (2009a) has studied the alternative concepts of material efficiency and waste prevention in the context of the new Finnish National Waste Plan. He concludes that in the future, waste prevention will be supplanted by material efficiency. In addition, he discusses the opportunities and challenges involved in applying sector-specific negotiated agreements for promoting waste prevention and material efficiency (Lilja, 2009b). Allwood et al. (2011) discuss material efficiency in business models, consumer preferences and policies to give an overview of the topic and engage insights from economics,
sociology, policy, design, environment and technical analysis. Worrell et al. (2016) broadly discuss material efficiency and dematerialization improvements, drivers and effects on human life, economy, climate change and sustainable development. Their discussion is based on consumer, industry and policy perspectives. The industrial perspective remains broad and generic, addressing the industrial system rather than material efficiency in a single manufacturing plant. Söderholm and Tilton (2012) present an economic perspective of material efficiency with a focus on the role of public policy to provide market incentives for a more efficient use of materials. Halmé et al. (2007) propose a conceptual framework for material efficiency services provided by external suppliers. Four business models are outlined with their main focus on financial aspects. In addition, numerous scholars have studied material efficiency in terms of critical materials and rare-earth metals for better design and recycling, given that the recycling rates of these materials are estimated to be less than one percent in most cases. Examples of these studies include Schmidt (2012), Massari and Ruberti (2013), Hallstedt and Isaksson (2017), Ayres and Peiró (2013), Roland Berger Institute (2011), Hedrick (2008) and Kingsnorth (2008).

3.4 Material Efficiency Barriers
The literature study revealed a scarcity of studies on barriers to material efficiency; among the few that exist are e.g., Allwood et al. (2011) and Watkins et al. (2013), and particularly in the manufacturing context, Abdul Rashid (2009). Further adding to this deficiency is the very limited number of material efficiency studies in Sweden, e.g., Luttropp and Johansson (2010) and Larsson et al. (2006), none of which address material efficiency barriers. Therefore, generic barriers to environmental sustainability were considered, e.g., barriers to environmental strategy implementation (Chan, 2008), barriers to cleaner production (Moors et al., 2005), barriers to green initiatives in the automotive industry (Nunes and Bennett, 2010; Amrina and Yusof, 2012), barriers to sustainable supply chains (Al Zaabi et al., 2013), barriers to recycling (Larney and Van Aardt, 2010; Zhu et al., 2011; Östlund et al., 2015), and barriers to sustainability in operating IT software solutions (Seidel et al., 2010), among other papers. The selected barriers range from general issues such as “financial and economic barriers” or “limited intra-organizational cooperation and interaction” to very technical/specific barriers such as “waste material awareness” relating to waste type, waste volume, homogeneity quality of the waste, related legislation and/or regulation, price volatility, potential markets and disposal options.

Regional factors are influential in material efficiency and a scant number of papers investigate the Swedish manufacturing industry. Therefore, the literature review performed was not limited to Sweden but included studies around the globe in countries such as China (Kuei et al., 2012; Zhu et al., 2011; Shi et al., 2008), India and Germany (Mittal et al., 2013), the UK (Abdul Rashid and Evans, 2012), Spain (Murillo-Luna et al., 2011), (Koho et al., 2011), the Netherlands (van Hemel and Cramer, 2002), South Africa (Larney and Van Aardt, 2010), Malaysia (Amrina and Yusof, 2012) and Finland (Pajunen et al., 2013).

Based on extensive literature study C, a list of material efficiency barriers were identified and then categorized into six main groups including Technological, Social, Informational, Legal, Organizational and Economic. This categorization aimed to facilitate understanding of material efficiency to effectively mitigate the barriers. Barriers in each category were then clustered further to ease prioritization and improvement actions. As it is difficult to remove all barriers simultaneously and barriers relate to different applications, products and processes of the company, this categorization and clustering helps companies to prioritize according to their predetermined goals, to increase recycling rates and also to move up the waste hierarchy steps.
Table 4 – Barriers that impede material efficiency improvement at manufacturing companies, presented in Paper I

<table>
<thead>
<tr>
<th>Barriers</th>
<th>Associated issue</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering</td>
<td>Engineering barriers, e.g., layout</td>
<td>Mu et al. (2008); Murillo-Luna et al. (2011); Ammenberg and Sundin (2005)</td>
</tr>
<tr>
<td></td>
<td>Technical and detailed knowledge, e.g., waste material awareness</td>
<td>Post and Alma (1994); van Hemel and Cramer (2002); Bey et al. (2013); Pajunen et al. (2013); Simpson, (2010)</td>
</tr>
<tr>
<td></td>
<td>Trade-offs and difficulty in balancing</td>
<td>Mittal et al. (2013); Bey et al. (2013)</td>
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<tr>
<td>Technological</td>
<td>Lack or scarcity of advanced technology and equipment with lower environmental impacts</td>
<td>Murillo-Luna et al. (2011); Luken and Van Rompaey (2008); Zhu et al. (2011); Simpson (2010); Abdul Rashid and Evans (2010); van Hemel and Cramer (2002); Moors et al. (2005); Bey et al. (2013); Al Zaabi et al. (2013); Seidel et al. (2010); Johansson (2002)</td>
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<tr>
<td>Machine, equipment and technology</td>
<td>Aversion to innovation and technological change</td>
<td>Murillo-Luna et al. (2011); van Hemel and Cramer (2002); Seidel et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>Difficulties and technological risks</td>
<td>Sarkis et al. (2007); Mittal and Sangwan (2014); Post and Alma (1994)</td>
</tr>
<tr>
<td>Environmental</td>
<td>Lack of relevant/suitable tools for environmental initiatives</td>
<td>Murillo-Luna et al. (2011); Amrina and Yusof (2012); Larney and Aardt (2010); Zhu et al. (2011); Ammenberg and Sundin (2005); Bey et al. (2013); Al Zaabi et al. (2013)</td>
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<tr>
<td>Budgetary</td>
<td>Limited financial capability for environmental investments</td>
<td>Post and Alma (1994); Hillary (2004); Shi et al. (2008); Chan (2008); Abdul Rashid and Evans (2010); Moors et al. (2005); Bey et al. (2013); Pajunen et al. (2012); Allwood et al. (2011); Simpson (2010); Al Zaabi et al. (2013); Amrina and Yusof (2012); Larney and Aardt (2010); Seidel et al. (2009); Murillo-Luna et al. (2011); van Hemel and Cramer (2002); Mittal and Sangwan (2014); Zhu et al. (2011); Luken and Van Rompaey (2008)</td>
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<tr>
<td></td>
<td>High short-term costs and low short-term economic benefits</td>
<td>Mittal and Sangwan (2014); Zhu et al. (2011)</td>
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<tr>
<td>Material &amp; product cost</td>
<td>Limited environmental awareness of directors</td>
<td>Murillo-Luna et al. (2011); Abdul Rashid and Evans (2010); Zhu et al. (2011); Moors et al. (2005); Simpson (2010)</td>
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<tr>
<td></td>
<td>Limited top management commitment and support for sustainability initiatives</td>
<td>Shi et al. (2008); Zhu et al. (2011); Post and Alma (1994); Moors et al. (2005); Amrina and Yusof (2012); Sarkis et al. (2007); Mittal and Sangwan (2014); Koho et al. (2011); Seidel et al. (2010); Zhu et al. (2011); Al Zaabi et al. (2013); Johansson (2002); Bey et al. (2013)</td>
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<td></td>
<td>Higher priority of other issues or requirements, e.g., production expansion/market share</td>
<td>Shi et al. (2008); Murillo-Luna et al. (2011); Simpson (2010); Seidel et al. (2009)</td>
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<td></td>
<td>Management resistance to change</td>
<td>Shi et al. (2008); Murillo-Luna et al. (2011); Amrina and Yusof (2012); Sarkis et al. (2007)</td>
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<tr>
<td>Supplier</td>
<td>Poor partnership formation and management</td>
<td>Sarkis et al. (2007); Simpson (2010)</td>
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<tr>
<td></td>
<td>Limited development of environmental supply sector</td>
<td>Murillo-Luna et al. (2011)</td>
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<td></td>
<td>Uncooperative supplier</td>
<td>Abdul Rashid and Evans (2010); Bey et al. (2013)</td>
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<td></td>
<td>Lack of demand from supplier</td>
<td>Koho et al. (2011)</td>
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<tr>
<td>Vision &amp; culture</td>
<td>Company culture</td>
<td>Pajunen et al. (2012); Ammenberg and Sundin (2005); Allwood et al. (2011); Chan (2008); Abdul Rashid and Evans (2010)</td>
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<tr>
<td>Lack of focus on corporate image and social responsibility</td>
<td></td>
<td>Bey et al. (2013); Pajunen et al. (2012); Seidel et al. (2010); van Hemel and Cramer (2002); Abdul Rashid and Evans (2010); Moores et al. (2005)</td>
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<tr>
<td>Unclear/weak strategic and business goals, capabilities and planning, and the existence of misalignment of short- and long-term strategic goals</td>
<td></td>
<td>Hillary (2004); Chan (2008); Seidel et al. (2010); Zhu et al. (2011); Koho et al. (2011); Shi et al. (2008); Al Zaabi et al. (2013); Allwood et al. (2011); Simpson (2010); van Hemel and Cramer (2002); Seidel et al. (2009)</td>
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<tr>
<td>Lack of vision, lack of environmental goals and corporate values, lack of specific goals for specific processes/products</td>
<td></td>
<td>Amrina and Yusof (2012); Bey et al. (2013); Pajunen et al. (2013); Johansson (2002)</td>
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<tr>
<td>Informational</td>
<td>Negative employee attitudes, limited environmental motivation and awareness among employees</td>
<td>Amrina and Yusof (2012); Post and Alma (1994); Hillary (2004); Chan (2008); Bey et al. (2013); Pajunen et al. (2012); Murillo-Luna et al. (2011); Seidel et al. (2010); Ammenberg and Sundin (2005); Zhu et al. (2011)</td>
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<tr>
<td>Lack of human resources and time</td>
<td></td>
<td>Hillary (2004); Chan (2008); Bey et al. (2013); Zhu et al. (2011); Shi et al. (2008); Ammenberg and Sundin (2005); Seidel et al. (2009)</td>
</tr>
<tr>
<td>Resistance to organizational change and operational inertia</td>
<td></td>
<td>Amrina and Yusof (2012); Post and Alma (1994); Murillo-Luna et al. (2011); Sarkis et al. (2007)</td>
</tr>
<tr>
<td>Insufficient technical and environmental training, education and reward systems</td>
<td></td>
<td>Pajunen et al. (2012); Murillo-Luna et al. (2011); Seidel et al. (2010); Ammenberg and Sundin (2005); Sarkis et al. (2007); Al Zaabi et al. (2013); Shi et al. (2008)</td>
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<tr>
<td>Lack of support and guidance, limited in-plant expertise/capability</td>
<td></td>
<td>Hillary (2004); Chan (2008); Ammenberg and Sundin (2005); Koho et al. (2011); Shi et al. (2008); Pajunen et al. (2013); Luken and Van Rompaey (2008); Johansson (2002)</td>
</tr>
<tr>
<td>Legal</td>
<td>Difficulties associated with the process of applying/complying with legislation and/or environmental management system</td>
<td>Hillary (2004); Chan (2008); Murillo-Luna et al. (2011); Amrina and Yusof (2012); Pajunen et al. (2013)</td>
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<tr>
<td>Lack of or low environmental enforcement</td>
<td></td>
<td>Shi et al. (2008); Murillo-Luna et al. (2011); Al Zaabi et al. (2013); Sarkis et al. (2007); Pajunen et al. (2012); Mittal and Sangwan (2014); Zhu et al. (2011); Seidel et al. (2009); Bey et al. (2013)</td>
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<tr>
<td>Methodology &amp; measurement</td>
<td>Lack of clarity, know-how, methodologies and processes</td>
<td>Sarkis et al. (2007); Murillo-Luna et al. (2011); Al Zaabi et al. (2013); Koho et al. (2011); Ammenberg and Sundin (2005); Pajunen et al. (2012); Mittal and Sangwan (2014)</td>
</tr>
<tr>
<td>Lack of effective approaches and measures to evaluate sustainability, difficulties in quantifying sustainability</td>
<td></td>
<td>Al Zaabi et al. (2013); Shi et al. (2008); Seidel et al. (2009); Koho et al. (2011); Sarkis et al. (2007); Johansson (2002); Zhu et al. (2011); Seidel et al. (2010)</td>
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<tr>
<td>Communication</td>
<td>Poor communication</td>
<td>Post and Alma (1994); Murillo-Luna et al. (2011); Ammenberg and Sundin (2005); Pajunen et al. (2012)</td>
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<tr>
<td>Limited intra-organizational cooperation and interaction</td>
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<td>Sarkis et al. (2007); Simpson (2010)</td>
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<tr>
<td>Uncertainty &amp; risk</td>
<td>Uncertainty about potential results, market benefits, performance impact and environmental benefits</td>
<td>(Hillary, 2004); Shi et al. (2008); Zhu et al. (2011); van Hemel and Cramer (2002); Post and Alma (1994); Murillo-Luna et al. (2011); Mittal and Sangwan (2014); Luken and Van Rompaey (2008); Koho et al. (2011); Moores et al. (2005); Pajunen et al. (2013); Simpson (2010)</td>
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<tr>
<td>Uncertainty regarding future legislation</td>
<td></td>
<td>Mittal and Sangwan (2014)</td>
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According to literature study C, the most-cited barriers (and associated issues) to material efficiency are as follows: (1) limited financial capability for environmental investments; (2) lack of information; (3) uncertainty about potential results, market benefits and environmental benefits; (4) weak commitment and support from top management; (5) unclear/weak strategic and business goals; (6) poor employee attitude, motivation and awareness; and (7) lack or scarcity of advanced technology and equipment with lower environmental impacts. As discussed in Paper I, the majority of the cited barriers are internal, i.e., they are dependent on each organization’s characteristics. According to this literature study C, the most influential barrier clusters related to material efficiency in manufacturing are Budgetary, Information; Technology, Management, Vision and Culture, Uncertainty, Engineering and Employees.

### 3.5 Material Efficiency Tools and Strategies

Adapted from Almeida et al. (2015), sustainability strategies in this dissertation refers to a series of maneuvers to “help society to design and implement short- and long-term approaches to achieve the transition to truly sustainable societal development”. According to literature study A, few sustainability strategies directly focus on waste generation, total raw material consumption and better waste segregation. Even fewer studies have described these strategies in relation to decision hierarchy and development of management systems to manage manufacturing companies’ material efficiency. These few strategies overlap by proposing similar solutions for industrial waste management (Lilja, 2009a), resulting in confusion and disorientation for companies aiming to synthesize their management systems with material efficiency strategies.

As discussed in Paper I, Almeida et al. (2015) describe a decision hierarchy that moves from global strategies with broad and long-term goals (top) to local strategies at individual plant or lower levels (bottom). Low-level strategies focusing on improvement in the individual manufacturing factory and lower levels such as operation, process, technology and shop floor are called tools. This pyramid aids in understanding each strategy in terms of time, scale and area of influence. In literature study A, several environmental sustainability strategies have been identified that, to various degrees, could relate to improving material efficiency, i.e., increasing waste segregation into high-quality circulated raw material, reducing waste generation, and reducing total virgin material consumption. The main strategies identified are Cleaner Production (e.g., Almeida et al.,
Zero Waste (e.g., Curran and Williams, 2012), Eco-efficiency (e.g., Ehrenfeld, 2005), Eco-design (e.g., Sundin et al., 2009), Closed-loop (e.g., Guide Jr. et al., 2003), Reverse Logistics (e.g., Dowlatshahi, 2000), Industrial Ecology (e.g., Kuehr, 2007), Product Stewardship (e.g., Rogers et al., 2010), Environmental Management System (e.g., Khalili and Duecker, 2013), Eco-mapping (e.g., Ehrenfeld, 2005), Material Flow Cost Accounting (e.g., Kokubu and Kitada, 2015), and Resource Efficiency (e.g., Abdul Rashid et al., 2008). The list of relevant tools and strategies for material efficiency is presented in Figure 6, categorized based on their application level and decision hierarchy, as suggested by Almeida et al. (2015). Although these strategies relate to material efficiency, the evidence concerning the actual implementation of these strategies in industry is unclear (Abdul Rashid et al., 2008; Bey et al., 2013). Figure 6 juxtaposes strategies both to provide clarification and to enable more precise understanding; however, it is not intended to select one strategy as superior.

As presented in Paper I, Eco-efficiency and Resource efficiency strategies are more related to the global level (Abdul Rashid et al., 2008) and have strong and long-term effects on material efficiency in a very broad sense. These strategies are more suited to decision makers at the macro-economic level and at the top levels of management and government, who are responsible for high-level policies, tactics and service measurements. Strategies in the middle of the pyramid are rather connected to the national level or even the sectoral level, where material costs, waste management systems, transportation and waste disposal as well as regulation and taxation to prevent environmental impacts, are essential. These strategies support optimization of entire industrial systems, processes, energy and material flows, and technologies.

At the bottom of the pyramid, the strategies (also called tools) are simpler and have a limited area of influence on processes, manufacturing operations, products or services. These tools assist organizations in pursuing and achieving specific environmental and sustainability goals, and in following environmental regulations. However, Life Cycle Assessment (LCA) and Zero Waste can also be correlated with the sectoral and supply chain level, or Environmental Management System can be associated with the enterprise level (between sectoral and individual) at which different operations sites around the world comply with the central environmental management system. As a result, few strategies/tools focus on the factory level, which is in line with the literature, where the
majority of sustainable development strategies are described as generic and at a high level, indicating a lack of guidance and tools at the operations level (Smith and Ball, 2012). Yet at the factory level, material efficiency-related strategies primarily concern management of the whole factory, rather than limited operations and processes (tools and techniques for process improvement). Consequently, it is difficult and complex to directly implement, measure and evaluate such strategies at the operational level, where regular measurement, revision and monitoring are necessary for continuous improvement of material efficiency. Some scholars have developed models or approaches to enhance resource or material efficiency at the operational level. For instance, Meyer et al. (2007) developed the PANTA RHEI model to improve material productivity to facilitate achievement of environmental and economic targets in Germany. Smith and Ball (2012) used material, energy and waste flow modeling to develop guidelines for analyzing manufacturing systems. Halme et al. (2007) proposed a business model for material efficiency services provided by third parties.

Three main tools from the bottom of the pyramid were used in this research during data collection and analysis to manage and improve material efficiency of companies. These tools include Green Performance Map (Romvall et al., 2011), Waste Flow Mapping (Kurdve et al., 2015) and Environmental Value Stream Map (EPA, 2015). As discussed in Paper IV, the selection of these tools to assess material and waste flows to improve material efficiency was based on certain characteristics that these tools share. These characteristics include

- Being hands-on and operational, supporting collaboration of different functions (internally or externally) and mutual understanding.
- Integrating lean and green principles such as easy learning and implementation, visualization, time efficiency, continuous improvement and engagement. Tools should also focus on root-cause analysis, harmonized with ISO 14001 (2004) and support go-to-gemba concept.
- Being goal oriented, supporting measurements, focusing on a limited area of influence and supporting a systematic work procedure.

As discussed in Paper IV, these tools collect and analyze different sets of data related to material efficiency; hence they complement one another in assessment and improvement of material and waste flows. In addition, current application of these tools among large manufacturing companies in Sweden including Volvo Group, Haldex, Volvo Cars, Alfa Laval and Scania played an important role to apply these tools during this research. In the following, these three tools are briefly summarized.

**Green Performance Map (GPM)**

As presented in Papers III and IV, GPM is a structured lean and green tool based on an input–output model for identifying and visualizing the different environmental aspects of a manufacturing process, operation or factory. GPM is reported to be a fruitful tool to identify, prioritize, measure and follow complementary improvement actions of environmental aspects of different operational levels by different functional positions (Shahbazi and Wiktorsson, 2016; Romvall et al., 2011). The tool divides the input materials into productive and auxiliary materials and the outputs into products and residual materials. In addition, energy and water consumption (as inputs) together with generated emissions to air (including heat or noise), soil or water (as outputs) are considered. This inclusion of input and output is in line with material flow cost accounting (Kokubu and Kitada, 2015) and the framework suggested by international environmental standards ISO 14001 (2004) and ISO 14051 (2011).
Waste Flow Mapping (WFM)
As presented in Papers II and IV, the WFM method provides a framework for identifying and analyzing potentials for waste management and material efficiency in the manufacturing industry, including residual material values of metals, combustible and inert waste, process fluids and other hazardous waste. It combines lean and green principles and tools, such as Eco-mapping and a Waste Sorting Analysis to identify inefficiency and improvement potential to gain value from residuals, and to reduce unnecessary material input (Shahbazi and Kurdve, 2014). WFM focuses on an analysis of the material waste management supply chain and particularly on the interface between waste management and production management because this interface is crucial for the rest of the waste management process.

Environmental Value Stream Mapping (EVSM)
As presented in Paper IV, Value Stream Mapping (VSM) is a well-known lean tool that identifies time inefficiencies in a manufacturing process. The United States Environmental Protection Agency (EPA, 2015) introduced EVSM to consider environmental aspects of a process for improvement, but less has been published on using EVSM on material flow and waste generation. The author used EVSM for material efficiency management and to map, measure and assess material and waste flows. This has bridged the gap between environmental studies (here material efficiency) and operations management by considering flows of input material, i.e., productive and auxiliary, and a flow of output residual material (Shahbazi and Amprazis, 2017).

Additional tools and strategies related to environmental sustainability do exist (literature study A), but they are excluded from this dissertation due to their indirect or limited links to material efficiency. Certain strategies are also subsets of the main strategies or very closely linked to another strategy, see Table 5.

Table 5 – Material efficiency strategies

<table>
<thead>
<tr>
<th>Strategies toward Material Efficiency</th>
<th>Subsets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eco-efficiency</td>
<td>Eco-effectiveness</td>
</tr>
<tr>
<td>Life Cycle Assessment (LCA)</td>
<td>Life Cycle Cost (LCC), Eco-design, Eco-compass, Eco-ideas Map</td>
</tr>
<tr>
<td>Industrial Ecology</td>
<td>Eco-industrial park, Industrial symbiosis</td>
</tr>
<tr>
<td>Product Stewardship</td>
<td>Individual Product Responsibility (IPR), Extended Product Responsibility (EPR)</td>
</tr>
<tr>
<td>Environmental Management System (EMS)</td>
<td>Sustainable Environmental Management System (SEMS)</td>
</tr>
<tr>
<td>Material Flow Cost Accounting (MFCA)</td>
<td>System Boundary Mapping, Green Impact Matrix, Green Big Picture Map, Environmental Management Accounting (EMA)</td>
</tr>
<tr>
<td>Zero Waste</td>
<td>Waste Prevention, Waste Minimization</td>
</tr>
<tr>
<td>Cleaner Production</td>
<td>Best Available Technology, Cleaner Technology, Pollution Prevention</td>
</tr>
</tbody>
</table>

3.6 Material Efficiency Measurement and Indicators

Here, literature study D is presented in three sections, including development and characteristics of sustainability guidelines and material efficiency key performance indicators.

3.6.1 Development of Sustainability Indicators and Guidelines

For many years financial, business, quality and market performance indicators were in the center of measurement targets without considering sustainability performance (in
particular environmental and social sustainability). With the publication of Our Common Future (World Commission on Environment and Development, 1987), sustainability objectives gradually began to appear in business strategies (Möller and Schaltegger, 2005), and social and environmental performance indicators were considered in managerial decision making (Bai and Sarkis, 2014) and externally communicated in the form of environmental reports (Azapagic and Perdan, 2000). The most common method for sustainability performance assessment is to develop an appropriate set of indicators. Sustainability indicators are a set of simple measures with a holistic approach on a large scale (Joung et al., 2013; Singh et al., 2012) that measure progress toward sustainability (Chee Tahir and Darton, 2010) in a defined area, e.g., a process/product, a manufacturing site, an organization, or at the regional, national or global level (Ness et al., 2007). In addition to measuring progress toward sustainability goals, these sustainability indicators are used to report sustainability performance, to promote improved process understanding and awareness, to determine the status of a system, to identify important issues and achievements, to anticipate future conditions and trends, to provide early warning information, to compare across locations and situations, to prioritize and provide guidance for reactive or proactive decision making and actions, and to communicate data to the stakeholders (Ahi and Searcy, 2015; Gallopín, 1997; Veleva et al., 2001b; Singh et al., 2012).

Sustainability management, measurement and reporting have been supported by many guidelines, frameworks, standards and numerous lists of sustainability performance indicators (Roca and Searcy, 2012) at different levels (Joung et al., 2013) such as global, national, organization and plant. As a result, the number of indicators, conceptual frameworks and methodologies has proliferated in recent decades (Chee Tahir and Darton, 2010). These indicators measure sustainability performance related to economic, social, and environmental systems of a corporation, or to particular processes, products or activities (Dočekalová and Kocmanová, 2016). Difficulties to define a set of sustainability indicators applicable to all organizations or manufacturing companies as well as contrary interpretations and opinions drawn from the same set of indicators, causes new guidelines and sustainability performance indicators to be proposed by different users in many different sustainability contexts and for diverse purposes (Hák et al., 2016), but with little or no guidance on their practical application and selection (Veleva et al., 2001b). The following are examples of guidelines:

- The United Nations Commission on Sustainable Development (CSD, 2007) developed a list of 96 indicators on different themes in their third edition which explicitly addresses the relationship to Agenda 21. The identified indicators cover four ‘pillars’ of sustainability: social, economic, environmental and institutional.

- The United Nations Sustainable Development Summit in New York proposed 17 global sustainable development goals (United Nations, 2015) with 169 targets and a preliminary set of 330 indicators. Furthermore, the United Nations Global Impact initiative (United Nations, 2004) introduced a set of 10 principles as a framework for businesses to improve human rights, labor, the environment and anti-corruption. The three environmental principles cover supporting a precautionary approach to environmental challenges, initiatives to promote greater environmental responsibility, and encouraging the development and diffusion of environmentally friendly technologies.

- The Global Reporting Initiative (GRI, 2015) developed a framework to facilitate sustainability reporting with a standard format. The GRI guideline, which is the world’s
most widely used sustainability reporting tool, includes 91 indicators of a generic nature with a broad coverage.

- The World Business Council on Sustainable Development (WBCSD, 2000) developed an eco-efficiency framework with a set of indicators grouped into two dimensions, economy, i.e., product/service value and ecology, i.e., environmental influence in product/service creation. The identified indicators are ‘generally applicable’ indicators across all industries and any other indicator falling outside of these criteria is labeled ‘business specific’.
- The Organization for Economic Cooperation and Development has introduced 30 indicators in a socio-economic context as green growth indicators (OECD, 2014) that address environmental and resource productivity, the natural asset base, the environmental dimension of quality of life, and economic opportunities and policy responses. In addition to green growth indicators, OECD has also named 10 key environmental indicators to support countries in their regular assessment of environmental performance.
- The Institution of Chemical Engineers (IChemE, 2002) has developed another set of indicators that address sustainability assessment based on triple bottom line reporting and 9 subsections.
- Sweden also introduced a list of environmental quality objectives (The Swedish Environmental Protection Agency, 2013) by focusing on a variety of environmental impacts, such as climate change, air pollution, toxicity, acidification, radiation and clean water, among others. This list includes 16 environmental quality goals with 110 indicators to be achieved by 2020.

In addition, other institutes, organizations, and scholars have developed guidelines, methodologies or sets of indicators to support measuring sustainability, e.g., ISO 14031 (2013); Spangenberg and Bonniot (1998); ISO 26000 (2010); Moldan et al. (1997); DVFA (2010); Hsu et al. (2016); CFA (2008); UNCTAD (2008); Azapagic and Perdan (2000); Veleva and Ellenbecker (2001); Roca and Searcy (2012); Krajnc and Glavič (2003). However, others have explored the process of developing and selecting indicators, e.g., Chee Tahir and Darton (2010); Mascarenhas et al. (2015). Many of these guidelines and standards are used for sustainability reporting to increase transparency and corporations’ reputation (brand image), to influence decision makers and customers, to follow legislation, and to enable comparisons between companies (Morioka and Carvalho, 2016b).

### 3.6.2 Characteristics of Sustainability Indicators

The European Environmental Agency (EEA, 1999) and the Organization for Economic Co-operation and Development (OECD, 2004) define *environmental indicator* as an observed value representative of a phenomenon that is tracked over a certain period of time for progress, supporting, evaluation and informing the public. An environmental indicator requires qualitative or quantitative bits of information, visualizes change chronologically and communicates the phenomenon in an easier and more understandable way as an early warning of environmental damage.

There is a consensus that sustainability KPIs ought to be measurable, action-oriented, concise, easy to communicate and easy to understand, few in number and methodologically sound to support decision making and continuous improvement (Veleva et al., 2001a). Morioka and Carvalho (2016a) argue that quantifiable indicators facilitate the alignment between a company’s strategy and environmental performance and that objective indicators promote better environmental management owing to their continuous...
improvement nature. Sustainable indicators should address efficiency and effectiveness in relation to determined targets, strategies and processes within the company; they also need to be communicated to both internal and external stakeholders (Nappi and Rozenfeld, 2015). Data availability, validity and reliability along with scientific methodology to translate the data are the main reasons for developing or selecting any sustainable indicators (Mascarenhas et al., 2015). Table 6 summarizes the characteristics of sustainable KPIs identified through literature study D.

Table 6 - Characteristics of indicators, presented in Paper V

<table>
<thead>
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<tbody>
<tr>
<td>Quantifiable and measureable</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<tr>
<td>Comparable (between companies and over time)</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<td>● ● ● ● ●</td>
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<tr>
<td>Easy to understand and interpret</td>
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<tr>
<td>Limited in number</td>
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</tr>
<tr>
<td>Linked to a defined goal and action-oriented</td>
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<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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</tr>
<tr>
<td>Universally applicable or specific to an industry</td>
<td>● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
</tr>
<tr>
<td>Concise and easy to communicate</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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</tr>
<tr>
<td>Supporting decision making</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
</tr>
<tr>
<td>Scientifically and methodologically valid and reliable</td>
<td>● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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</tr>
<tr>
<td>Involve of internal and external stakeholders</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<td>● ● ● ● ●</td>
</tr>
<tr>
<td>Promote continuous improvement toward sustainable development</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<td>● ● ● ● ●</td>
</tr>
<tr>
<td>Have a wide scope (e.g. financial and non-financial)</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
</tr>
<tr>
<td>Raise awareness</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
</tr>
<tr>
<td>Provide sufficient information</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<td>● ● ● ● ●</td>
</tr>
<tr>
<td>Represent aggregated data on the impacts</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
</tr>
<tr>
<td>Compatible with the organization context</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
</tr>
<tr>
<td>Support process and strategies in the company</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
<td>● ● ● ● ●</td>
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</tbody>
</table>

3.6.3 Material Efficiency Indicators

Indicators of sustainable manufacturing are the subjects of many scientific articles, see e.g., Veleva et al. (2001b), Krajnc and Glavič (2003), Dočekalová and Kocmanová (2016), Rahdari and Rostamy (2015), Joung et al. (2013), Herva et al. (2011) and Azapagic and Perdan (2000). The most common indicators of sustainable manufacturing related to assessing the environmental performance of an operation or a product can include acidification potential (measured in SO₂ equivalent), kilograms of emissions to the air, amount of energy used per unit of product made or service provided, total amount of water consumption and total waste generation of entire manufacturing plants.

Waste is an increasingly significant environmental and economic indicator. With current land use pressure, increasing transportation cost, and rigid disposal standards yet to come, diverting waste from disposal and increasing recycling and reuse is beneficial for the environment and creates additional revenues for companies. The study performed by Roca and Searcy (2012) on 585 indicators disclosed in corporate sustainability reports of 94 Canadian corporations shows that slightly above 20% of total KPIs are categorized under
the waste theme, whereas financial, operational, employee-related, health and safety, and emissions are the top dominant themes. However, waste-related indicators were consistently used across different sectors, such as “total waste”, “quantity of recycled materials” and “amount of goods and services purchased”. Another study, by Skouloudis and Evangelinos (2009) reviewing Greek sustainability reporting, shows that the environmental indicators mostly addressed energy and water consumption, carbon dioxide emissions, and energy efficiency. Waste-related indicators disclosed “waste treatment methods” and “quantities of materials recycled” over the reporting period (Skouloudis and Evangelinos, 2009).

Table 7 presents the most common ME-KPIs identified through literature study D. The selection was made by identification of the most relevant and cited indicators concerning manufacturing. Selected ME-KPIs were properly defined within the system boundary and were also congruent with this dissertation’s research questions and objective, as suggested by Rahdari and Rostamy (2015). In total, fifty unique ME-KPIs were identified, although only thirteen had more than two frequencies. Frequency refers to the number of KPIs mentioned by different scholars that have the same meaning and goals, though they could be formulated differently. Defining frequency is in line with overcoming the negative concerns about corporate environmental indicators, “ignorance on similarities and differences among the existing indicators” (Herva et al., 2011). The characteristics of the KPIs in terms of being “Relative or Absolute” and Direct or Indirect” are indicated in the second and third columns, respectively. Being a direct or indirect KPI is associated with material efficiency options at a manufacturing plant (see Introductory Definitions).

According to literature study D, essential performance indicators in the area of material efficiency are minimization of virgin raw material consumption, avoidance of environmentally harmful materials, the use of environmentally safe alternatives for material, waste minimization and diversion, more recycling and reusing, low embodied energy, the use of biodegradable packaging, product durability, eco-design of products, and having a life cycle perspective. Product durability is the only KPI in Table 7 that has an indirect effect on material efficiency at the manufacturing stage, because it mainly pertains to the design phase. However, the inclusion was based on the emphasis on this KPI in the literature and LCA.
<table>
<thead>
<tr>
<th>Material efficiency-related KPIs identified in the literature</th>
<th>R</th>
<th>A</th>
<th>D</th>
<th>Frequency</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total material consumption</td>
<td>A</td>
<td>D</td>
<td>12</td>
<td></td>
<td>Ditz and Ranganathan (1997); Azapagic and Perdan (2000); Mwasha et al. (2011); Vermeulen et al. (2012); Dočekalová and Kocmanová (2016); WBCSD (2000); Veleva et al. (2001b); IChemE (2002); Krajnc and Glavič (2003); Veleva et al. (2001a); Roca and Searcy (2012); Ness et al. (2007)</td>
</tr>
<tr>
<td>Total waste generation</td>
<td>A</td>
<td>D</td>
<td>10</td>
<td></td>
<td>Azapagic and Perdan (2000); Bai and Sarkis (2014); Ali and Searcy (2015); Čuček et al. (2012); WBCSD (2000); Krajnc and Glavič (2003); Veleva et al. (2001a); Roca and Searcy (2012); Ness et al. (2007); Mwasha et al. (2011)</td>
</tr>
<tr>
<td>Material input per unit of production/service (MIPS) or material intensity</td>
<td>R</td>
<td>D</td>
<td>8</td>
<td></td>
<td>Herva et al. (2011); Ditz and Ranganathan (1997); Winn (1999); Azapagic and Perdan (2000); Vermeulen et al. (2012); IChemE (2002); Krajnc and Glavič (2003); Ness et al. (2007)</td>
</tr>
<tr>
<td>Environmentally safe alternatives for material consumption, e.g., renewable raw materials</td>
<td>R</td>
<td>D</td>
<td>8</td>
<td></td>
<td>Bai and Sarkis (2014); Vampeli and Rozenfeld (2015); Ali and Searcy (2015); IChemE (2002); Winn (1999); Mwasha et al. (2011); Raga et al. (1995); Krajnc and Glavič (2003)</td>
</tr>
<tr>
<td>Recycling or reusing percentage of waste or recycling mass fraction</td>
<td>R</td>
<td>D</td>
<td>7</td>
<td></td>
<td>Azapagic and Perdan (2000); Vermeulen et al. (2012); Hák et al. (2016); Dočekalová and Kocmanová (2016); Krajnc and Glavič (2003); Roca and Searcy (2012); Worldsteel Association (2012)</td>
</tr>
<tr>
<td>Total hazardous waste</td>
<td>A</td>
<td>D</td>
<td>7</td>
<td></td>
<td>Rahdari and Rostamy (2015); Vermeulen et al. (2012); Ditz and Ranganathan (1997); Dočekalová and Kocmanová (2016); IChemE (2002); Krajnc and Glavič (2003)</td>
</tr>
<tr>
<td>Share of recycled/reused material in production</td>
<td>R</td>
<td>D</td>
<td>6</td>
<td></td>
<td>Bai and Sarkis (2014); Mwasha et al. (2011); Hák et al. (2016); Dočekalová and Kocmanová (2016); IChemE (2002); Krajnc and Glavič (2003)</td>
</tr>
<tr>
<td>Waste sent to landfill</td>
<td>A</td>
<td>D</td>
<td>4</td>
<td></td>
<td>Vermeulen et al. (2012); Hák et al. (2016); Krajnc and Glavič (2003); Roca and Searcy (2012)</td>
</tr>
<tr>
<td>Product durability</td>
<td>A</td>
<td>I</td>
<td>4</td>
<td></td>
<td>Winn (1999); Azapagic and Perdan (2000); Chee Tahir and Darton (2010); Krajnc and Glavič (2003)</td>
</tr>
<tr>
<td>Waste reduction</td>
<td>A</td>
<td>D</td>
<td>4</td>
<td></td>
<td>Azapagic and Perdan (2000); Nappi and Rozenfeld (2015); Ali and Searcy (2015); Dočekalová and Kocmanová (2016)</td>
</tr>
<tr>
<td>Ecological rucksack or auxiliary material consumption</td>
<td>A</td>
<td>D</td>
<td>3</td>
<td></td>
<td>Spangenberg (2002); Ness et al. (2007); Vermeulen et al. (2012)</td>
</tr>
<tr>
<td>Life cycle assessment</td>
<td>A/</td>
<td>D</td>
<td>3</td>
<td></td>
<td>Herva et al. (2011); Ali and Searcy (2015); Ness et al. (2007)</td>
</tr>
<tr>
<td>Percent of products designed with regard to material efficiency options</td>
<td>R</td>
<td>D</td>
<td>3</td>
<td></td>
<td>Mwasha et al. (2011); Krajnc and Glavič (2003); Veleva et al. (2001a)</td>
</tr>
<tr>
<td>New environmentally sound product or process</td>
<td>A</td>
<td>D</td>
<td>2</td>
<td></td>
<td>Bai and Sarkis (2014); Nappi and Rozenfeld (2015)</td>
</tr>
<tr>
<td>Waste sent to energy recovery</td>
<td>A</td>
<td>D</td>
<td>2</td>
<td></td>
<td>Vermeulen et al. (2012); Krajnc and Glavič (2003)</td>
</tr>
<tr>
<td>Waste recycled or reused</td>
<td>A</td>
<td>D</td>
<td>2</td>
<td></td>
<td>Ali and Searcy (2015); Roca and Searcy (2012)</td>
</tr>
<tr>
<td>Mass of non-recycled or non-reused waste /Total mass of waste generation</td>
<td>R</td>
<td>D</td>
<td>2</td>
<td></td>
<td>Krajnc and Glavič (2003); Roca and Searcy (2012)</td>
</tr>
<tr>
<td>Waste disposal and management in general</td>
<td>A</td>
<td>D</td>
<td>2</td>
<td></td>
<td>Ragas et al. (1995); Chee Tahir and Darton (2010)</td>
</tr>
<tr>
<td>Hazardous materials input mass</td>
<td>A</td>
<td>D</td>
<td>2</td>
<td></td>
<td>Krajnc and Glavič (2003); Ness et al. (2007)</td>
</tr>
<tr>
<td>Total non-hazardous waste</td>
<td>A</td>
<td>D</td>
<td>2</td>
<td></td>
<td>IChemE (2002); Roca and Searcy (2012)</td>
</tr>
<tr>
<td>Percent of biodegradable/reusable packaging</td>
<td>R</td>
<td>D</td>
<td>2</td>
<td></td>
<td>Krajnc and Glavič (2003); Veleva et al. (2001a)</td>
</tr>
<tr>
<td>Reducing the waste generation and natural resources</td>
<td>A</td>
<td>D</td>
<td>2</td>
<td></td>
<td>Nappi and Rozenfeld (2015); Chee Tahir and Darton (2010)</td>
</tr>
</tbody>
</table>
4. Empirical Findings

This chapter presents empirical findings from the case studies on material efficiency in the manufacturing industry in Sweden. The presentation is based on the appended papers. The design of the empirical studies can be found in the method chapter and the empirical findings are presented in detail in the appended papers (see Table 2 in the method chapter).

4.1 Summary of Paper I: Material Efficiency Barriers and Strategies

Paper 1 aims to investigate material efficiency improvement opportunities, barriers, and strategies in manufacturing companies in Sweden. The paper is based on a combination of literature studies A and C together with empirical studies A and B. In total six manufacturing companies were included in the empirical data collection for this paper, see Table 1. Detailed descriptions of the empirical and literature studies are presented in the method chapter. This paper contributes to answering research questions 1 and 2.

The main empirical findings and conclusions related to this paper are presented in three sections. Table 8 presents the empirically identified barriers from five large manufacturing companies. Table 9 presents the extent of implementation of material efficiency strategies among the four companies studied. Finally, waste segregation improvement potentials identified in four companies studied are depicted in pie charts in Figure 7.

4.1.1 Material Efficiency Barriers

Using the same format as Table 4, this table presents the identified barriers and their empirical evidence for improved material efficiency.

<table>
<thead>
<tr>
<th>Barriers</th>
<th>Evidence from the empirical studies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technological</strong></td>
<td></td>
</tr>
<tr>
<td>Engineering</td>
<td>Insufficient waste volume</td>
</tr>
<tr>
<td></td>
<td>Contamination of waste</td>
</tr>
<tr>
<td></td>
<td>Incorrect ordering system</td>
</tr>
<tr>
<td></td>
<td>Insufficient number of bins</td>
</tr>
<tr>
<td></td>
<td>Engineering barriers, e.g., layout</td>
</tr>
<tr>
<td></td>
<td>Low volume of new material</td>
</tr>
<tr>
<td></td>
<td>Design constraints, e.g., quality versus environment for packaging or function versus environment for products</td>
</tr>
<tr>
<td>Material substitution</td>
<td></td>
</tr>
<tr>
<td><strong>Economic</strong></td>
<td></td>
</tr>
<tr>
<td>Budgetary</td>
<td>Economic limitations and inadequate economic incentives</td>
</tr>
<tr>
<td>Material and product cost</td>
<td>---</td>
</tr>
<tr>
<td><strong>Management</strong></td>
<td></td>
</tr>
<tr>
<td>Higher priority of other issues or requirements, e.g., production expansion/market share</td>
<td></td>
</tr>
<tr>
<td>Limited top management commitment and support for sustainability initiatives</td>
<td></td>
</tr>
<tr>
<td>Limited environmental awareness of directors</td>
<td></td>
</tr>
<tr>
<td>Lack of support and guidance, limited in-plant expertise/capability</td>
<td></td>
</tr>
<tr>
<td><strong>Supplier</strong></td>
<td></td>
</tr>
<tr>
<td>Different plant involved in outsourcing</td>
<td></td>
</tr>
<tr>
<td>Supplier quality</td>
<td></td>
</tr>
<tr>
<td>Packaging standardization</td>
<td></td>
</tr>
<tr>
<td>Overseas supply chain constraints</td>
<td></td>
</tr>
<tr>
<td>Uncooperative supplier</td>
<td></td>
</tr>
<tr>
<td><strong>Vision and culture</strong></td>
<td></td>
</tr>
<tr>
<td>Unclear/weak business model</td>
<td></td>
</tr>
<tr>
<td>Lack of vision, environmental goals and corporate values</td>
<td></td>
</tr>
<tr>
<td><strong>Employees</strong></td>
<td></td>
</tr>
<tr>
<td>Lack of resources (time and human)</td>
<td></td>
</tr>
<tr>
<td>White-collar oversight</td>
<td></td>
</tr>
</tbody>
</table>
Oversight and reluctance of employees due to, e.g., indolence, weariness and exhaustion
Lack of life cycle thinking
Lack of LCC thinking (especially when buying new equipment)
Insufficient technical and environmental training and education
Presence of different functions and actors

Legal
Legislation and regulation
Lack of means of pressure/Lack of or inadequate environmental enforcement
Lack of assistance from government agencies
Lack of sufficient ambition to go beyond regulations and legislation
Methodology and measurement
---

Methodology and measurement

Information
Communication
Lack of or incorrect visualization and 5S, e.g., incorrect or hidden labels, incorrect bin locations
Lack of communication
Lack of eco-design and communication with product development

Information
Uncertainty and risk
Uncertainty about potential results, market benefits, performance impact and environmental benefits

Information
Lack of information and knowledge sharing

Social
Preference and demand
Lack of market preference and customer demand
Low public pressure, lack of demand from shareholders, investors and the community

Understanding and perception
Lack of awareness, understanding, knowledge and experience related to environmental issues
Lack of environmental education

4.1.2 Applied Material Efficiency Strategies
Several environmental sustainability strategies have been identified in literature study A that, to various degrees, could relate to improving material efficiency. According to the results, there are few material efficiency strategies being practiced by companies. Best Practice and Environmental Management System are the basic strategies implemented by companies to begin improving their productivity and reducing their environmental burden. In addition, Waste Minimization activities are undertaken primarily to comply with legal requirements, which is not a proactive step. In general, Waste Minimization is the first step toward material efficiency due to its simplicity and its explicit goal of waste reduction (Abdul Rashid et al., 2008).

Although there is insufficient implementation of material efficiency strategies in the manufacturing companies studied, the results indicate that companies consider implementation of material efficiency strategies an environmental performance-improving step for the future. As seen in Figure 6, the companies studied do not work with strategies at the top and middle of the pyramid, as they found them abstract and confusing with no or ambiguous implementation guidance on the shop floor, where actual manufacturing occurs and waste is generated. However, operational tools at the bottom of the pyramid were found applicable among the companies studied. It was found that certain attributes and criteria are necessary drivers for companies to implement material efficiency tools and strategies at the operational level. As discussed in Paper IV and section 3.5, these criteria in short include being hands-on, easy to use, and easy to visualize, promoting employee and management engagement, and being connected to a predetermined goal. In addition, the results suggest that a lean company is most likely to have the potential for material
efficiency improvements because a culture of continuous improvement, engagement and waste elimination already exists. As stated by the interviewees, lean philosophy not only helps improving delivery performance, reducing manufacturing cycle time, and increasing efficiency and customer satisfaction but also contributes to daily waste management activities, environmental impact reduction and overall material efficiency. The companies’ lean activities primarily include waste elimination (mainly referring to wasted time, not material waste), the involvement of all employees in continuous improvement, visualization and go to gemba, i.e., the shop floor, where production takes place and problems occur.

4.1.3 Material Efficiency Improvement Potentials

Waste segregation plays a major role for improved material efficiency in manufacturing. The waste sorting rate ($\Sigma$ sorted / ($\Sigma$ mixed + $\Sigma$ sorted)) has proven to be a valuable indicator of material efficiency in manufacturing. It was calculated in different studies by dividing the segregated portion of each waste segment by the total waste generated for each segment (sum of segregated and mixed waste) to determine the waste homogeneity of each segment. The main segments include metal, combustibles, inert materials, fluids and other hazardous materials. These segments can be further segregated into separate fractions; metal segments, for instance, can be separated into aluminum, cast iron, and steel, and plastic can have its own segment and fractions. Homogeneously segregated waste retains a larger portion of its original material value and economic value (Zackrisson et al., 2014). Waste sorting analysis or similar waste segregation measurements can also be linked to environmental reporting, because they can be used to collect information and control material efficiency performance measures. They are also useful in reporting and external scrutiny by stakeholders and authorities. Figure 7 illustrates two examples of improvement opportunities in further segregation of waste material. The pie chart on the right shows a waste sorting analysis on a random mixed metal bin at one of the case companies. As shown, 34% is cast iron and 7% is aluminum, both of which can be segregated into separate fractions. Therefore, only 28% of the bin is truly mixed scrap, which is difficult to segregate. The pie chart on the left shows the aggregated proportions of different types of plastics in a waste sorting analysis performed at four companies. This figure shows that 74% of the plastics were PE and 11% were PET, both of which could potentially be separated into improved/new fractions. Plastics in general should not be mixed in combustible bins; they can be further segregated as polystyrene (PS), polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polytetrafluoroethylene (TPFE) and rubber, although it might be difficult for operators to differentiate the type. Unsegregated plastic is incinerated, whereas correctly segregated plastics are recycled, which provides greater economic and environmental benefits. The recycling of plastic is as environmentally beneficial as the recycling of many metals, although the plastic recycling process might in general be a little more expensive, complex and energy consuming compared to metal recycling processes.
Figure 7 – Potentials for waste segregation. The pie chart on the right shows a waste sorting analysis on a random mixed metal bin at one of the case companies. The pie chart on the left shows the aggregated proportions of different types of plastics in a waste sorting analysis performed at four companies.

4.2 Summary of Paper II: Waste Flow Mapping

This paper aims to enhance the knowledge of how operations management and environmental management can be integrated on an operational level, focusing on waste management and material efficiency. The paper is mainly based on a combination of literature study B and empirical study B. Four manufacturing companies were included in the empirical data collection for this paper, see Table 1. Detailed descriptions of the empirical and literature studies are presented in the method chapter. This paper contributes to answering research questions 1 and 2.

Literature study C and empirical study A indicated several barriers to material efficiency improvement, including lack of a suitable tool for environmental initiatives (Bey et al., 2013), unclear/weak strategies and goals (Koho et al., 2011), limited environmental motivation and engagement (Murillo-Luna et al., 2011; Ammenberg and Sundin, 2005), lack of effective measures to evaluate sustainability (Seidel et al., 2010), and poor visualization and limited intra-organizational interaction (Simpson, 2010; Sarkis et al., 2007). In addition, certain criteria such as being hands-on, easy to use, and easy to visualize, promoting engagement and pursuing a predetermined goal were identified in previous studies for applying tools and strategies to assess, manage and improve material efficiency. Hence, based on identified barriers and criteria, a lean-based hands-on tool from the bottom of the pyramid in Figure 6 was used in this research to assess, manage and improve material efficiency of companies studied. WFM presented in the paper was designed to integrate lean and green continuous improvement to analyze materials flow from both an operation management and a sustainability perspective while promoting inter-organizational collaboration between different actors involved in waste management processes.

A main conclusion of this paper is the importance of determining various waste segments and relative fractions to facilitate material efficiency improvement. The paper also emphasizes preventing and reducing waste generation, avoiding blending and correctly segregating waste into segments and fractions to move toward material efficiency. Improving the value of waste fractions, i.e., creating more specific cost-effective fractions, is also vital. The main indications include waste sorting rate for the non-hazardous waste segment to determine what proportion of the material could be segregated into high-quality fractions. Figure 8 provides an overall picture of the amount of industrial waste generated by the case companies in different segments (the numbers are based on percentage by weight). The metals segment primarily included aluminum, cast iron, steel and copper; the
inert segment primarily included sand, glass and landfill waste, and the combustible segment primarily included paper, cardboard, biodegradable waste, wood and plastics.

In addition, several performance measurements were suggested in this paper to facilitate assessment, management and improvement of material efficiency. Table 10 presents some of these indicators related to each segment.

Table 10 – Suggested performance measurements for waste segments

<table>
<thead>
<tr>
<th>Segments</th>
<th>Example of fractions</th>
<th>Segment sorting rate (%)</th>
<th>Weight per produced unit (ton/#)</th>
<th>Average segment treatment cost (SEK/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-hazardous</td>
<td>Metals: Aluminum, copper, steel, cast iron</td>
<td>Σ segregated / (Σ mixed + Σ segregated)</td>
<td>W(segment total) / P</td>
<td>C (segment total) / W (segment total)</td>
</tr>
<tr>
<td></td>
<td>Combustibles: Paper, cardboard, biodegradable, wood,</td>
<td>Σ segregated / (Σ mixed + Σ segregated)</td>
<td>W(segment total) / P</td>
<td>C (segment total) / W (segment total)</td>
</tr>
<tr>
<td></td>
<td>inert materials: Sand, glass, landfill waste</td>
<td>Σ segregated / (Σ mixed + Σ segregated)</td>
<td>W(segment total) / P</td>
<td>C (segment total) / W (segment total)</td>
</tr>
<tr>
<td>Hazardous</td>
<td>Fluid waste: Oils, chemicals, solvents, glycols,</td>
<td>Not applicable</td>
<td>W(segment total) / P</td>
<td>C (segment total) / W (segment total)</td>
</tr>
<tr>
<td></td>
<td>emulsions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>hazardous waste: Electronic waste, fluorescent waste,</td>
<td>Not applicable</td>
<td>W(segment total) / P</td>
<td>C (segment total) / W (segment total)</td>
</tr>
<tr>
<td></td>
<td>batteries</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Through a multiple case study at four manufacturing companies, this paper concluded that the proposed WFM is a time-efficient and easy tool for practitioners to work with industrial waste management and material efficiency assessment, management and improvement. It is harmonized with ISO 14001 (2004) and fills the gap between existing operational improvement and environmental improvement through an analytical approach to ensure having a holistic perspective, supporting lean principles, in particular go to gemba, visualization, systematic problem solving, support teamwork collaboration, communication and mutual understanding.

4.3 Summary of Paper III: Material efficiency via the Green Performance Map

This paper aims to reduce the functional gap between material efficiency management and operations management by presenting empirical data on application of a lean and green tool helping to measure material efficiency at different organizational levels through monitoring material consumption and waste generation. The paper is primarily based on literature studies A, B and D as well as empirical studies B and C, however only four
manufacturing companies were included in the empirical data collection for this paper. Detailed descriptions of the empirical and literature studies are presented in the method chapter. This paper contributes to answering research questions 2 and 3.

Based on barriers to material efficiency improvement from literature study C as well as previously defined criteria to select tools and strategies to assess material efficiency in manufacturing, another lean-based hands-on tool from the bottom of the pyramid in Figure 6 was used in this research to assess, manage and improve material efficiency of the companies studied. GPM is an easy-to-use and practical tool for industry that can be used for different purposes including environmental training, environmental and operational improvement, identification of environmental aspects for developing a production line, and reporting and setting annual environmental targets. The lean and green characteristics of GPM including visualization, involvement of different functions through go to gemba, goal orientation for improvement, simplicity, and coverage of top-down and bottom-up approaches are the essential aspects to help assessment and improvement of material efficiency. As discussed in Paper IV, GPM could also be used as a stepping-stone for more comprehensive sustainability measurement methods such as LCA, or to regularly measure, monitor and report the material efficiency performance of a process at shop floor level or at an aggregate level for the plant and even on corporative level. In this paper, GPM was used to measure the material efficiency of individual companies. In the GPM, the input materials were divided into productive materials (i.e., primary product material) and auxiliary materials (i.e., process materials, non-value-adding material, and non-productive material) and the output materials into products and residual materials (i.e., waste, by-products, intermediate products, sub-products, and rest material). This inclusion of input and output material flow is in line with material flow cost accounting (Kokubu et al., 2012), a framework suggested by international environmental standards ISO 14001 (2004) and ISO 14051 (2011), an LCA perspective (Zackrisson et al., 2014), as well as lean and green thinking (Zokaei et al., 2013). It also supports the go to gemba concept to identify environmental aspects via engaging management and employees on the shop floor in continuous improvement. In this paper, GPM was mainly used to measure “total material efficiency” and “value-adding material efficiency” of an individual plant through the GPM framework. Therefore, different equations were tested and used for calculation and for determining accuracy.

Equation 1 (a or b) can be derived based on the definition of material efficiency (the ratio of output to input). Equation 2 can also be used to calculate and report total material efficiency, because incoming materials data are not always collected, and if they are, the
data are not always precise. In contrast, the total product weight and the total waste weight are more of a valid approximation, principally indexed per units produced (ton/#).

**Total material efficiency** = \( \frac{\text{Product output}}{\text{Material input}} \)  
or \[ \frac{\text{Product weight}}{\text{Incoming material weight}} \]

\[ = \frac{A}{(C + D)} \]

**Total material efficiency** = \( \frac{\text{Product output}}{(\text{Generated waste} + \text{Manufactured product})} \)  
or \[ = \frac{\text{Product weight}}{(\text{Waste weight} + \text{Product weight})} \]

\[ = \frac{A}{(A + B)} \]

Looking at Figure 9, in an ideal circumstance with precise data, the sum of product output (A) and residual material (B) should be equal to the sum of productive material (C) and auxiliary material (D), i.e., \( A + B = C + D \). Therefore, the denominator in equation 1 (material input or \( C + D \)) should be equal to the denominator in equation 2 (generated waste and manufactured products or \( B + A \)), i.e., equation 1 equals equation 2. However, this was not the case in the studies performed owing to a lack of data on input material and output waste. Residual material (section B) can also be divided into B1: recycling/reusing material (which retains a large amount of value) and B2: materials that are landfilled or incinerated. This division was also discussed at the case companies regarding calculation of total material efficiency according to equation 3.

**Total material efficiency** = \( \frac{(\text{Product output} + \text{Recycling material})}{\text{Material input}} \)

\[ = \frac{(A + B1)}{(C + D)} \]

Further discussions on value-adding material efficiency were carried out at the companies studied regarding only considering value-adding materials (A and C). The discussion led to equation 4, although the correctness of the equations remained a relatively unexamined issue due to a lack of precise data from the companies. The same logic on recycling/reusing materials, materials to landfill, and incineration can be applied here in equation 5.

**Value-adding material efficiency** = \( \frac{\text{Product output}}{\text{Value-adding material input}} \)

\[ = \frac{A}{C} \]

\[ = \frac{(\text{Product output} + \text{Recycling material})}{\text{Value-adding material input}} \]

\[ = \frac{(A + B1)}{C} \]

Eventually, it was concluded that the importance lies in continuously measuring material efficiency regardless of which equation to use. The importance is on how much improvement a company can achieve in term of material efficiency rather than just measuring it, i.e., continuous improvement in material efficiency. The quantified GPM can be used to regularly measure and monitor the material efficiency measurements for a process, at an aggregate level for the plant and even at the corporate level. The homogeneity of generated waste can be calculated by GPM if specified data are collected. For instance, the segment waste sorting rate for metals (which is the sum of sorted metals divided by the sum of sorted and mixed metals) is obtainable from the GPM. However, further material efficiency KPIs ought to be set and measured regularly to achieve improved material efficiency.
4.4 Summary of Paper IV: Comparison of Lean and Green Tools for Material Efficiency

This paper reports on the application of four environmental assessment tools, commonly used among Swedish manufacturing companies: GPM, EVSM, WFM and LCA. The objective of this paper is to provide clarifications and to enable a more precise understanding of the relevant environmental issues, and help practitioners and scholars use correct tools by considering particular questions and the industrial setting. The industrial setting refers to the type and amount of industrial activity, data accessibility, staff engagement level, etc. This paper is mainly based on literature studies A and B as well as empirical studies D and E, however a single manufacturing plant was studied in this paper where all four tools were applied on a single manufacturing process. Detailed descriptions of the empirical and literature studies are presented in the method chapter. This paper contributes to answering research question 2.

In empirical study D, four different tools (mainly lean and green) were used to collect and analyze data, map the manufacturing process studied and improve the material and waste flows. The results achieved from using these tools on the same set of data and the same manufacturing process were evaluated, compared and discussed in different criteria to find strengths and weaknesses of each tool as well as their ability to help solving a particular problem related to environmental and material efficiency. The comparison is presented in Table 11. The first part of the table, cross-comparison of tools, compares tools in different terms through experience of using the tools on the same manufacturing process. The second part of the table, interpretation and cross-comparison of case results, compares results achieved from using the tools on the same manufacturing process. The manufacturing process studied includes metal sheet bending, punching, plasma cutting, blasting, phosphating, painting, heat treatment and shipping to customers. Although the empirical focus was on material efficiency and metal scrap reduction, environmental aspects such as energy use, material consumption and chemicals (hazardousness) were also considered.

Comparing tools based on the experience of using them, shows that whereas there are overlaps among several criteria, there are also differences, which make these tools to complement each other in data collection and analysis. Each tool has its own strengths and weaknesses, which depend on the question posed, expected results, the level of evaluation (site, process or cell), accessibility of data, competence requirement, etc. GPM is an effective tool as an input-output model to get an overview of environmental problems; WFM gives a detailed analysis of material and waste flows along with the waste management supply chain; EVSM shows environmental effects alongside production-related data and information flow, which enhances understanding; LCA stands out as a tool to help understanding the degree of environmental impact associated with different environmental aspects and therefore is essential for correct prioritization and to avoid sub optimization. This paper does not intend to select one tool as superior to others. Empirical study showed that there is no such thing as “one right tool” and it is recommended to use a combination of tools with their strength and weaknesses to include different types of data collection and analysis along with different environmental impacts, which can lead to better prioritization and decision-making. Accordingly, based on the predetermined improvement goal, one tool per se might not deliver the outcome desired and different tools and methods should be used simultaneously, as these tools are set for increasing effectiveness and efficiency of the operation and the value stream in terms of lean and green.
<table>
<thead>
<tr>
<th>Tools</th>
<th>GPM</th>
<th>EVSM</th>
<th>WFM</th>
<th>LCA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Results type</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Overview of material and energy flows at both the process and the sub-process level</td>
<td>• Focus on the amount, location and type of scrap</td>
<td>• Total amount of waste</td>
<td>• Quantitative results at the site level in the form of calculated environmental impacts, e.g., climate impact</td>
<td></td>
</tr>
<tr>
<td>• Qualitative results in form of environmental aspects in each sub-process</td>
<td>• Overview of the operation</td>
<td>• Cost of waste bins, handling and transport available</td>
<td>• Overview of material and energy flows at the site level</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Information flow regarding production</td>
<td>• Sorting degree of different material fractions</td>
<td>• Transportation and end-of-life information</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Supplier customer information</td>
<td>• Categorization, quantification and localization of scrap</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Operation level (site, process, cell)</strong></td>
<td>Cell/Process and a summary of the process</td>
<td>Entire process from coil to finished frame pair</td>
<td>Entire process from coil to finished frame pair</td>
<td>Entire process from coil to finished frame pair (cradle-to-gate model built by site/process and database data)</td>
</tr>
<tr>
<td><strong>Environmental aspect included</strong></td>
<td>All flows (mainly those seen on shop floor)</td>
<td>Specific selected material, in this case metal scrap</td>
<td>All types of materials and waste, but with a focus on scrap</td>
<td>All types of materials and waste, but with a focus on flows with significant environmental effect</td>
</tr>
<tr>
<td><strong>Time for data collection and analysis (in this case)</strong></td>
<td>2-4 hours for expert, 30 man-hours of operator time</td>
<td>2-4 hours for expert, 20 man-hours of operator time</td>
<td>2 days for expert, 50 man-hours of operator time</td>
<td>5 days for expert, excluding most data collection, 10 man-hours of technical personal time, in addition to the use of data from other tools</td>
</tr>
<tr>
<td><strong>End-of-life scenario</strong></td>
<td>Partially included</td>
<td>Not Included</td>
<td>Included</td>
<td>Included</td>
</tr>
<tr>
<td><strong>Software demand ($)</strong></td>
<td>No software</td>
<td>No software needed but, e.g., Visio recommended for drawings</td>
<td>No software. Excel needed for calculations.</td>
<td>SimaPro, Gabi, Open LCA, minimum cost for databases</td>
</tr>
<tr>
<td><strong>Visualization type</strong></td>
<td>• One-page input and output material/energy flow</td>
<td>• Process flow and one environmental parameter</td>
<td>• Ecomap shows waste generation points</td>
<td>System boundary figure showing process flow</td>
</tr>
<tr>
<td></td>
<td>• Ecomap shows waste generation points</td>
<td></td>
<td>• Waste-sorting analysis via pie chart</td>
<td>Eco-profile</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Waste-handling logistics via spaghetti diagram</td>
<td>Environmental impacts at midpoint or endpoint level in absolute or relative terms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Software-dependent graphs</td>
</tr>
<tr>
<td><strong>Easy learning (knowledge requirements and days)</strong></td>
<td>• Workshop leader</td>
<td>• Workshop leader</td>
<td>• Expert needed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Team needs previous Lean experience</td>
<td>• One-week training</td>
<td>• Several days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• One-day introduction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Go to gemba</strong></td>
<td>Takes place at shop floor via walkthroughs</td>
<td>Requires shop floor visit</td>
<td>Requires shop floor visit</td>
<td>Data normally not found at shop floor but a factory visit recommended to understand and complement data. Thus, go-to-gemba is recommended but not necessary</td>
</tr>
</tbody>
</table>
Improvement actions regarding the following environmental aspects were recommended:

- Energy consumption for compressed air, hydraulic system, painting and heat treatment
- Hazardous material including chemicals and lubricants
- Processed water from heat treatment including phosphating and blasting
- Scrap generation and wastage of productive material
- Noise from punching machines

### Tools

<table>
<thead>
<tr>
<th>GPM</th>
<th>EVSM</th>
<th>WFM</th>
<th>LCA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interpretation and cross-comparison of case results based on the achieved results from using the tools</strong></td>
<td><strong>Almost all main processes produce quality scrap</strong></td>
<td><strong>Further waste segregation potential</strong></td>
<td><strong>The production of the steel for the frames has the greatest climate impact</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Surface treatment including blasting, phosphating, painting and paint curing oven consumes 1/3 of plant energy</strong></td>
<td><strong>Average metal sorting rate is 88% for the frame pair production, which could be improved to 95%</strong></td>
<td><strong>Design scrap and quality scrap have more climate impact than powder paint production</strong></td>
</tr>
<tr>
<td></td>
<td><strong>OEE is average 80%</strong></td>
<td><strong>100% of open-loop metal scrap recycling</strong></td>
<td><strong>Set-up scrap, 8.22 kg/frame pair, has slightly less climate impact than powder paint production</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Categorization, quantification and localization of metal scrap generation. Pair vehicle frames are respectively scrapped in punching machine, plasma cutting, surface treatment, metal sheet forming.</strong></td>
<td><strong>Average lead of trucks is low, especially for one type of cutting (with 39 tons/truck for that type).</strong></td>
<td><strong>Conclusions above are consistent for other included impact categories: eutrophication, acidification and smog.</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Lead time 115-176 min is a fast process compared to for example assembly</strong></td>
<td></td>
<td><strong>Energy use in production has a slightly lower climate impact than the inbound steel transports.</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Takt time: 8,064 min/week/1,730 frame pairs produced = 4.7 min/frame pair</strong></td>
<td></td>
<td><strong>Transporting the scrap to steel supplier for closed loop recycling was identified as a potential improvement action alongside the obvious improvement action steel scrap reduction.</strong></td>
</tr>
<tr>
<td></td>
<td><strong>95% first time through is good, 3.5% is reworked</strong></td>
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</tbody>
</table>
4.5 Summary of Paper V: Material Efficiency Measurement
This paper aims to improve material efficiency in manufacturing via a structured model for performance measurements. The paper highlights the need to develop a common understanding of what material efficiency in manufacturing entails and link existing performance measurements to this common understanding through material efficient operations. The paper is mainly based on literature study D and empirical studies C, D and E. In total, nine manufacturing companies were included in the empirical data collection for this paper, see Table 1. Detailed descriptions of the literature and empirical studies are presented in the method chapter. This paper contributes to answering research question 3.

Literature study C and empirical study A indicated several barriers to material efficiency improvement, including lack of effective approaches and measures to evaluate sustainability and difficulties in quantifying sustainability (Al Zaabi et al., 2013; Shi et al., 2008; Koho et al., 2011; Sarkis et al., 2007). Hence, material efficiency measurements and indicators were studied at different companies. Paper V reports on current ME-KPIs at seven manufacturing companies (empirical study C) and suggested ME-KPIs in the literature (literature study D). The concept of material efficiency in manufacturing is based on the value of incoming materials and outgoing waste as well as the costs associated with operational inefficiencies. Therefore, productive material flow and auxiliary material flow and their ME-KPIs were studied separately in two single case studies (empirical studies D and E) to assess, manage and improve material efficiency and its performance measurement system.

Empirical study C in seven manufacturing companies and their performance measurement systems indicated that on average 11% of the KPIs at each company (regardless of their sizes and environmental priorities) were related to material efficiency, i.e., waste generation and material consumption (see section 2.2.6 on the iterative selection process). The performance indicators at each manufacturing site studied were structured with different categories including Cost, Quality, Environment, Delivery, Safety, People, Lean, Improvement, Leadership etc. (Landström et al., 2016). However, results show that ME-KPIs are generally measured under the Cost, Quality and Environment categories. The number of ME-KPIs belonging to Environmental indicators that measure material consumption and waste generation for the sake of the Environment was found to be low (8% of ME-KPIs or 1% of all KPIs), whereas more than half of the ME-KPIs were Quality indicators. Figure 10 shows the identified ME-KPIs proportions related to each category. It is important to note that an ME-KPI can be related to several categories; for instance, scrap generation can be measured in any of the Cost, Quality or Environment categories. However, to maintain consistency in the results, each ME-KPI was considered only in one category.
Table 12 lists the most common ME-KPIs identified in the empirical studies. A given indicator could be connected to more than one of the ME-KPIs listed in Table 12. For example, one company measured chemicals, painting material, hazardous fluids, oil and lubricants using a single indicator called “oil and chemicals”. However, to maintain consistency among the results, this indicator was considered within the more general category “volume of chemicals, solvents and fluids used”. The characteristics of the KPIs in terms of being “relative or absolute” and “direct or indirect” are indicated in the second and third columns, respectively (see Introductory Definitions).

<table>
<thead>
<tr>
<th>Most common industry ME-KPIs</th>
<th>R or A</th>
<th>D or I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of oil and lubricants used</td>
<td>R and/or A</td>
<td>D</td>
</tr>
<tr>
<td>Painting materials per unit produced</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>Volume of chemicals, solvents and fluids used</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>Total hazardous waste (tons)</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>Total cost of auxiliary materials</td>
<td>R and/or A</td>
<td>D</td>
</tr>
<tr>
<td>Scrap generation (# or %)</td>
<td>R and/or A</td>
<td>D</td>
</tr>
<tr>
<td>Cost of scrap</td>
<td>R and/or A</td>
<td>D</td>
</tr>
<tr>
<td>Material costs</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>Total waste generation (tons)</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>Rejected parts</td>
<td>R and/or A</td>
<td>D</td>
</tr>
<tr>
<td>Products produced (# or tons)</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>Internal customer claims</td>
<td>R and/or A</td>
<td>D</td>
</tr>
<tr>
<td>Repair and reworking</td>
<td>A</td>
<td>D</td>
</tr>
<tr>
<td>Quality deviations</td>
<td>R and/or A</td>
<td>D</td>
</tr>
</tbody>
</table>

Material efficiency related KPIs categories

![Figure 10 – Categories of the identified material efficiency-related KPIs, presented in Paper V.](image)

After studying the current ME-KPIs used by seven manufacturing companies in case study C, the material flows of production processes, assessment, improvements and revision of current ME-KPIs were studied at two specific companies in case studies D and E (see sections 2.2.7 and 2.2.8. for the detailed data collection method and research process).

Empirical study D specifically focused on productive material consumption and metal scrap generation. For production to maintain the primary value of material (in this case steel) and to be the most environmentally and economically efficient, preventing and reducing scrap generation as well as avoiding the unnecessary use of input materials were investigated. Therefore, in addition to improvement suggestions, certain ME-KPIs were developed to monitor various forms of scrap generation at various points and to calculate the associated costs; examples include “scrap generation per produced product”, “cost of scrap”, “waste sorting analysis” and “type of metal scrap”. To facilitate improvement, metal scraps were categorized into Design scrap, Quality scrap and Process scrap in order to indicate the reason behind scrap generation and specify preventive actions. In
accordance with previous Papers II, III and IV on tools and strategies to assess and improve material efficiency, an EVSM was used to visualize the waste flow and indicate the amount of metal scrap at each workstation in kilograms, see Figure 11.

Empirical study E focused on the auxiliary materials flow and combustible residuals. To be the most environmentally and economically efficient and move up the waste hierarchy steps, better segregation of auxiliary materials (in this case, plastic plugs) was investigated. After data collection and analysis, it was perceived that prevention and reduction of the use of plastic plugs was not possible and the reuse option was not economically viable either with the current in-house equipment, due to the cleanliness and sensitivity requirements of the products. Therefore, improvement actions were focused on recycling. In accordance with previous sections on tools and methods to assess and improve material efficiency, an EVSM was used to visualize the flow and indicate the number of plastic plugs removed and mixed in combustible bins at each workstation, see Figure 12.

The results indicated that plastic plugs are composed of polyethylene (PE, 53%), ethylene vinyl acetate (EVA, 41%), and polyvinyl chloride (PVC, 6%). Hence, certain KPIs were defined to measure plastic plug consumption levels and segregation possibilities including “total plastic plug disposal levels”, “type of plastic plug disposed” and “total cost of plastic plugs” as well as the “waste-sorting” KPI. This measurements enabled the company to assess the plastic types and different disposal options using the waste hierarchy approach.
and evaluate their applications and color-coding distinctions. Segregating plastic plugs from combustibles could not only cut costs but also benefit the company economically and reduce the environmental burdens associated with using and burning virgin material. These measurements proved to be helpful in increasing the company’s waste efficiency levels.

The rest of the paper discusses the ME-KPIs in the literature and empirical findings and proposes a model for a material efficiency performance measurement system. This model will be discussed in section 5.3.
5. Discussion
This chapter discusses the research results derived from both theoretical and empirical findings presented in previous chapters, which have been analyzed and validated. The results are discussed in the context of the research questions and their interdependence to fulfill the research objective.

5.1 Material Efficiency Barriers
As discussed in Paper I, manufacturing companies encounter several barriers to improved material efficiency. These barriers hinder the achievement of increased homogeneous waste segregation, reduced waste generation and reduced total virgin raw material consumption. As seen in Tables 4 and 8, most of the barriers that were empirically identified are the same as barriers identified in the literature study, e.g., economic limitations, unclear environmental targets and visions, lack of environmental awareness and lack of communication and information. In addition, some barriers that were not mentioned in the literature were identified in the empirical studies as relevant to material efficiency, e.g., employee oversight and lack of life cycle thinking. Generally, the barriers to material efficiency can be viewed as a small subset to the generic barriers to environmental sustainability strategies, although some additional, specific barriers related to type of material and waste flows should be added, e.g., detailed knowledge of material science and recycling processes. The primary empirically identified barriers to improved waste segregation (as a key component of material efficiency in manufacturing) include insufficient volume of waste fractions, waste contamination, incorrect visualization and labeling, and an inadequate number of waste bins. These barriers are compounded by the oversight and reluctance of employees (both white-collar and blue-collar) to engage in daily waste segregation and recycling activities, primarily due to indolence, weariness and lack of awareness and/or information.

Uncertainty about investment payoffs, market potential, likely results, effect on performance and environmental benefits is another barrier encountered by manufacturing companies. These issues relate directly to a lack of information and knowledge sharing as well as to inadequate communication and awareness (Bjelkemyr et al., 2015; Shahbazi et al., 2014). More support and guidance by experts, environmental training and education, government financial assistance or tax reductions, and the deployment of life cycle thinking are key success factors that will help manufacturers overcome these barriers (Sannö et al., 2016). With respect to life cycle thinking, the integration of LCA thinking into organizational practice remains relatively immature. Another major barrier to material efficiency is the inability to identify market demand. The majority of recycling/waste management entrepreneurs tend to buy materials that can readily enter a primary material processing stream; as a result, many types of waste end up in the combustible bin. Adding to this problem is management’s reluctance to devote time, resources and money to the search for relevant information and opportunities, along with its aversion both to regular audits of waste material and to cost accounting. The main causes of this attitude are limited financial capability for environmental investments and limited environmental awareness.

As discussed in Paper II, collaboration among waste management actors including suppliers, customers, retailers and waste management entrepreneurs is also essential. Enhancing supply chain interactions and increasing information sharing is essential for the discovery of new disposal options, innovative economic and environmental solutions and new market opportunities. Such collaboration will also contribute to increased knowledge and awareness of material efficiency improvement potential and recycling to facilitate waste segregation, minimize waste and reduce total consumption of virgin raw materials.
Lack of information and uncertainty concerning payoffs, alternative disposal options, unrealized material value and potential markets could be resolved through increased interaction in the supply chain (Abdul Rashid and Evans, 2012).

Lack of ambition and motivation to improve waste segregation and material efficiency activities beyond what is legally required was evident in several cases among the companies studied. The current environmental enforcement scheme addresses only chemicals and hazardous waste; the perceived sufficiency of compliance with current environmental regulations is viewed as a barrier because there is an absence of regulatory pressure or government incentives (e.g., tax reductions) to motivate companies to act proactively. In other words, manufacturing companies comply with current legislation only to protect themselves from legal penalties.

It is crucial to consider all barriers, their effects and their linkages when implementing material efficiency strategies, using a tool to assess and improve material efficiency or develop and revise ME-KPIs. However, it is not possible to break down all barriers simultaneously. Therefore, it is necessary for manufacturing companies to prioritize the most significant barriers based on their operations, products, business strategy and environmental goals. Nevertheless, most of the identified material efficiency barriers are interlinked and thus cannot be considered or eliminated independently. For instance, a lack of information and knowledge sharing is linked to insufficient communication, visualization, education and training, employee oversight and inadequate time and human resources. A lack of environmental targets and corporate environmental values is associated with for example limited top management commitment and awareness, a lack of support and guidance throughout the organization, supplier issues, and a weak business model.

As seen in Paper I, the clustered barriers cited most often in the literature are Budgetary, Information, Technology, Management, Vision and Culture, Uncertainty, Engineering and Employees. Comparing this list to those barriers identified in empirical studies, Vision and Culture, Technology and Uncertainty were replaced by Communication. The exclusion of Vision and Culture might be because the companies participating in this study, have environmental care as a corporate core value in their production systems and long-term visions. The absence of Technology could be justified by the companies’ environmental engagement and strategies that consider renewal of production technologies to be a competitive advantage in the long term (Ahlbom, 2013). In addition, being located in an environmentally conscious country puts extra pressure on these companies to adopt clean production technologies. Nevertheless, this exclusion confirms that future material efficiency improvements may not be based on technological changes (Atlas, 2001).

Furthermore, although the literature names Uncertainty as one of the major challenges to any environmental initiative, e.g., Koho et al. (2011); Luken and Van Rompaey (2008) and to material efficiency, e.g., Allwood et al. (2012), empirical results exclude it as a barrier to material efficiency improvement in manufacturing. As lack of information and knowledge (Bey et al., 2013) and lack of communication (Mittal and Sangwan, 2014) are the main drivers behind uncertainty and both are already included as influential barriers to material efficiency, the exclusion of uncertainty could be justified.

Most of the identified material efficiency barriers appear to be internal, as seen in Paper I. Internal barriers originate within a company itself and are dependent on the manufacturing company’s characteristics, whereas external barriers originate outside the company and are to some extent beyond the company’s control. Identified external barriers relate primarily to (1) suppliers, (2) legislation and legal issues, and (3) market preference and customer
demand. As the majority of barriers to material efficiency are internal within the manufacturing company, those barriers can be eliminated given sufficient resources (human, time and financial), better management (commitment) (Murillo-Luna et al., 2011; Post and Altna, 1994), inclusion of related environmental goals in business model and strategy, inclusion of ME-KPIs in the performance measurement system, environmental education, knowledge and motivation, along with better communication and information sharing.

5.2 Material Efficiency Tools and Strategies
As discussed in Paper I, several environmental sustainability strategies and tools have been identified that, to various degrees, could relate to material efficiency management and improvement. As shown in Figure 6, material efficiency strategies can relate to different levels of the decision hierarchy. There are few practical low-level tools appropriate for the operational level that are able to precisely assess, manage and improve the material and waste flows of a manufacturing operation. Therefore, tools and strategies need to be more focused toward the bottom of the pyramid and shop floor to relate to daily routines, operation and manufacturing processes. Material efficiency in general is researched, promoted and discussed at the top level in the decision hierarchy related to a global context, e.g., Ehrenfeld (2005); Allwood et al. (2011), national context, e.g., Lilja (2009a); Pajunen et al. (2012) or sectoral or supply chain context, e.g., Allwood et al. (2013); Milford et al. (2011). There is little research on the individual manufacturing plants (bottom-up approach as opposed to current top-down approach) to improve and manage material efficiency in practice. Current research at an individual company level is also mainly related to the managerial level, which is more difficult to implement, measure and evaluate as it encompasses a broad perspective and indicators are both elusive and difficult to define.

As presented in Papers II, III and IV, this research has focused on the bottom of the pyramid and practical tools to assess, manage and improve material efficiency. Empirical studies indicated certain criteria to select operational tools, in short including being hands-on, time-efficient, based on lean principles, easy to use and learn, visualized, promoting engagement and connected to a predetermined goal. These criteria are essential for mutual understanding, intra-organizational communication, performance improvement and becoming a learning organization (Ellinger et al., 2000). However, current environmentally focused tools and methods are mainly complex and require expert knowledge of environment management, which makes it difficult for different functions to apply these tools regularly and practiced them integrally in daily improvement projects.
The main tools deployed in this research, including GPM, EVSM, WFM and LCA, have the above-mentioned characteristics to be used for material efficiency assessment, management and improvement. Table 11 shows a comparison of these tools with different criteria.

According to the literature studies, material efficiency improvement actions might focus on technological shifts toward more advanced cutting-edge machines and equipment (Garetti and Taisch, 2011), better (environmental) management and decision making (Darnall et al., 2008), process improvement and modifications to production systems (Wiktorsson et al., 2008), substitutions of materials whose extraction, processing, manufacturing and use phases have less environmental impact (Worrell et al., 2016), challenging existing mindsets and encouraging new ways of thinking, i.e., circular economy and life cycle thinking (Frostell, 2006), and promoting concrete legislation (Pajunen et al., 2013). However, results from Papers I, II, III and IV indicated that material efficiency improvement actions are not necessarily technology-driven; instead, material
efficiency improvements in the short term should focus on process improvements (kaizen), management commitment, employee engagement and the transformation of mindsets towards life cycle thinking.

Nevertheless, certain strategies are required on various levels to include material efficiency management and improvement through the entire product life cycle and supply chain, even among different socio-economy actors, including government and regulators, manufacturers, waste management entrepreneurs and customers. Each single strategy on each level plays a small part in material efficiency improvement. According to the results from the appended papers, manufacturing companies have insufficient experience of implementation of material efficiency strategies. This point suggests that the government should intervene and help (Allwood et al., 2013) through economic motivations and penalties (carrot-and-stick approach) and legislation and regulations. Note that an idealized unattainable policy is not a viable option. Instead, an iterative modification of existing regulations accompanied by long-term, consistent and well-defined goals and effective monitoring, reporting and communication is more likely to improve material efficiency (Allwood et al., 2013). Increased environmental enforcement is also necessary because companies tend to flout legislation if it is not adequately enforced. Material efficiency-related regulations could be introduced in decision-making discussions both to increase awareness and to present potential options.

Presented tools and strategies can have different material efficiency goals – to reduce to reduce the total consumption of virgin raw material in the manufacturing industry, to reduce the waste generated by manufacturing companies, to enhance the homogeneity of generated industrial waste (i.e., increase waste segregation), or a combination of them. Material efficiency goals are also connected to each other and can have cause-and-effect relationships with one another. For instance, enhancing the homogeneity of waste leads to increased recycling, which in turn reduces the consumption of virgin raw material. Management plays an important role in the implementation of material efficiency strategies. The environmental commitments of staff and/or a brand name associated with environmental management can stimulate and affect material efficiency strategies.

5.3 Material Efficiency Measurements and Indicators

As discussed in Paper V, past literature on material efficiency leaves practitioners with scant guidance on material efficiency measurement and relevant performance indicators. In addition, among different environmental sustainability performance indicators, waste generation and material consumption have received less attention. This lack is mainly due to regulations that force companies to measure, monitor and report their total energy and water consumption as well as total greenhouse gas emission caused by manufacturing; emission is usually indicated in total carbon dioxide and potential global warming equivalents. Note that there are fewer difficulties associated with energy-, water- or CO₂-related indicators, as they are common to all manufacturing companies. However, material consumption and waste indicators have to be defined separately dependent on the process, product, type of material consumed and industrial sector.

ME-KPIs must be methodologically designed and tested prior to adoption through a conceptual framework (Hák et al., 2016). One essential aspect of measuring and developing indicators is target value. Improving material efficiency requires defined goals and measurement of performance, progress and improvement through appropriate indicators. ME-KPIs must be relevant to convey a clear and unambiguous message to decision makers and must be clearly linked to at least one sustainability goal and must provide a measure of progress toward achieving that goal; ME-KPIs should also be
appropriate for the right level, e.g., a process/product, a manufacturing site, an organization, a regional, national or global level (Hák et al., 2016). However, the process of developing or choosing ME-KPIs is complicated and challenging, as the alignment of determined goal and indicators is difficult considering different dimensions and aggregation of them into a single value (Singh et al., 2012). The process of selecting indicators usually take place through transdisciplinary and participatory approaches (Mascarenhas et al., 2015) and must include stakeholders (Morioka and Carvalho, 2016b); however, little is known about selection stage, accuracy, validity, feasibility and redundancy (Cloquell-Ballester et al., 2006). The selection stage and the involvement of stakeholders are crucial as both are closely connected to institutionalization, utilization, prioritization, monitoring and maintaining of material efficiency indicators (Moreno Pires and Fidélis, 2015), increase stakeholders’ awareness related to waste generation and material consumption (Mascarenhas et al., 2015), and ensure representativeness of a broad range of values, viewpoints and opinions.

Material efficiency management and improvement depends on correct waste segregation and on achieving fractions that are as close as possible to being completely homogeneous. However, as presented in Papers I and II, not all material flows and segments are handled in an optimal manner. In general, metal fractions (as the primary material) are separated and handled appropriately at the manufacturing companies studied, see, e.g., Rastegari et al. (2017), and related recycling is mature. The primary issue is auxiliary and residual materials, such as plastics and packaging, which are not part of the main product and are considered less valuable. This can be connected to performance measurements too. While scrap generation was common among all companies studied, related KPIs such as “scrap generation” and “cost of scrap” were measured on a regular basis. However, auxiliary material and residual material were not measured (if at all) in the same manner or with the same precision and frequency. There was an absence of material efficiency performance measurement systems at manufacturing companies to measure different material flows equally, as cost and environmental benefits are associated with all types of material consumption and waste generation.

Furthermore, the current environmental enforcement scheme addresses (1) chemicals and hazardous waste and (2) critical metals of high value and low volume. Consequently, KPIs related to hazardous materials such as “volume of oil and lubricants used”, “painting materials per unit produced”, “volume of chemicals, solvents and fluids used” and “total hazardous waste (tons)” were measured sufficiently to comply with current environmental regulations, fulfill the environmental reporting requirements (reactive action) and protect companies from legal penalties. In such a situation, there is an absence of regulatory pressure or government incentives (e.g., tax reductions) to motivate companies to act proactively and stay a step ahead of the legislation.

Comparing the most common ME-KPIs in the literature (Table 7) with the most common ME-KPIs identified in the empirical studies (Table 12) reveals significant similarities between industry and the literature to a large extent. However, current ME-KPIs in industry have largely focused on cost rather than the amount or environmental effects, i.e., material efficiency performance measurements currently in use largely have financial goals and a limited focus on environmental concerns. Therefore, the perspective that economic and environmental benefits go hand in hand has not been fully realized. The most frequently used ME-KPIs among all companies are related to quality deviations and internal customer quality claims, cost of scrap, and cost of auxiliary materials and hazardous material. Empirical analysis in Paper V revealed that approximately 11% of the KPIs measured by
the companies studied were related to material efficiency, even including the KPIs measuring for Quality (60.5%) and Cost (26%), purposes (compared to Environment purposes with 8%). This pattern is justifiable based on the high revenues associated with selling metal scrap (but without considering environmental burdens), the high cost of input materials and the environmental enforcement and legislation associated with hazardous material reporting. However, further economic benefits of other materials are missed. Measuring ME-KPIs under either of quality, cost or environment labels is not crucial on the shop floor level as long as material efficiency measurements are performed, the results are evaluated, improvements are made and material and waste are considered in decision making. Consequently, an indicator can be relevant to several categories; for example, scrap generation can be measured under cost, quality or environment. However, at the site level, material efficiency measurements should be addressed under the purview of environmental performance so that material and waste flows are communicated to stakeholders and authorities for improvement action planning and to cascade down to the newly revised ME-KPIs.

Comparing the literature with the empirical studies, some ME-KPIs such as “total waste generation” and “total hazardous waste” are measured exactly as suggested in the literature, e.g., by Krajnc and Glavič (2003) and Roca and Searcy (2012). Despite recommendations in the literature to measure indicators such as “life cycle assessment” (e.g., Ahi and Searcy, 2015), “percentage of products designed with regard to material efficiency options” (e.g., Mwasha et al., 2011), “product durability” (e.g., Chee Tahir and Darton, 2010), “waste reduction” (e.g., Nappi and Rozenfeld, 2015) and “ecological rucksack” (e.g., Spangenberg, 2002), few such KPIs were actually found in the companies studied. The absence of the “life cycle assessment” KPI can be justified because of its broadness and the difficulty of measuring this KPI (Hetherington et al., 2014); similarly, the absence of the “product durability” KPI can be related to the type of industry studied. Despite recommendations in the literature to measure the end-of-life scenarios of generated waste, such as “shared recycled/reused material in production” (e.g., Dočekalová and Kocmanová, 2016) and “recycling mass fraction” (e.g., Hák et al., 2016), only two out of seven companies had indicators that measured the end-of-life stage of wasted materials in terms of the waste volume sent for incineration or recycling. Nevertheless, waste sent to landfills has been measured at the site level for legislative and reporting purposes. The “environmentally safe and renewable materials” KPI suggested in the literature (e.g., Mwasha et al., 2011) was measured as “chemical substitution”, to use environmentally friendly alternatives. “Total material consumption” (e.g., Veleva and Ellenbecker, 2001; IChemE, 2002) and “material intensity” (e.g., Herva et al., 2011; Krajnc and Glavič, 2003) were measured differently by different companies and only in terms of economic losses. “Material intensity” was measured through considering “total hazardous materials” or only “cost of auxiliary materials.” “Total material consumption” (e.g., Veleva et al., 2001b; Roca and Searcy, 2012) was not measured in the companies studied, although the total aggregated costs of purchased materials were measured for entire plants as “cost of material”. Surprisingly, only one of seven companies frequently measured “waste segregation” to improve the quality and economic value of waste and promote the recyclability of material fractions.

Approximately three-fourths of all empirically identified ME-KPIs are absolute values that express overall levels of material efficiency performance for an operation or an entire company. Absolute KPIs are easy to understand but have limited functionality for comparisons and benchmarking when size and production rates vary, despite the recommendations for comparable KPIs in the literature (Maas et al., 2016; Morioka and
Carvalho, 2016a). Other ME-KPIs are relative values (ratios) that are generally normalized based on the number of products made. These ME-KPIs can be expressed as the material efficiency performance correlated with the performance in another area (primarily in terms of products made). Both absolute and relative KPIs can be used to address underlying sustainability issues (Ahi and Searcy, 2015). However, most indicators can be expressed as relative performance indicators (e.g., amount per production unit), whereas others, particularly when connected with legal or health limits, must be absolute (Kurdv, 2008).

Based on the model shown in Figure 6, the most commonly cited ME-KPIs in the literature (Table 7) and the most common ME-KPIs identified via empirical studies (Table 12), a model is proposed in Figure 13 for material efficiency performance measurement in manufacturing. In this model, the ME-KPIs are categorized as productive input materials, auxiliary input materials, products and residual output materials. The most commonly cited ME-KPIs in the literature are listed in blue boxes (from Table 7), the most common ME-KPIs identified via empirical studies (from Table 12) are shown in red boxes, and less common but crucial ME-KPIs for better material efficiency management are shown in a green box. The ME-KPIs presented are consistent with the characteristics of indicators presented in Table 6. The proposal is that the most commonly cited ME-KPIs in the literature should be consistent with or complemented by those identified via the empirical studies. However, a one-size-fits-all ME-KPI should not be applied; rather, a toolbox of different measures should be applied for different purposes and strategies (Maas et al., 2016). Therefore, the four main categories should be measured equally to realize material efficiency performance improvements in an operation. The “life cycle assessment” and “eco-design” KPIs proposed in the literature can be linked to all four areas; therefore, they were placed at the bottom.

To closely examine manufacturing and improve material efficiency performance, indicators that are clearly related to production on the shop floor and processes must be included (Nappi and Rozenfeld, 2015; Mascarenhas et al., 2015). KPIs with aggregated figures are of interest to external stakeholders and authorities, whereas internal performance improvements require access to detailed disaggregated information related to shop floor processes (Maas et al., 2016). This is inconsistent with the common environmental KPIs, which are based on aggregated figures for an entire manufacturing site, measured on an infrequent basis, and reactively reported to authorities and external stakeholders. ME-KPIs should not only be measured at the enterprise and site levels (via environmental management) but also at the operational level (via operators and production...
managers). For reporting purposes, proposed guidelines, such as those given by the Global Reporting Initiative (GRI, 2015), can be used to ensure transparency.

According to Morioka and Carvalho (2016b) and Maas et al. (2016), sustainability measurements involve the assessment of a company’s situation and sustainability goals as well as the implementation context, selection and use of indicators, and eventually involve reassessing and communicating sustainability performance information to support better management decisions and improve indicator systems. Thus, a continuous process of setting goals and measuring performance by cascading updated KPIs down to the production level is necessary (Veleva et al., 2001b). Material efficiency measurements must include indicators that reflect both the achievement of desired outcomes (lagging) and the direction of the market and where to focus efforts (leading) (Chee Tahir and Darton, 2010). The whole process can vary for different manufacturing companies as they enter different phases of integrating sustainability (including material efficiency) into production and implementing performance measurement systems. The challenge involves ensuring the selection of correct indicators and determining that management teams (operation and environment) understand how ME-KPIs should be used to align business improvement with environmental and operational strategies and goals.

5.4 Cross Interdependence of Research Questions

As mentioned in previous chapters, the area of material efficiency is under-researched. In particular, there are very few publications reporting case studies on material efficiency in the manufacturing industry. Few publications have focused on material efficiency in a broad sense related to a national context, e.g., Lilja (2009a); Pajunen et al. (2012) or a sectoral and supply chain context, e.g., Allwood et al. (2013); Milford et al. (2011). Among those publications, very few studies were carried out in Sweden, even fewer were performed in the Swedish manufacturing industry. According to the levels of sustainability proposed by Winroth et al. (2016), the research presented in this dissertation focused on the micro level (individual company level) and lower operational levels in a factory, i.e., the shop floor, and addressed different aspects related to understanding material efficiency management and improvement among manufacturing companies in Sweden.

To be able to manage and improve the material and waste flows in manufacturing, identification of the current status was necessary. Therefore, the first step in this research was to investigate the current practical situation of material efficiency among manufacturing companies in Sweden and study the literature describing it. The literature search started to find relevant strategies, approaches, concepts, methods and tools contributing to material efficiency (presented in Paper I and Figure 6). Next, some of the identified tools from the literature such as WFM and Eco-map were then used in practice in case studies to assess the existing state of material efficiency in manufacturing in Sweden (presented in Paper II). The result provided a list of empirically identified barriers to improved material efficiency (Table 8), which was complemented with a list from a literature study (Table 4), although barriers in the literature were obtained from generic sustainability barriers due to a lack of correlated literature. Analyzing the identified material efficiency barriers, two main areas were identified as key improvement points for further research and to fulfill the research objective defined. These two areas are (1) tools and strategies for assessment, e.g., “lack of relevant/suitable tools for environmental initiatives” and (2) measurement, e.g., “lack of effective approaches and measures to evaluate sustainability and difficulties in quantifying sustainability”. As a consequence, the research continued to focus on these two areas. To pursue this goal, additional tools and strategies for improved material efficiency were identified and a variety of them such
as EVSM, GPM, waste sorting analysis and LCA were deployed in empirical studies to assess and improve material efficiency of different processes and operations (presented in Papers I, II, III and IV). Afterwards, material efficiency measurements and related KPIs were studied to understand what has to be measured and monitored to first improve material and waste flows and then maintain the improvements. Hence, empirical studies on material efficiency performance measurement were performed (presented in Paper V).

Figure 14 depicts the interconnection of the areas in relation to the research objective.

Material production and extraction is energy-intensive, and reaching the emissions and energy consumption reduction goals by 2050 (European Commission, 2011b) requires new low-carbon energy supplies, capturing CO₂ to be stored safely, reducing the total requirements for materials production, and substituting virgin materials for renewable (particularly auxiliary) materials that are less CO₂ intensive, have the same performance and are available in the same quantities (Allwood et al., 2013). In short, manufacturing companies in Sweden underestimate the importance of material efficiency in manufacturing and its contribution to energy efficiency and CO₂ emissions. Material efficiency in manufacturing is rather considered as an economic benefit and/or quality deviation problem. Although material efficiency is clearly connected with and contributes to overall carbon emissions and global warming potential as well as energy efficiency, companies do not seem to perceive this connection yet. This is mainly because these contributions occur beyond the boundaries of a business or a manufacturing plant, which makes it very difficult for companies to translate it to their own economic and environmental benefit. For example, the current ME-KPIs suggested in the literature or used in industry do not measure the effects of material efficiency on CO₂ or energy efficiency. In addition, the main goal of manufacturing companies is to increase shareholder value, which obliges managers to increase productivity, efficiency, quality, and delivery precision levels and to reduce the costs (Worrell et al., 2016) to run their business and fulfill customer needs. As a result, improvements in these areas appear to occur naturally, although waste and material consumption improvements require their own (environmental and economic) motivations and proactive attitudes and could impose initial short-term costs.
6. Summary and Conclusions
This concluding chapter begins by reviewing the research objective fulfillment and summarizing the answers to the research questions. The chapter continues by outlining the scientific and industrial contributions. Next, the quality of the applied methodology is discussed, and finally possibilities for future research are presented.

6.1 Review of Research Objective and Answering Research Questions
One of the most crucial areas in future manufacturing is material efficiency, i.e., material demand, supply and consumption as well as increased volumes of industrial waste and its treatment, which positively contributes to concerns related to global sustainability, climate change, emission generation, resource capacity, waste generation, and total energy demand in the long and short term. Material efficiency in manufacturing helps to reduce (or ideally to prevent) the production of new materials and to increase recycling and reuse (or ideally to reduce and prevent industrial waste generation).

The objective of this dissertation was to contribute to existing knowledge on management and improvement of material efficiency in manufacturing. This dissertation deliberately concentrated on different aspects of material efficiency, with a focus on decreasing the amount and increasing the value of generated waste material, reducing (virgin) raw material consumption without influencing the function or quality of a product or process and increasing the homogeneous quality of generated waste through higher segregation rates. To fulfill the research objective, the following research questions were formulated:

*RQ1: What barriers hinder increased material efficiency in manufacturing?*

Barriers that hamper material efficiency improvement must be identified to be able to manage material and waste flows and improve material efficiency.

Empirical study A directly, empirical study B indirectly and literature studies A, B and C contribute to the identification of material efficiency barriers. The theoretical results are presented in section 3.4 and empirical results are presented in section 4.1. The identified material efficiency barriers are discussed in section 5.1 and Paper I is the main article related to this research question.

The main conclusions regarding this research question are as follows: various barriers to material efficiency have been identified and categorized. Barriers in each category were then clustered further and their empirical evidence were presented in Tables 4 and 8. As it is difficult to eradicate all barriers in the initial stages, this categorization and clustering helps companies to prioritize their goals toward improved material efficiency. The identified barriers are also related to one another and thus cannot be considered or eradicated separately even though it is impossible to overcome all barriers together simultaneously. The most-cited barrier clusters are *Budgetary, Information; Technology, Management, Vision and Culture, Uncertainty, Engineering and Employees*. Comparing this list to those identified in empirical studies, *Vision and Culture, Technology and Uncertainty* were replaced by *Communication*. In addition, most of the identified material efficiency barriers are internal and dependent on each organization’s characteristics. Therefore, barriers can be overcome with sufficient resources (including human, time, and financial resources), better management (commitment), inclusion of related environmental goals in business model and strategy, inclusion of ME-KPIs in the performance measurement system, environmental education, knowledge and motivation, along with better communication and information sharing.
RQ2: What tools and strategies help to assess and improve material efficiency in manufacturing?

Industrial waste and the depletion of virgin material force manufacturing companies to find new, viable strategies consistent with environmental, social, and economic sustainability. This research also identified several material efficiency barriers including lack of a suitable tool for environmental initiatives (Bey et al., 2013), unclear/weak strategies and goals (Koho et al., 2011), lack of detailed methodologies for manufacturing improvement in terms of environmental sustainability and operational performance (Smith and Ball, 2012), limited environmental motivation and engagement (Murillo-Luna et al., 2011; Ammenberg and Sundin, 2005), lack of effective measures to evaluate sustainability (Seidel et al., 2010), and poor visualization and limited intra-organizational interaction (Simpson, 2010; Sarkis et al., 2007). Therefore, material efficiency tools and strategies as well as material efficiency measurement and KPIs were selected to pursue the research. Thus, this research question was formulated to help companies assess, manage and improve material efficiency in their operation via using different tools and strategies, each appropriate for different purposes and levels.

Empirical studies A, B, D and E and literature studies A and B contribute to the identification of related tools and strategies as well as the application of several of them. The theoretical results are presented in section 3.5 and empirical results are presented in section 4 with exception of 4.5. The material efficiency tools and strategies are discussed in section 5.2 and Papers II, III and IV are the articles related to this research question.

The main conclusions regarding this research question are as follows: several environmental sustainability strategies and tools have been identified that, to various degrees, could relate to material efficiency management and improvement. As shown in Figure 6, material efficiency strategies can relate to different levels of the decision hierarchy (Almeida et al., 2015), from global strategies with broad and long-term goals (top) to local and practical tools with limited coverage at the individual company, operation, shop floor or technology (bottom). However, empirical studies showed that very few strategies are being practiced at the studied manufacturing companies in Sweden. According to the results, Best Practice and Environmental Management System are the basic strategies implemented by companies to begin improving their productivity and reducing their environmental burden. In addition, Waste Minimization activities are undertaken primarily to comply with legal requirements, which is not a proactive step. The number of practical low-level tools appropriate for the operational level that are able to precisely assess, manage and improve material and waste flows of a manufacturing operation is small. Empirical studies also indicated that strategies must be connected to a predetermined goal, and contribute to improvement on the shop floor to influence material efficiency. Tools must also be hands-on, time-efficient, based on lean principles, easy to use and learn, and easy to visualize; they also should promote engagement and support process improvements, mutual understanding, communication, collaboration, and information sharing while fulfilling scattered material efficiency responsibilities. This can be supported by legislation and regulations as a carrot-and-stick approach to motivate companies to implement strategies, use tools for improvement and understand life cycle thinking regarding products, materials and waste. In this research, GPM, EVSM, WFM and LCA were mainly used to assess, manage and improve material efficiency in the companies studied. A variety of improvement potentials were identified at the manufacturing companies studied that could bring economic and ecologic advantages to the companies. Results related to using tools (presented in Papers I, II, III and IV) indicated
that material efficiency improvement actions are not necessarily technology-driven; instead, material efficiency improvements should focus on process improvements (kaizen), management commitment, employee engagement and the transformation of mindsets (toward life cycle thinking).

**RQ3: How can material efficiency performance measurement be developed and integrated in manufacturing?**

Manufacturing companies have to measure material consumption, waste generation and other performance indicators related to waste and material to be able to manage and improve material efficiency.

Empirical studies C, D and E and literature study D contribute to the identification of current and missing ME-KPIs as well as a framework to guide manufacturing companies aiming to improve their material efficiency. The theoretical results are presented in section 3.6 and empirical results are presented in section 4.5. The material efficiency measurements and tools are discussed in section 5.3 and Paper V is the main article related to this research question.

The main conclusions regarding this research question are as follows: empirical studies revealed that on average approximately 11% of KPIs in the seven manufacturing companies studied could be related to material efficiency. The most common ME-KPIs in the literature (Table 7) and the most common ME-KPIs in empirical studies (Table 12) were presented, and compared, see Paper V. Additionally, some characteristics of identified ME-KPIs such as direct or indirect, leading or lagging, or absolute or relative values were discussed. Current ME-KPIs in industry are mainly measured under quality and cost labels; the most frequently used ME-KPIs relate to quality deviations and internal customer quality claims, cost of scrap, and cost of auxiliary materials and hazardous material. This point suggests that the ME-KPIs largely have cost-related goals with little focus on environmental issues. This pattern is justifiable based on the high revenues associated with selling metal scrap (without considering environmental burdens), the high cost of input materials and the environmental enforcement and legislation associated with hazardous material reporting. Furthermore, a material efficiency performance measurement model was proposed in Figure 13, dividing material and waste flows into productive input materials, auxiliary input materials, products and residual output materials. Identified and suggested ME-KPIs from the literature and empirical studies are provided for each category. This research does not suggest a one-size-fits-all material efficiency performance management system to be applied across all manufacturing industries; rather a toolbox of different measures should be applied for different purposes and strategies. Therefore, the four main categories should be measured equally to realize material efficiency performance improvements in an operation. In addition, a set of characteristics derived from the literature (Table 6) is presented for ME-KPIs. It was concluded that ME-KPIs should be central to the operation and linked to predetermined goals. ME-KPIs ought to be concise and easy to communicate to convey an unambiguous message to decision makers and different external and internal actors in order to promote improvement.

**6.2 Scientific and Industrial Contribution**

Material efficiency and its different aspects in manufacturing are under-researched despite its potential contributions to reduce waste volumes, (virgin) material extraction and consumption, energy demand, carbon emissions and overall environmental impact of the global economy. The European Commission (2011a), the World Economic Forum (2012)
and Mistra (2011) have emphasized that a circular economy and resource efficiency (material efficiency being part of those) are the most important strategic options to capture value in industry because these strategies will provide major economic opportunities, improve productivity, drive down costs and boost competitiveness.

This research contributes to science and extends the body of knowledge regarding material efficiency in manufacturing by increasing understanding and describing the existing situation in Sweden, particularly with respect to (1) existing barriers, (2) tools and strategies, and (3) measurement and indicators. All of these aspects are inter-connected, affect one another and contribute to assess, manage and improve material efficiency in a manufacturing context. Understanding barriers is essential to be able to take steps toward improved material efficiency. Identified barriers clearly indicated that there is inadequate knowledge about what tools, strategies, and KPIs to use to manage and improve material efficiency. Tools, strategies and performance measurements are necessary to be able to assess, manage and improve material efficiency in manufacturing.

Material efficiency in manufacturing improves waste segregation and recyclability and helps manufacturing industry to move up the waste hierarchy steps to prevent and reduce excess material and waste generation. Understanding the material efficiency barriers, performance measurement, related tools and strategies as well as improvement potentials facilitates an assessment of why companies do not recycle more waste and why the success rates of waste management initiatives vary so significantly. Material efficiency enables companies to increase their contributions to reducing carbon emissions, solid industrial waste, the demand for virgin raw material and total energy consumption. There is a significant potential in industrial processes to retain high-quality residual material; however, the waste must comply with both legal requirements and quality demands from recycling entrepreneurs and their customers. Many factors contribute to the confusion and difficulties surrounding material efficiency, including the presence of numerous internal and external actors, low levels of information and knowledge management, little correlation among the different actors’ business models, the method of allocating gains and costs in the system, and the relationships between legal and regulatory systems and environmental and economic benefits. Thus, suboptimal system solutions are implemented. The full potential benefits of material efficiency can only be realized if the barriers that influence its implementation are identified, correct sets of ME-KPIs are measured and tools and strategies are employed. Improving material efficiency not only provides environmental benefits but also yields both short- and long-term economic advantages.

6.3 Review of Applied Methodology

This research is based on both extensive structured literature reviews and carefully designed multiple case studies. This research was also pursued through a back-and-forth process between theory and empiricism, with literature study, empirical data collection and analysis performed simultaneously. As discussed in section 2, data collection and analysis employed different methods and techniques to elude the weaknesses of the mono method and to triangulate from different sources of evidence. In total, four literature studies with structured keyword search and five empirical studies with structured case design are included in this dissertation to answer the research questions and fulfill the research objective. A summary of the empirical studies is presented in Table 2. In addition, the main aspects of the research quality, including internal and external validity and reliability, are discussed in section 2.3.
First, the research was explorative in nature and thus material efficiency was broadly investigated to have a system perspective. Therefore one might argue that in retrospect, the research process could have been more focused on certain areas. However, the broadness of the study was deliberately designed to cover different aspects of material efficiency in manufacturing, as the subject studied is elusive, particularly in Sweden. The system perspective and broadness also helped to comprehend the subject better, gather information from various sources and be able to cooperate with and learn from different scientific fields. To avoid any bias and errors from the data source side (i.e., companies and interviewees), the interviews and most of the communication that took place throughout the empirical studies were conducted in Swedish. Furthermore, although replication of these results at Swedish manufacturing companies is probable, because the research aimed to take a broad perspective and gathered information from different functions, the likelihood of replicating the results decreases in the medium and long term. Furthermore, this research primarily describes the situation at Swedish automotive companies, which use metal as their primary product material and generate common types of residual material such as plastics, aluminum, steel, cardboard, wood, hazardous waste and combustibles. Thus, the results might not be generalized to other industries, to similar manufacturing companies outside of Sweden, or to SMEs in Sweden.

### 6.4 Future Research

This research aimed to understand material efficiency in a manufacturing context. Therefore, there are several opportunities for further research.

The participating case companies are predominantly large companies in Sweden that are leading manufacturers in their respective industries. Their products are manufactured, assembled and sold worldwide, and their international reputation and success have forced them to maintain tighter control of environmental issues, including material and waste flows. Thus, there are sets of factors that might be changed in future research; future researchers might, for example, include either SMEs (which generally have fewer resources to monitor environmental issues) or other types of large manufacturers. Furthermore, this research primarily describes the situation at Swedish automotive companies, which use metal as their primary product material. Future research could replicate this research in other industries that use the same primary product materials or industries that use different primary product materials, such as plastics. In summary, future research might focus on case studies with different variables relating to, for example, company size, industry type, product type, and auxiliary and residual material types.

The case companies involved in this research are leading manufacturers in lean production. Their production systems are based on the Toyota production system and the elimination of waste (referring to wasted time, not wasted material). Empirical studies showed that a lean company is most likely to have a material efficiency improvement potential because the adoption of a lean paradigm indicates that a culture of continuous improvement, engagement and waste elimination already exists in the company. Therefore, future research could either replicate the research at manufacturing companies with lower levels of lean implementation or investigate the influence of the lean philosophy on material efficiency as a focused part of lean and green manufacturing. These suggestions are in line with the interview results, which indicate that a lean philosophy contributes to daily waste management activities, environmental impact reduction and overall material efficiency.

This research revealed several barriers and clusters toward improved material efficiency. Further research could investigate each of these clustered barriers in detail in different manufacturing companies with the above-mentioned variables. These barriers could also
be followed through the entire supply chain such as, the effect of a consortium’s culture on suppliers concerning packaging and use of materials. A possible trade-off between different sustainability dimensions and how to balance them or behavioral changes in producers and consumers would be also interesting to research further.

Individuals’ intuitions, perceptions and awareness of the environmental and economic benefits of waste segregation and recycling are critical factors because they influence waste handling, segregation and recycling behaviors. Thus, more detailed research analyzing not only individuals’ economic and environmental intuitions regarding waste fractions and segregation, but also the correlation between environmental and economic benefits is warranted. Additionally, more environmental data regarding the life cycle assessments of different waste fractions and the costs of different end-of-life scenarios are necessary for both manufacturers and designers.

Many internal and external functions are involved in material efficiency management. These scattered responsibilities, their linkages to each other, their main intention, their respective roles, and communication and information sharing could be further investigated, e.g., within the company itself or between the company and waste management entrepreneurs. Knowledge sharing and communication during sourcing, product design, material selection, manufacturing and assembly processes, services and aftermarket scenarios are also crucial and deserve further investigation.

Additive manufacturing is expected to increase dramatically in the future and it contributes to sustainability in a way that contrasts with current machines and subtractive technologies used to carve plastics and metals into appropriate shape, i.e., no scrap, milling, or sanding requirement. Therefore, less raw material is used, and less waste is generated. In some applications associated with additive manufacturing particularly in the metal sector, waste of raw materials was reduced by up to 40%, whereas 95% – 98% of waste material (powder that is not fused) could be recycled. This can largely influence material efficiency in manufacturing, with a local recycling facility instead of take-back infrastructures and transportations to collect and recycle the products or materials. Hence, the area of additive manufacturing and its contribution to material efficiency in manufacturing is worth further research.

One important aspect of future production is digitalization, e.g., how digitalization affects material efficiency-related data collection and analysis as well as performance measurement. Multi-materials and increased product complexity are becoming increasingly common owing to their attributes such as light weight – how does this influence material efficiency? A products made of more than fifty different materials (such as an electronic device) would be more difficult for recycling, and perhaps remanufacturing should be more developed in the future to facilitate increased material efficiency. In addition, how will other circular models such as product service systems, leasing and shared ownership together with role changes in the value chain affect material efficiency? These questions are also interesting to research further.
References


