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MATERIAL EFFICIENCY MANAGEMENT IN MANUFACTURING

Sasha Shahbazi

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School of Innovation, Design and Engineering

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Abstract

An improved material efficiency contributes to reducing the total environmental impact of global manufacturing by helping achieve reductions in the volume of generated industrial waste, the extraction and consumption of resources, energy demand and carbon emissions. However, the subject of material efficiency in manufacturing has been under-researched, and related knowledge is limited.

The research objective of this thesis is to contribute to the existing body of knowledge regarding material efficiency in manufacturing to increase understanding, describe the existing situation and develop support for improvement. This thesis focuses on the value of process and residual materials in material efficiency, with a particular concentration on enhancing the homogeneity of generated waste by increasing segregation rates, decreasing the generation of waste material and reducing total virgin raw material consumption without influencing the function or quality of a product or process.

To achieve this objective, this research investigates material efficiency strategies, the existing state of material efficiency in manufacturing and barriers to further improvements in material efficiency. The results are supported by four structured literature reviews and by multiple empirical case studies that were conducted at large Swedish global manufacturing companies, most of which operate in the automotive industry. These empirical studies entailed observations, interviews, waste stream mapping, waste sorting analyses, environmental report reviews and company walkthroughs to investigate material efficiency and industrial waste management systems.

The empirical results reveal that the material efficiency improvement potential of further waste segregation to gain economic and environmental benefits remains high. The determination of various waste segments and their relative fractions, along with the calculation of material efficiency performance measures, will facilitate improvements in material efficiency. In addition to attempts at reducing waste generation, avoiding blending and correctly segregating various waste fractions is an essential step towards material efficiency. Improving the value of waste fractions, i.e., creating more specific cost-effective fractions, is also vital.

Multiple barriers that hinder material efficiency were identified. The most influential barriers to improved material efficiency concern the areas of *Budgetary*, *Information*, *Management* and *Employees*. The majority of identified material efficiency barriers are internal, originate within the company itself and are dependent upon the manufacturing company's characteristics.

Sammanfattning

En förbättrad materialeffektivitet bidrar till att minska den totala effekten av den globala tillverkningens sammantagna miljöpåverkan, genom att undvika större volymer av industriavfall, minska utvinningen och förbrukningen av ännu mer resurser och minska energibehovet och koldioxidutsläppen. Materialeffektivitet inom tillverkning har emellertid inte varit föremål för forskning i tillräcklig utsträckning, och kunskaperna inom det här området är därför begränsade.

Forskningsmålet för denna avhandling är att bidra till den befintliga samlingen kunskaper beträffande materialeffektivitet inom tillverkning – att öka förståelsen, beskriva den aktuella situationen och utveckla stöd för förbättring. Denna avhandling lägger fokus på värdet hos process och restmaterial i materialeffektivitet: Att öka den homogena kvaliteten hos genererat avfall med en högre sorteringsgrad, minska den mängd material som blir till avfall och minska den totala förbrukningen av ursprungliga råvaror utan att påverka produktens eller processens funktion och kvalitet.

För att nå målet har vi undersökt strategier för materialeffektivitet, befintlig status för materialeffektivitet inom tillverkning och hinder som står i vägen för en förbättrad materialeffektivitet. Resultaten stöds av fyra strukturerade litteraturgenomgångar och empiriska flerfallsstudier vid stora globala tillverkningsföretag i Sverige, främst inom fordonsindustrin. De empiriska studierna omfattar observationer, intervjuer, kartläggning av avfallsströmmar, analys av avfallssortering, granskningar av miljörapporter och genomgångar vid företag för att fastställa materialeffektiviteten och systemen för hantering av industriavfall.

De empiriska resultaten visade att det fortfarande finns en stor potential till förbättringar av materialeffektiviteten genom ytterligare avfallssortering för att uppnå ekonomiska och miljömässiga fördelar. Fastställandet av olika avfallssegment och relativa fraktioner samt beräkningen av prestandamått för materialeffektivitet underlättar förbättringar inom materialeffektivitet. Utöver försöken att minska den mängd avfall som genereras, är korrekt avskiljning och förhindrande av att olika avfallsfraktioner blandas ett väsentligt steg mot materialeffektivitet. Nästa steg är att förbättra avfallsfraktionernas värde, dvs. uppnå en mer specifik, kostnadseffektiv fraktion. Kartläggningen av avfallsflöden har visat sig vara ett effektivt och praktiskt verktyg att använda vid tillverkningsföretag för att kontrollera och utforska möjligheterna till förbättring.

Dessutom identifierades ett antal hinder som motverkar materialeffektivitet. De främsta hindren mot materialeffektivitet är *budget, information, förvaltning* och *anställda*. Merparten av de fastställda hindren mot materialeffektivitet är interna, härrör inifrån företaget i sig och är beroende av tillverkningsföretagens egenskaper.

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Easter 2015, Eskilstuna, Sweden

Sasha Shahbazi

Publication

Appended papers

Paper I: Shahbazi, S., Kurdve, M., Bjelkemyr, M., Jönsson, C., Wiktorsson, M. (2013). Industrial waste management within manufacturing: a comparative study of tools, policies, visions and concepts, *11th International Conference on Manufacturing Research (ICMR),* Cranfield University, United Kingdom.

Shahbazi collected and analysed the theoretical data and was the main and corresponding author of the paper. The rest of the authors reviewed and assured the quality of the paper.

Paper II: Shahbazi, S., Sjödin, C., Bjelkemyr, M., Wiktorsson, M. (2014). A foresight study on future trends influencing material consumption and waste generation in production, *24th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM)*, University of Texas, San Antonio, United States.

Shahbazi collected the theoretical data and was the main and corresponding author of the paper. Sjödin contributed to the data analysis and, together with the rest of authors, reviewed and assured the quality of the paper.

Paper III: Shahbazi, S., Wiktorsson, M., Kurdve, M., Bjelkemyr, M., Jönsson, C., (2015). Material efficiency potentials and barriers: results from Swedish industry, *Submitted to Journal for review*.

Shahbazi was the main and corresponding author of the paper. Bjelkemyr participated in empirical data collection, and the rest of authors contributed to the writing and review processes and to the quality assurance of the paper.

Paper IV: Kurdve, M., Shahbazi, S., Wendin, M., Bengtsson, C., Wiktorsson, M. (2015). Waste flow mapping to improve sustainability of waste management: A case study approach*, Journal of Cleaner Production, Volume 98, Pages 304-315*.

Kurdve and Wendin developed the method. Shahbazi contributed to the literature review and theoretical analysis of existing methods. Shahbazi also participated in the writing process at later stages of the study and in the review of the paper.

Relevant publications

Paper V: Shahbazi, S., Kurdve, M. (2014). Material efficiency in manufacturing, *Swedish Production Symposium (SPS),* Gothenburg, Sweden, 2014.

Shahbazi was the main and corresponding author of the paper. Kurdve participated in empirical data collection and reviewed and assured the quality of the paper.

Paper VI: Shahbazi, S., Bjelkemyr, M., Jönsson, C., Wiktorsson, M. (2014). The effect of environmental and economic perception on industrial waste management, *1st International EurOMA Sustainable Operations and Supply Chains Forum*, Groningen University, Netherlands.

Shahbazi was the main and corresponding author of the paper. Bjelkemyr participated in data analysis and, together with the rest of authors, reviewed and assured the quality of the paper.

Paper VII: Bjelkemyr, M., Shahbazi, S., Jönsson, C., Wiktorsson, M. (2015). Perceived importance of recycling waste fractions, *APMS International Conference: Advances in Production Management Systems,* Musashi University in Tokyo, Japan.

Bjelkemyr was the main and corresponding author of the paper. Shahbazi participated in empirical data collection, literature review and analysis.

Additional publications

Shahbazi, S., Delkhosh, A., Ghassemi, P., Wiktorsson, M. (2013). Supply chain risks: an automotive case study, *The 11th International Conference on Manufacturing Research (ICMR)*, Cranfield University, United Kingdom.

Javadi, S., Shahbazi, S. (2012). Supporting production system development through the Obeya concept, *APMS International Conference: Advances in Production Management Systems*, Rhodes, Greece.

Mohammadi, Z., Shahbazi, S., Kurdve, S. (2014). Critical Factors in Designing of Lean and Green Equipment, *Cambridge International Manufacturing Symposium (CIM conference)*, Cambridge University, UK.

Sannö, A., Shahbazi, S., Ström, C., Deleryd, M., Fundin, A. (2015). Towards future environmental requirements - managing change in production system, *Submitted for review*.

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Introductory definitions

Combustible waste: A mixture of different types of solid waste that is incinerated, usually to provide energy (heat) and ash.

Compostable waste: This term typically refers to organic waste generated by eating establishments that can be composted into soil fertiliser, occasionally while providing methane gas.

Environmental impact: Any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organisation's activities, products or services (ISO 14001, 2004).

Environmental sustainability strategy: A sustainability strategy that focuses on the environmental aspect of sustainability, although it might also have an impact on the economic and social aspects of the sustainability concept.

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

Macro trends: External changes that affect business operations but are beyond the control of the business (Carruthers, 2009).

Manufacturing: Processes within a plant where the necessary operations are performed to produce a product.

Material efficiency: "The ratio of output of products to input of raw materials" (Rashid and Evans, 2010) 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 thesis, this term refers to environmental sustainability strategies that support material efficiency.

PEST analysis: A method for investigating macro business and market factors from political, economic, social and technological perspectives (Badu, 2002, Lee et al., 2013, Yılmaz and Ustaoğlu, 2013).

Process 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 thesis, the term is synonymous with non-value added material, non-productive material and auxiliary material.

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 thesis, the term is synonymous with rest material and by-product, co-products, intermediate products, non-core products or sub-products.

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

Sustainability: Development that meets the needs of present generations while not compromising the ability of future generations to meet their needs (Brundtland, 1987).

Sustainable manufacturing: "The ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviours, are able to satisfy economic, environmental and social objectives, thus preserving the environment, while continuing to improve the quality of human life" (Garetti and Taisch, 2011).

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 its original production.

Waste: waste is any substance or objects that the holder discards or decides or requires to dispose or sell, but it is not a product of the operations (EU, 2008).

Waste Flow Mapping: A method developed at Mälardalen University to analyse the existing state of material efficiency and industrial waste management and to identify improvement potentials of material efficiency at manufacturing companies. Through Waste Flow Mapping, different lean and green tools are applied, including the Green Performance Map (Romvall et al., 2011), eco-mapping (Engel, 2002), waste sorting analysis, continuous reduction of losses or lean waste, value stream mapping and material handling analysis.

Waste fractions: The segregation of industrial waste segments into different types of materials. For instance, metal waste can be segregated into aluminium, copper, steel and cast iron, and combustible waste can be separated into paper, cardboard, biodegradable, 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 reuse: Any operation in which waste 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 thesis, repairs, refurbishments and remanufacturing are subsets of waste reuse.

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 thesis, the term is synonymous with waste sorting and waste separation, which refer to the separation of waste into different waste segments and fractions.

1. Introduction

This chapter introduces the research by presenting background and a problem statement, followed by the research objective and research questions. This chapter concludes with research delimitations.

1.1. Background

The pace of change has accelerated due to breakthroughs in products, technologies, materials and production methods. In addition, manufacturing activities and industrialisation have increased as a result of economic development and wealth growth. Between 2001 and 2010, global manufacturing increased by 35% and global gross domestic product (GDP) increased by 26% (Wiktorsson, 2014). Industrialisation and mass production created a culture of manufacturing, consumption and disposal without consideration for the rapid increases in virgin 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.

One of the most crucial issues for the future is resource consumption, i.e., the consumption of water, energy and renewable and non-renewable materials. Total global material consumption has increased from 6 billion tons in 1900 (for a population of 1.6 billion people) to 49 billion tons in 2000 (for a population of approximately 6 billion people); today, global material consumption is approximately 60 billion tons, for a population of more than 7 billion people (Mills, 2013). 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 light of both increasing wealth and the anticipated population growth to 9 billion people by 2050, demand for material is likely to at least double by 2050 (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 taken into consideration. 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.

The generation of industrial waste is another critical cause for concern given its impact on both sustainability and the environment (Macarthur, 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 winds up in landfills and incinerators, thus contaminating land, water and air. In the

United States, 93% of the natural capital extracted for production purposes becomes waste through production and extraction processes; only 7% of these materials are components of final products (Abdul Rashid et al., 2008). In Europe, waste generation is expected to increase by 10-20% between 2005 and 2020 (Frostell, 2006). In 2012, the total waste generated by households and economic activities in Europe amounted to 2.4 billion tons, 11% of which (270 million tons) was contributed by the manufacturing sector. The total waste generated by households and economic activities in Sweden in 2012 amounted to 156 million tons, a 25% increase over 2010; the manufacturing industry contributed 6.2 million tons, or approximately 4%, of Sweden's total generated waste (European Commission, 2015). Excluding the mining industry, only 47% of non-hazardous material was recycled in 2012. The amount of waste incineration has increased slightly since 2010, primarily due to the increased burning of mixed industrial and imported waste (Naturvårdsverket, 2014). In addition to waste volume, the quality of waste is significant. The current challenge is not only to reduce the amount of generated waste and to decrease virgin material consumption but also to maintain the high homogeneity of material in the industrial system. Ideally, industrial waste could be utilised directly in another process or reused within its own loop, thereby reducing demand for virgin material.

Material efficiency contributes to reduced industrial waste volumes, reduced extraction and consumption of resources, and decreased energy demand, carbon emissions and overall environmental impact of the global economy. Implementing material efficiency in manufacturing results directly in cost and energy savings in transformation, transportation and disposal, along with reduced greenhouse gas emissions, which is in line with European long-term visions for 60% carbon dioxide reduction and 80% greenhouse gas reduction by 2050. Improvements to material efficiency (and waste management) are imperative even if annual production remains at its current level.

In sum, improved material efficiency, including both reductions in the volume of industrial waste and improvements in the homogeneity of generated waste, is vital to ensure resource availability for future generations, reduce environmental impacts, decrease production costs and improve standards of living.

In general, awareness has been increased through research on sustainability, which is exemplified by, for example, the development of green manufacturing (Manzan and Ikuo Miyake, 2013), cleaner production (van Dam-Mieras et al., 1995), resource efficiency (Schmidt-Bleek, 1996, Foxon, 2000), environmentally conscious design and manufacturing (Zhang et al., 1997), natural capitalism (Hawken et al., 1999) and product service systems (Cook et al., 2006, Mont, 2002). However, detailed research on specific issues remains lacking. For instance, although material efficiency has been widely discussed by, inter alia, Allwood et al. (2013) and Lilja (2009a), detailed investigations of material efficiency characteristics, including strategies and barriers, are lacking. Developed environmental sustainability strategies do not explicitly aim for material efficiency improvement in the manufacturing context. Furthermore, although barriers to environmentally sustainable manufacturing are well investigated, very few studies investigate barriers to material efficiency in manufacturing; one of the few such studies that does exist is Abdul Rashid (2008) study of material efficiency barriers in the United Kingdom's manufacturing industry. Moreover, there is scant case study research on material efficiency in manufacturing.

1.2. Problem statement

Material efficiency and waste management knowledge, recycling and reusing infrastructures, along with technologies and capacities for returning material flows to their environmental origins or introducing them into new cycles are not as developed as manufacturing flows. Material efficiency in the manufacturing context as a means to improve the recyclability, reusability, reduction and prevention of industrial waste is under-researched, and sufficient knowledge and clear information about material efficiency in the manufacturing industry are not available. To increase understanding of and insight into material efficiency in the manufacturing context, the existing state of material efficiency must be evaluated, the implementation of material efficiency strategies at manufacturing companies should be investigated, and barriers should be identified to extend related knowledge and to take steps to achieve the full potential of material efficiency activities.

1.3. Research objective and questions

As explained above, material efficiency in manufacturing has been under-researched, and related knowledge is limited. Therefore, the research objective of this licentiate thesis is to ***contribute to the existing body of knowledge regarding material efficiency in manufacturing*** to increase understanding, describe the existing situation and develop support for improvement. Within the subject of material efficiency, this thesis focuses on the value of process and residual materials, with a particular concentration on increasing the homogeneity of generated waste through achieving higher segregation rates, decreasing the volume of material that becomes waste, and reducing total virgin raw material consumption without influencing the function or quality of a product or process. To fulfil the research objective, the following research questions have been formulated.

RQ1: What environmental sustainability strategies support material efficiency, considering different criteria?

Multiple strategies have been developed to support environmental sustainability in manufacturing. However, it is not clear which of these environmental sustainability strategies support material efficiency in manufacturing. These strategies lack sufficient clarity regarding various criteria, including scope, contributions, requirements, life cycle phase and end-of-life stage. This research question contributes to material efficiency by presenting and comparing relevant strategies based on relevant criteria.

RQ2: What is the existing state of material efficiency in manufacturing?

This research question addresses the existing state of material efficiency in the manufacturing industry. This question contributes to the field by presenting a clear picture of material efficiency in the manufacturing context, thereby enabling companies to see the potential in material efficiency improvement and recycling activities.

RQ3: What barriers prevent manufacturing companies from achieving higher material efficiency improvement?

This research question involves the identification of barriers to material efficiency based on both the literature and the industry. These barriers hinder the achievement of increased homogeneous waste segregation, reduced waste generation and reduced total virgin raw material consumption.

1.4. Delimitations

The majority of the empirical data in this research relate to the situation at large global manufacturing companies in Sweden's automotive industry. Metal is their primary product material, and they generate common types of waste, including plastics, aluminium, steel, cardboard, wood, hazardous waste and combustible waste. In addition, certain other manufacturing companies whose operations, processes and input materials are similar to those of the automotive industry were included. Companies were selected primarily based on availability (as industrial partners in a project), which in turn was based on their respective global ecological footprints, their enthusiasm for improvements in material efficiency and their international reputations and success in implementing appropriate environmental management systems. Furthermore, automotive manufacturers and their sub-contractors constitute a major part of Swedish industry and contribute substantially to Sweden's economy. However, the automotive industry's products and manufacturing processes also contribute significantly to various types of environmental pollution (Nunes and Bennett, 2010); large volumes of solid waste; high energy consumption; air, water and solid emissions; depletion of natural resources; and the moderate recycling rate of residual material and packaging.

In line with research objective and questions, this licentiate thesis concentrates exclusively on the exploration and description of material efficiency in manufacturing and does not prescribe or suggest any model or framework.

In this thesis, the term manufacturing is limited to the manufacturing processes within a plant where the operations necessary to produce a product are performed. Figure 1, which is adapted from the life cycle assessment perspective and the Green Performance Map (Romvall et al., 2011), illustrates the manufacturing phase of the product life cycle. This thesis addresses material efficiency within the *manufacturing* phase of the product life cycle, in which productive material and process material are used to produce products.

More specifically, this thesis focuses closely on process material and residual material and only indirectly on productive material. Thus, this research excludes the obsolescence and disposal 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. By focusing on process and residual material to decrease recycling and reusing demands, manufacturing companies can not only reduce the amount of waste generated but also decrease the total amount of input material (both non-productive and productive materials).

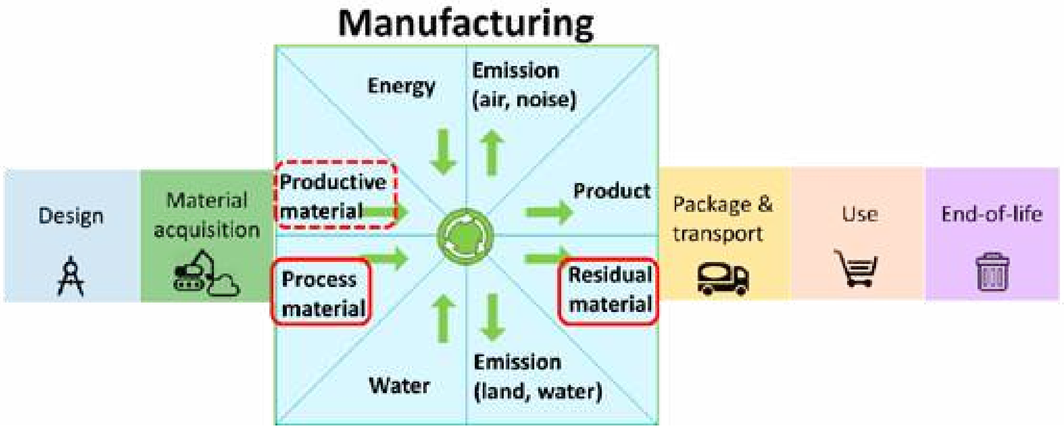

Figure 1 - Manufacturing phase of the product life cycle, adapted from Romvall et al. (2011)

1.5. Project context

This research was conducted as part of a project called "Material Efficiency Management in Manufacturing - MEMIMAN", which is financed by *Mistra* (The Swedish Foundation for Strategic Environmental Research) in the programme *Closing the Loop*. The MEMIMAN project is conducted by key Swedish industrial partners and academic partners, including Mälardalen University, Lund University and the research institute Swerea IVF. The core research group is connected through the strategic initiative *XPRES* – the Initiative for Excellence in Production Research, which is a joint initiative of KTH, Mälardalen University and Swerea. This group focuses on life cycle perspectives on product realisation, which is one of three focus areas of XPRES. The MEMIMAN project aimed to determine both why companies do not recycle more waste and why the success rate of waste management initiatives varies by analysing future trends, current barriers relating to particular waste types and factors that contribute to these barriers. The researcher is an industrial Ph.D. student in the MEMIMAN project, which made it easier to obtain interviews, visit production facilities, collect empirical data, and monitor material efficiency activities and waste management systems.

This research was also conducted within *INNOFACTURE*, an industrial graduate school for innovative production development in product industrialisation and production sustainability that is funded by the Knowledge Foundation, key industrial partners and Mälardalen University. In addition, the research contributes to *MITC* (Mälardalen Industrial Technology Centre), a regional team that disseminates industrial knowledge related to production, product development, energy and material efficiency, and innovation management. MITC is funded by European Union (EU) structural funds, the municipality of Eskilstuna and Mälardalen University.

2. Research methodology

This chapter aims to describe the research path taken and to explain the research design for performing this research. First, research approach is presented, followed by research strategy, research process and data collection method. This chapter then is concluded by research quality.

2.1. Research design

2.1.1. Research approach

An *abductive approach* was chosen for this licentiate thesis because such an approach aims to understand an existing phenomena using a new framework and perspective (Kovács and Spens, 2005) by capturing and utilising both theory and empiricism (Dubois and Gadde, 2002). 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 theory development, empirical data collection and simultaneous case analysis that evolve in a learning loop (Spens and Kovács, 2006).

Established (prior) theoretical knowledge within the research area was gathered through a pilot study. Next, the collection of real-life observations and empirical data was commenced by investigating material efficiency management at global manufacturing companies in Sweden. Analyses of the literature and empirical findings were conducted simultaneously, leading to an iterative process from theory building to empirical study. Figure 2 illustrates the research approach.

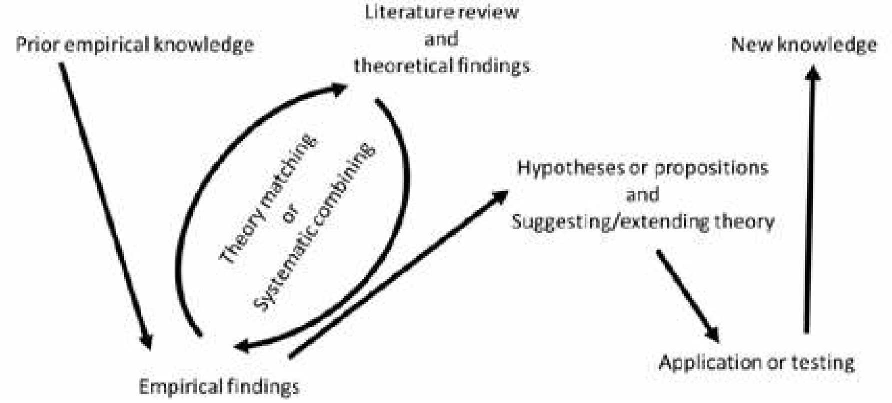

Figure 2 - The abductive approach adapted from Spens and Kovács, (2006)

2.1.2. Research strategy

The objective of this *exploratory research* is to increase understanding, describe the existing situation and develop support for improvement. The primary objective of exploratory research is to gain insight into a subject with insufficient related awareness by focusing on answering "what" questions. Exploratory research is often used in the early stages of research to generate a list of research questions that are worth pursuing (Voss et al., 2002).

This licentiate thesis uses a *multiple methods research design*. Throughout the research process, various types of qualitative methods and few quantitative methods were utilised to collect, analyse and interpret data. Deploying *mixed methods research* provides contextual background and a better understanding of the research problem; facilitates the formulation of research and its follow-ups; permits the redrafting of research questions; and supports the research's generalisability (which is consistent with the abductive approach) and credibility. In sum, the mixed methods research design produces more complete knowledge (Saunders et al., 2009). In this research, the few quantitative methods that were employed were primarily used to support the qualitative methods employed.

Research strategy describes the manner in which the researcher plans to answer the research questions and may be influenced by the research objective, the types of research questions, research approach, the nature of the research, existing knowledge, available resources and of course, the time available to conduct the research (Saunders et al., 2009). In short, this thesis is exploratory and supported by a mixed methods research design. It employs two research strategies: *multiple case study and survey.*

The main strategy used to collect empirical data was the *multiple case study* strategy, i.e., empirical studies A, B, and D. 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 analyse data. Bearing in mind the objective of this licentiate thesis and the formulated "what" questions in this exploratory investigation, the case study approach was selected as the primary strategy to fulfil 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 minimise the risks and drawbacks inherent in single-case studies, including misinterpretation, observation biases and most importantly, a limited ability to generalise 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 experiments (Yin, 2014) but also allows for a wider exploration of the research questions and theoretical elaboration (Eisenhardt and Graebner, 2007).

A survey regarding individuals' perceptions of the environmental and economic benefits of industrial waste segregation was also conducted to support the second research question. The survey strategy is suitable both for "what" questions and for exploratory and descriptive studies (Saunders et al., 2009). Surveys enable standardised, quantitative data collection and permit comparisons to facilitate understanding of a subject, which in this case is individuals' ability to evaluate the environmental impacts of common waste fractions in the manufacturing industry. Figure 3 depicts a summary of the research design.

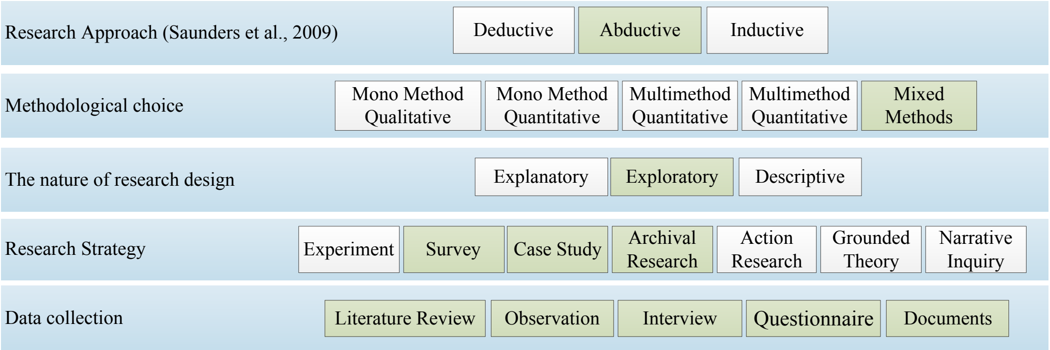

Figure 3 - Research design summary

2.2. Research process

The research process is the summary of all of the steps taken by the researcher that are necessary to follow the path of a specific research approach. The research process used for this thesis is characterised by an abductive approach and "systematic combining" (Dubois and Gadde, 2002), and thus, it entailed a continuous back and forth process between theory and empirical study as a portion of the data analysis was simultaneously performed. Taking into consideration the Design Research Methodology (DRM) described by Blessing and Chakrabarti (2009), this licentiate thesis covers *Research Clarification* and *Descriptive Study I*, leaving the pursuit of *Prescriptive Study* and *Descriptive Study II* for after the licentiate. Table 1 shows the correlated DRM stages for the performed studies. Research Clarification is associated with pilot study and aims to formulate a realistic and meaningful objective based on a study of the literature. Descriptive Study I is consistent with both empirical studies and literature studies.

Table 1 – Research design within the DRM framework (Blessing and Chakrabarti, 2009)

	Pilot study	**Literature studies**	**Empirical studies**
DRM stage	Research Clarification	Descriptive Study I	Descriptive Study I
Type of research	Review-based	Review-based	Comprehensive

2.2.1. Data collection

Literature study was an essential part of this research. Theoretical data were collected not only from scientific papers and reports but also from non-academic sources. 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 conducted in parallel with empirical data collection and analysis.

Empirical data for this thesis were collected through *embedded mixed methods* (Saunders et al., 2009). One survey and multiple case studies were conducted to collect, analyse and interpret data. Note that the survey supplemented the case studies. As suggested by Yin (2003), participant observation, document review and semi-structured interviews were performed in multiple case studies to develop a rich understanding of the cases. Participant observation was accomplished through a participant-as-observer method whereby the researcher participated in the activities and revealed his purpose as a researcher (Saunders et al., 2009). Two sets of focused semi-structured interviews were conducted at two different points of time 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 documents. Archival research is fruitful in exploratory studies and helps answer questions by providing information about both the past and developments over time (Saunders et al., 2009).

2.2.2. Selection of participating companies

Six large and medium global manufacturing companies in Sweden are involved in this licentiate thesis, although not all of them were included in each study. Four of the case companies (CC1 - CC4) are industrial partners in a research project that aims to determine both why companies do not recycle more waste and why the success rate of waste management initiatives varies by analysing future trends, current barriers relating to particular waste types and factors that contribute to these barriers. Therefore, the selection of these companies was 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. Companies CC5 and CC6 were included on a limited basis in later stages of the research due to their accessibility and similar interest in material efficiency improvement practices. In addition, the companies' international reputations, prior successful implementation of appropriate environmental management systems and significant interest in improving their current systems led to their initial selection for participation in this research. Table 2 describes the companies and their respective involvement in the research process.

Table 2 - Overview of selected companies

	Type of industry	**Empirical studies**
Company CC1	Remanufacturer of engines and components of trucks, buses and construction equipment	Empirical study A
Company CC2	Manufacturer of construction equipment and industrial material handling	Empirical studies A, B
Company CC3	Manufacturer of products for heat transfer, separation and fluid handling	Empirical studies A, B, C, D
Company CC4	Manufacturer of heavy trucks and buses, gearboxes and engines	Empirical studies A, B, C, D
Company CC5	Manufacturer and assembler of gearboxes for trucks, heavy equipment and marine equipment	Empirical studies B, C, D
Company CC6	Manufacturer of surface drilling equipment and underground rock excavation equipment	Empirical study B

2.2.3. Pilot study

This licentiate thesis commenced with a structured, qualitative, literature-based study to become familiar with the subjects of material efficiency, industrial waste management and sustainability. The pilot study encompassed exploration of black holes and white spots within these subjects, determination of a worthwhile research objective, formulation of research questions and development of a research plan. The pilot study included keywords such as "material efficiency", "industrial waste", "sustainability" and "waste management strategy", along with the combination of these terms with "manufacturing" and "automotive". In addition, qualitative upstream and downstream searches of the literature were conducted for relevant references. The research objective and questions and the initiation of Papers I and II are based on this literature study.

2.2.4. Literature studies

Four separate literature studies were conducted using keyword searches in scientific databases and non-academic sources, along with qualitative upstream and downstream searches for references.

Literature study A focused on research question 1 and aimed to identify environmental sustainability strategies that support material efficiency. To find relevant literature, keywords including "material efficiency", "dematerialisation" and "resource efficiency", combined with "strategy", "approach", "method", "principle", "concept" and "tool", were utilised to search scientific databases. This early stage of the study contributed first to Paper I and later to Papers III and IV.

Literature study B aimed to provide insight into and increased awareness of influential future macro trends related to material efficiency, raw material consumption and waste generation. This literature study helped to answer research question 2, which relates to the existing state of material efficiency, because the future is the consequence of current practices, and current developments will save the future. To find relevant literature, keywords including "future trends", "roadmap" and "future scenario" were combined with "production", "material consumption" and "waste generation" to search scientific databases. The outcome was the identification of various future macro trends and their categorisation into political, economic and sociocultural, and technological shifts. Paper II presents some of the results obtained through this study.

Literature study C considered both municipal and industrial waste management to gain an understanding of the thought processes, cognitive psychology and intuition involved in the prioritisation of environmental and economic aspects in waste management. This study indirectly contributed to answer research question 2 and, together with the empirical studies, was included in Papers VI and VII.

Literature study D directly contributed to answering research question 3, which relates to barriers to material efficiency. 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 a full-paper skim and scan. This study provided a theoretical background to Paper III.

2.2.5. Empirical study A: waste stream mapping

Empirical study A used embedded mixed methods. The objective of this study was both to increase knowledge and to gain a detailed understanding of the existing state of material efficiency and the residual material value chain among manufacturing companies. The quantitative method used in this study was Waste Flow Mapping (see Paper IV), which included different methods and tools for environmental and operational management, including the Green Performance Map (Romvall et al., 2011), eco-mapping (Engel, 2002), waste sorting analysis, continuous reduction of losses or lean waste (Netland, 2012), value stream mapping, and material handling analysis. Through waste sorting analysis, the homogeneous quality of industrial waste bins was measured by weighing and differentiating the wasted material (for details, see Papers III and IV).

The qualitative method employed in this study was a multiple case study conducted at four large global manufacturing companies in Sweden (see table 2). Empirical data were collected through participant observation, focused semi-structured interviews and reviews of environmental reports.

Table 3 - Overview of empirical study A

Empirical study A	
Purpose	Investigation of the existing state of material efficiency and the residual material value chain in manufacturing
Unit of analysis	Existing material efficiency practices in manufacturing
Type of study	Exploratory
Research strategy	Multiple case study
Methodological choice	Embedded mixed methods, although quantitative methods constituted a relatively small portion of the performed research
Data collection method	Semi-structured interviews, participant observation, archival research and document review, on-site visits and company walkthroughs, layouts and photographs
Data analysis method	Waste flow mapping, expert opinion and discussions through workshops, data matrix, pie chart, cross-case analysis
Case companies	CC1, CC2, CC3, CC4
Related RQs	RQ2 and RQ3, indirectly to RQ1
Related publication	Papers III and IV, (paper V)
DRM stage	Descriptive Study I (Comprehensive)

The role of the researcher was participant-as-observer (Saunders et al., 2009), meaning that the researcher played an active role in the application of Waste Flow Mapping and revealed his purpose as a researcher. In the focused semi-structured interviews, 44 participants in different functions were asked predefined questions. Although the researcher participated in only one-third of the interviews, the interviews were documented through a common template (appendix B) and thus the researcher had access to all of the interview data; he also played 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 contractors.

2.2.6. Empirical study B: material efficiency strategies

The objective of this study was to evaluate material efficiency strategies in an industrial context. Empirical data regarding the levels of awareness of identified strategies and their implementation (if any) were investigated through a questionnaire and 13 semi-structured interviews at five manufacturing companies. Interviewees included environmental coordinators/environmental managers, operators, manufacturing engineers, plant directors and production managers. The researcher played an active executive role in the collection, documentation and analysis of data.

Table 4 - Overview of empirical study B

Empirical study B	
Purpose	Evaluate material efficiency strategies within an industrial context
Unit of analysis	Manufacturing companies' familiarity and implementation of material efficiency strategies
Type of study	Exploratory
Research strategy	Multiple case study
Methodological choice	Qualitative study
Data collection method	Semi-structured interviews and questionnaire
Data analysis method	Cross-case analysis, categorisation and clustering, data matrix
Case companies	CC2, CC3, CC4, CC5, CC6
Related RQs	RQ1, indirectly RQ2
Related publication	Paper III
DRM stage	Descriptive Study I (Comprehensive)

2.2.7. Empirical study C: environmental and economic perception

Empirical study C is a survey designed to assess individuals' intuition regarding the environmental impact of industrial waste segregation and recycling. To achieve an interdisciplinary, collaborative perspective, 31 environmental researchers from the Mistra programme were surveyed. Participants were asked to rank the following common types of industrial waste: sorted soft plastics, sorted hard plastics, aluminium, glass, cotton, steel, wood, cardboard, paper and compostable (see the additional publications, Paper VI and VII). The purpose of the survey was to understand how well individuals are able to assess the economic and environmental impact of industrial waste generation. Respondents were first asked to rank different common industrial waste fractions according to their environmental impact and then to rank them according to their cost per weight. In line with the purpose of the survey, all of the respondents were to some extent connected to manufacturing and its environmental issues, i.e., were involved in production and/or environmental programmes and conducting research on sustainable manufacturing.

Table 5 - Overview of empirical study C

Empirical study C	
Purpose	To understand how well individuals are able to assess the economic and environmental impact of industrial waste
Unit of analysis	Individuals' perceptions of the economic and environmental impact of industrial waste
Type of study	Exploratory
Research strategy	Survey
Methodological choice	Quantitative study
Data collection method	Questionnaire and semi-structured interview
Data analysis method	Ranking, data matrix, diagrams and charts, cross-case analysis
Case companies	-
Related RQs	RQ1, RQ2, RQ3
Related publication	(Papers VI and VII)
DRM stage	Descriptive Study I (Comprehensive)

2.2.8. Empirical study D: barriers to material efficiency

Empirical study D is a multiple case study to identify barriers that impede material efficiency improvements and waste segregation. This study entailed 11 semi-structured interviews at three manufacturing companies. At each company, the interviewees included the environmental manager, plant director, production leader and machine operator to achieve a broad perspective on material efficiency characteristics. The semi-structured interviews comprised predefined questions regarding barriers, improvement potential and the actors involved in improving material efficiency and waste segregation (see appendix C). In addition, questions were asked regarding external and internal cooperation and improvement possibilities. The interviews lasted from 40 to 70 minutes; and the researcher played an active executive role in empirical study D, i.e., he conducted interviews and collected, documented and analysed the data.

Table 6 - Overview of empirical study D

Empirical study D	
Purpose	To identify barriers that impede material efficiency improvement and waste segregation
Unit of analysis	Barriers to improved material efficiency experienced by manufacturing companies
Type of study	Exploratory
Research strategy	Multiple case study
Methodological choice	Qualitative study
Data collection method	Semi-structured interviews, observations
Data analysis method	Categorisation and clustering, cross-case analysis
Case companies	CC3, CC4, CC5
Related RQs	RQ3 and, indirectly RQ2
Related publication	Paper III
DRM stage	Descriptive Study I (Comprehensive)

Figure 4 depicts the research process and studies over time.

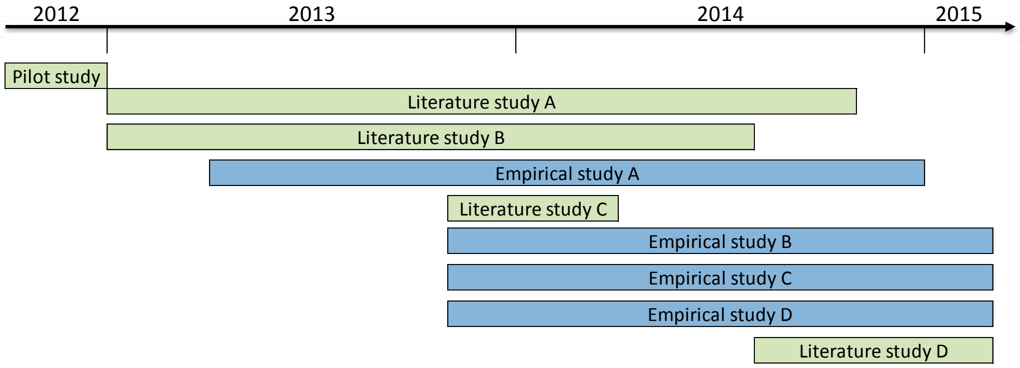

Figure 4 - Research timeline

2.2.9. Data analysis

As suggested by Yin (2014), data analysis was conducted while the data were collected, which is consistent both with this research's abductive approach (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 endeavoured 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 to the results of the literature review to draw conclusions.

The collected quantitative data in this research fell into a categorical data type - specifically, ranked (ordinal) data (Saunders et al., 2009) - wherein the relative position of each case within the data set was determined. Thus, keeping in mind the research objective and questions, an exploratory and descriptive data analysis approach was deployed. This approach involved the use of diagrams, charts, matrixes and tables.

In terms of quantitative data analysis, a variety of techniques were deployed depending on the study, including categorisation and clustering, cross-case analysis, colour coding, data matrix, mind-mapping, PEST (political, economic, social, and technological factors) analysis, etc. The analysis of collected quantitative data was conducted 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, organised (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.

According to Eisenhardt (1989), cross-case analysis - one of the major techniques employed in this research - both "forces investigators to look beyond initial impressions and see evidence thru multiple lenses" and "also, cross-case searching tactics enhance the probability that the investigators will capture the novel findings which may exist in the data". This quantitative technique not only enhances understanding and explanation but also increases generalisability (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 analysed individually to understand the particular dynamics of each case.

2.3. Research quality

2.3.1. 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 (Gummesson, 2000, Saunders et al., 2009). Therefore, structured documentation and a case study protocol were utilised to assure the reliability of the performed research, the latter of which is consistent with Yin (2014) suggestion that a case study protocol is appropriate for multiple case studies. Throughout empirical study A, structured protocols were written and documented for each case company visit and internal project meeting. Collected data and results were also documented in both hard- and soft-copy form. Empirical studies B and D were conducted pursuant to interview guidelines, the study objective, questions and propositions, which ensured that the same procedures were followed during each interview and data collection effort and prevented participant and researcher error and bias. Empirical study C was conducted in accordance with survey guidelines, the study objective, pictures and descriptions. In addition, all of the empirical studies used multiple sources of data to enhance reliability (Voss et al., 2002). 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) but maintained control over the conversation. To ensure the quality 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. Moreover, in the second set of interviews, which constituted the primary source of empirical data, the conversations were recorded to facilitate more precise interpretation (Yin, 2014). Most of the recorded interviews were listened to and interpreted within a week or two of the interview, when the memory was fresh.

2.3.2. 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 validity and assures that the information being collected is correct (Meredith, 1998). Therefore, the sources of evidence were triangulated by collecting data from multiple sources, including interviews, a questionnaire, observations, content analysis of documents and archival research. Additionally, a case study database was created in which environmental reports, photographs, written protocols, personal reports and relevant scientific papers, along with all of the recorded interviews and performed analyses, were collected.

Triangulation and peer examination by MEMIMAN project members and research fellows at conferences, along with a participatory research approach, ensured internal validity, as suggested by Merriam (1997). External validity relates to the generalisability of findings to other contexts (Saunders et al., 2009). Because empirical studies A, B and D were multiple case studies, replication logic was employed as a case study tactic to increase external validity, as suggested by (Yin, 2014).

3. Literature review and theoretical findings

This chapter provides a summary of previous research and the theoretical findings of this thesis. It begins by reviewing sustainable manufacturing, waste management and material efficiency. Next, future macro trends affecting material efficiency are discussed, followed by an introduction to material efficiency strategies. This chapter concludes with a description of generic barriers to environmental sustainability.

3.1. Sustainable manufacturing

Since the introduction of the "sustainable development" concept in a report titled "our common future" (Brundtland, 1987), there has been an awareness of the risks related to limited resources and waste generation. The Brundtland report defines sustainable development as "development that meets the needs of present generations while not compromising the ability of future generations to meet their needs". Although many other definitions have evolved over time, this definition remains valid. The current definition of sustainability encompasses 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). Because this research addresses the environmental dimension of sustainable development in the manufacturing context, the definition of *sustainable manufacturing* proposed by Garetti and Taisch (2011) is adopted for this thesis: "The ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviours, are able to satisfy economic, environmental and social objectives, thus preserving the environment while continuing to improve the quality of human life".

The data underscore manufacturing's importance to sustainability. Specifically, 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 CO_2 emissions generation; in both cases, manufacturing's share is greater than the shares attributable to transportation, households and services (IMS, 2009). The effects of manufacturing on raw material consumption, the greenhouse effect, climate change, waste generation and water and air emissions should also be considered.

By relating the general aspects of sustainability in manufacturing to material efficiency and waste management, the Swedish manufacturing industry has successfully increased material efficiency. In 2012, the total amount of waste generated by the manufacturing industry in Sweden was 6.2 million tons, or approximately 4% of total generated waste (European Commission, 2015), as shown in Figure 5. The amount of waste generated by Sweden's manufacturing industry has decreased by half relative to 2004, when manufacturing waste was 12 million tons and represented 14% of the total waste generated in Sweden (Eurostat, 2014, Naturvårdsverket, 2014). Meanwhile, economic activity in manufacturing (in constant 2005 prices) has remained constant.

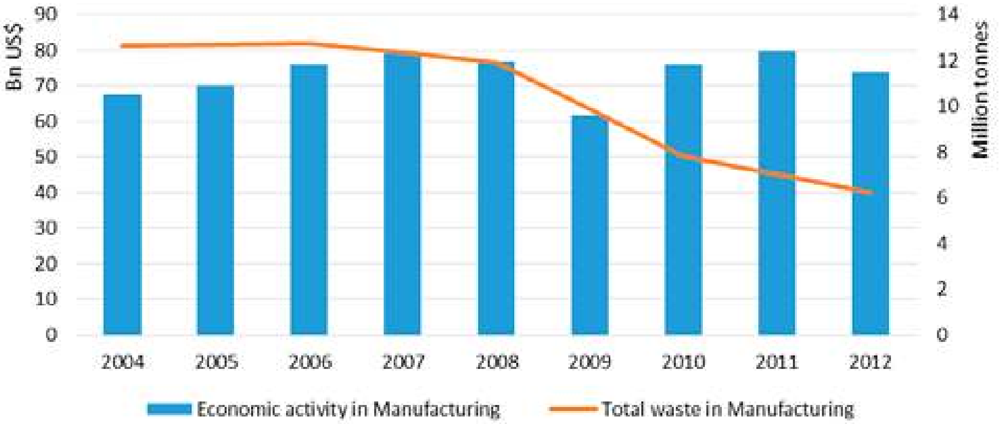

Figure 5 - Economic activity within manufacturing and total waste generated in manufacturing in Sweden during 2004 – 2012. Data sources: UN Statistics and Eurostat (presented in Paper III)

Despite the successful reduction of waste generation, information about the existing state of material efficiency in manufacturing, the implementation and deployment of material efficiency strategies, and barriers to increased material efficiency remains both insufficient and imprecise.

3.2. Waste management

Industrial waste is a key factor to consider when assessing the sustainability of a manufacturing process or 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 and is not a product of the operations" (EU, 2008). However, "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" (European Commision, 2012). Therefore, if the given residual material has no possible use and is destined to be discarded, it would be considered waste.

Proper waste management implies monitoring and fully controlling all stages of waste 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 the waste is rendered harmless to humans, animals and the environment (Hogland and Stenis, 2000, Taiwo, 2008). This practice involves the use of materials with less environmental impact; the use of processes with lower emissions; the minimisation of waste; proper waste disposal; and energy efficiency. In other words, proper waste management implies reduction of the environmental burden generated throughout a product's life cycle to decrease the effect of waste on health and the environment. Waste management includes the acquisition and dissemination of necessary information about waste disposal techniques and options, fuel handling, spillage control, waste sorting, pollution measurements, and health and safety issues (Atlas, 2001).

Given the focus of this thesis on material efficiency in manufacturing, industrial waste management is of particular interest. Proper industrial waste management can create a positive local and international image, strengthen shareholder trust and increase product demand (Atlas, 2001). It conserves resources, reduces the total consumption of virgin materials, saves money through reuse and recycling, encourages companies to transition from landfills to superior waste treatment processes, minimises environmental pollution, prevents serious health and social problems and helps counteract global warming.

The waste hierarchy is an international strategy that prioritises various waste streams to achieve optimal environmental and economic benefits. The steps involved in the waste hierarchy can vary. Several scholars have divided the higher stages into multiple levels, such as refurbishment or repair. The research presented in this thesis also contributes to efforts to climb the waste hierarchy. Increasing the homogeneity of generated waste through higher segregation rates leads to increased levels of industrial waste recycling and reusing instead of incinerating mixtures of materials. As a result, residual materials can be reused either directly in another process or within their own loop, or they can be recycled to reduce the demand for virgin material.

Figure 6 - Waste hierarchy (Kurdve et al., 2011)

3.3. Material efficiency

Material efficiency has been defined by various scholars, including Peck and Chipman (2007) and Worrell et al. (1997), and its semantic characteristics are similar to other sustainability concepts such as dematerialisation, eco-efficiency and resource efficiency. Simple and practical definitions have been provided both by Rashid and Evans (2010) "the ratio of output of products to input of raw materials" and by Allwood et al. (2013) "to continue to provide the services delivered by materials, with a reduction in total production of new material". The first definition relates primarily to plants and manufacturing entities, whereas the second definition is more holistic and general and relates to the entire supply chain and to society as a whole.

Numerous scholars have studied material efficiency in critical materials and rare-earth metals for better design and recycling, given that the recycling rates of these materials are estimated to be under one percent in most cases. Some examples of these studies are (Schmidt, 2012), (Massari and Ruberti, 2013), (Messenger, 2013), (European Commission, 2010a), (Ayres and Peiró, 2013), (Massari and Ruberti, 2013), (Roland Berger Institute, 2012), (Hedrick, 2008) and (Kingsnorth, 2008).

Material efficiency has been also 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. discuss material efficiency within business models, consumer preferences and policies to give an overview of the topic (Allwood et al., 2011) and engage insights from economics, sociology, policy, design, environment or technical analysis (Allwood et al., 2013).

Some scholars have developed models or approaches to enhance resource or material efficiency. For instance, Worrell et al. (1995) has proposed an approach for analysing material efficiency improvement in plastic packaging in the Netherlands and found a 31% improvement in the energy efficiency of the life cycle of plastic packaging. Meyer et al. (2007) have developed the PANTA RHEI model to improve material productivity to facilitate achievement of environmental and economic targets in Germany. Smith and Ball (2012) have used material, energy and waste flow modelling to develop guidelines for analysing manufacturing systems. Halme et al. (2007) have proposed a business model for material efficiency services provided by third parties. Figure 7 illustrates the evolution of the material efficiency concept in reports, books and papers.

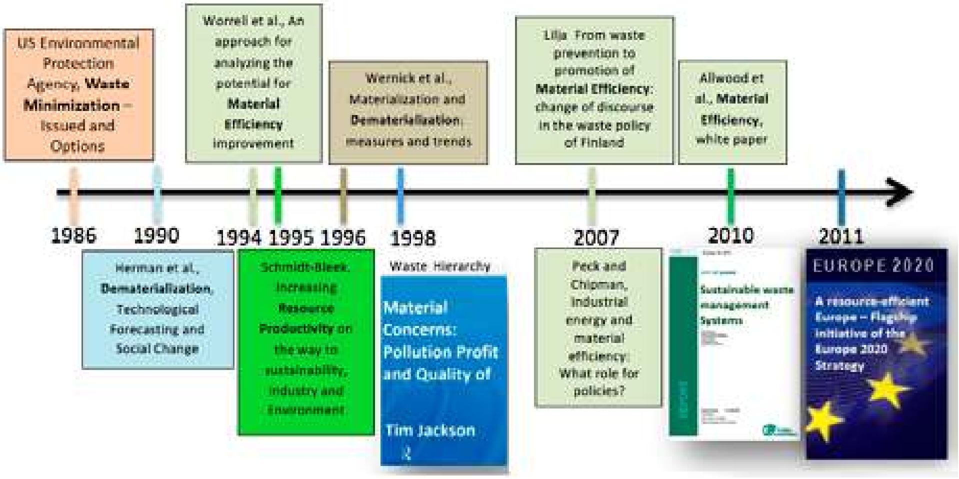

Figure 7 – The evolution of material efficiency

Material efficiency is considered complementary to energy efficiency in the effort to move towards sustainable manufacturing. As stated by Lilja (2009a), taking a life cycle approach to material efficiency is a strategy that is preferable to waste prevention. He also asserts that material efficiency should be promoted in the near future because waste avoidance appears to be an insufficient driving force for the transformation of consumption and production patterns. Lilja (2009a) also suggests that actions taken to achieve waste prevention goals should not be viewed as alternatives to investments in waste recycling, waste recovery or final disposal.

Equation 1 can be derived based on the definition of material efficiency (the ratio of output to input). However, industrial material input data are not always precise, which leads to equation 2.

$$\begin{aligned}\text{Material efficiency} &= \text{Product output/Material input} \\ &= \text{Product weight /Incoming material weight}\end{aligned} \tag{1}$$

$$\begin{aligned}\text{Material efficiency} &= \text{Product output /(Generated waste} + \text{Produced product)} \\ &= \text{Product weight /(Waste weight} + \text{Product weight)}\end{aligned} \tag{2}$$

These criteria can also be indexed per unit produced, per production or per tonne of products. It is also possible to utilise cost equivalents or volume measures (Kurdve, 2008), as shown in equation 3.

$$\text{Material efficiency} = \text{Product value /(Waste cost} + \text{Product value)} \tag{3}$$

Moreover, material efficiency is related to economy, and economical efficiency is measured in terms of money. Thus, equations 4 and 5 can be written as suggested by Allwood et al. (2013).

$$\begin{aligned}&\text{Materials required/Service provided} = \\ &\quad \text{Materials required/Money spent} \times \text{Money spent/Service provided}\end{aligned} \tag{4}$$

$$\text{Physical material efficiency} = \text{Economic material efficiency} \times \text{Price of service} \tag{5}$$

All of these measures consider total material efficiency, including product material. Because the focus of this thesis is on residual material, efforts were made to identify literature on material efficiency that addresses residual material. However, there is scant research on material efficiency in the manufacturing industry that addresses the segregation of residual material.

3.4. Trends influencing material efficiency in manufacturing

A boundless multitude of factors influence the future development of material efficiency and industrial waste in manufacturing. Although the majority of companies have an excellent understanding of internal factors, most fail to adapt to external changes in an effective and timely manner (Rohrbeck and Gemünden, 2011). In fact, it is common to lose sight of external trends and developments, including social, legal, political, environmental and cultural developments. Conversations about the future rarely occur and if they do, they are both informal and lacking in formal documentation. Consequently, the potential not only for developing a systemic viewpoint but also for considering macro trends in decision making is high (Goodier et al., 2010), particularly with respect to environmental issues and influential upcoming macro trends related to material efficiency and industrial waste.

Paper II presents several macro trends that directly or indirectly affect material efficiency, waste generation and total virgin raw material consumption in manufacturing. The identified macro trends are then categorised through PEST analysis to show their respective areas of contribution and the circumstances of their influence on material efficiency.

The macro trends that will specifically influence the material efficiency of residual material in manufacturing are as follows in five clusters:

- *Material availability:* key resource consumption (Mills, 2013, Teknikföretagen, 2013); scarcity of raw material (Schwenker and Raffel, 2012, Ribeiro et al., 2012, Teknikföretagen, 2013); global competition for resources (Ribeiro et al., 2012); higher prices for products and raw materials (Schmidt, 2012); the substitution of materials (European Union, 1987, Garetti and Taisch, 2011, European Commission, 2010b, European Union, 2011).
- *Material management:* social networks for waste (Öko-Institut e.V, 2009, Crichton, 2012); recycling infrastructure (Öko-Institut e.V, 2009, MANUFUTURE); business models that incorporate life cycle thinking and opportunities for waste management (Frostell, 2006, MANUFUTURE, Garetti and Taisch, 2011)
- Environmental protection: climate change and global warming (Ribeiro et al., 2012, Garetti and Taisch, 2011, Schwenker and Raffel, 2012); the carbon tax (Norgate and Rankin, 2002, Stahel, 2010)

- Consumers/social: the global middle-class wave (Kharas, 2010, Schwenker and Raffel, 2012, United Nations, 2012); world population growth (European Commission, 2011b, Ribeiro et al., 2012, Garetti and Taisch, 2011, MANUFUTURE); behavioural changes by producers and consumers (European Commission, 2011a, Garetti and Taisch, 2011);
- Production: increased material complexity (Schmidt, 2012, Teknikföretagen, 2013); mass customisation and additive manufacturing (Birtchnell and Urry, 2013, Markillie, Berman, 2012, Garetti and Taisch, 2011, Jovane et al., 2008); increased automation (Garetti and Taisch, 2011, IFR - Internation Federation of Robotics, Spohr, 2009)

3.5. Material efficiency strategies

The scope of material efficiency is broad and encompasses various terminologies. Both industrial waste and the depletion of virgin material pressure manufacturing companies to find new, viable strategies consistent with environmental, social, and economic sustainability. A multitude of sustainability strategies have been developed in both academia and industry to alleviate the environmental impact of manufacturing (Lindhqvist, 2007); a majority of these strategies bear directly on industrial waste. However, these strategies lack sufficient clarity in terms of application area, goals, organisational entities, semantic aspects, life cycle phase, prevalence and waste hierarchy stage. There is also significant overlap between these proposed strategies' goals and approaches to material efficiency and industrial waste management (Lilja, 2009a), resulting in confusion for manufacturing companies aiming to synthesise their management systems with a material efficiency strategy. To facilitate resolution of the aforementioned challenges, this section contributes to the material efficiency field by presenting relevant environmental sustainability strategies identified in both the pilot study and literature study A. Table 7 shows environmental sustainability strategies that support material efficiency. The strategies presented here are slightly different than those presented in Paper I, primarily because of the knowledge development and accumulation of complementary data that occurred during the research process.

Table 7 - Environmental sustainability strategies that support material efficiency (See Paper III)

Strategies	References	Similar strategies and subsets
Cleaner production	(Lebersorger, 2008), (Williams and Curran, 2010), (Gravitis, 2007), (Williams and Curran, 2010)	Best available technology, Cleaner technology, Pollution prevention
Waste minimisation	(Lebersorger, 2008), (Curran and Williams, 2012), (Lilja, 2009a), (Gravitis, 2007), (Atlas, 2001), (Zhang et al., 1997), (Tang and Yeoh, 2008), (Williams and Curran, 2010), (Anthony and Cumming, 2008)	Waste prevention, Zero waste
Eco-efficiency	(Lilja, 2009a), (Ehrenfeld, 2005), (Schmidheiny and Stigson, 2000)	Eco-effectiveness
Life cycle assessment (LCA)	(Knight and Jenkins, 2009), (ISO/TR14062, 2002), (Jönbrink et al., 2011), (Kurk and Eagan, 2008), (Zackrisson et al., 2014)	Life cycle cost (LCC), Eco-design, Eco-compass, Eco-ideas map
Best practice (including lean)	(Zhang et al., 1997), (Mezher, 2001), (Romvall et al., 2011), (Zokaei et al., 2013)	
Closed-loop	(Curran and Williams, 2012), (Welsh Government, 2012), (Orecchini, 2007), (Guide et al., 2003)	
Reverse logistics	(Rogers and Tibben-Lembke, 2001), (Dowlatshahi, 2000), (Östlin et al., 2009), (van Hoek, 1999), (Jayant et al., 2012)	
Industrial ecology	(Kuehr, 2007), (Williams and Curran, 2010), (Gibbs and Deutz, 2005), (Roberts, 2004), (Erkman, 1997)	Eco-industrial park, Industrial symbiosis
Product stewardship	(Curran and Williams, 2012), (Lewis, 2005), (Snir, 2001), (Dillard et al., 2010), (Watson et al., 2014), (Tojo, 2004)	Individual product responsibility (IPR), Extended product responsibility (EPR)
Environmental management system (EMS)	(Nawrocka and Parker, 2009), (Khalili and Duecker, 2012), (Darnall et al., 2008), (Wiengarten et al., 2013)	Sustainable environmental management system (SEMS)
Eco-mapping	(Arina and Viktoria, 2007), (Engel, 2002), (Tóth, 2003), (Zorpas, 2010)	
Waste hierarchy	(Anthony and Cumming, 2008), (Brisson, 1997), (Kurdve, 2008), (Schmidt et al., 2007), (WelshGovernment, 2013)	
Material flow cost accounting (MFCA)	(Romvall et al., 2011), (Allen et al., 2009), (Kokubu and Kitada, 2014)	Green performance map (GPM), System boundary mapping, Green impact matrix, Green big picture map, Environmental management accounting (EMA)
Resource efficiency	(Norgate et al., 2007), (Labys, 2004), (Allwood et al., 2011), (Peck and Chipman, 2007), (Worrell et al., 1997), (Dahlström and Ekins, 2005)	Resource effectivity, Resource productivity, Dematerialisation, Material and energy efficiency, Factor 10, Natural capitalism

Additional strategies related to environmental sustainability were identified but were excluded due to their indirect or limited link to material efficiency (see appendix A for a list of all of the identified strategies related to environmental sustainability). Certain strategies are also subsets of the main strategies or very closely linked to another strategy; these strategies are listed in the third column of table 7. For instance, eco-industrial parks and industrial symbiosis are applications of industrial ecology; both of these strategies involve the sharing and exchange of raw material, energy, residual material, water and waste flows among various companies within close geographic proximity as a method of managing resource and environmental issues. However, the eco-industrial park strategy adopts a wider perspective than industrial symbiosis. Specifically, industrial symbiosis concentrates exclusively on physical exchanges of material, energy and waste, whereas the eco-industrial park strategy includes exchanges of not only management strategies, infrastructure and knowledge but also physical material, energy and waste. Individual product responsibility (IPR) and extended product responsibility (EPR) are also subsets of product stewardship. Eco-design and life cycle assessment are closely linked to each other, but eco-design primarily relates to the design phase rather than the manufacturing phase of the product life cycle.

All of the identified strategies contribute to material efficiency, and the majority contribute to more than one aspect of material efficiency (e.g., reduced waste generation, decreased resource extraction and material processing, and increased homogeneity of generated industrial waste). For example, the closed-loop and industrial ecology strategies contribute to all three aspects. The strategies that are tangibly connected to the residual material aspect of material efficiency in manufacturing are waste minimisation, life cycle assessment, eco-mapping and best practice. Nevertheless, evidence regarding the actual implementation of these strategies in industry is unclear (Abdul Rashid et al., 2008, Bey et al., 2013). These strategies also overlap insofar as they propose similar solutions for material efficiency and industrial waste management (Lilja, 2009a), which causes confusion for companies aiming to synthesise their management systems with a material efficiency strategy. This research juxtaposes its strategies both to provide clarification and to enable more precise understanding; however, it does not intend to select one strategy as superior.

3.6. Barriers to the environmental sustainability strategies

Literature study D revealed a scarcity of studies on barriers to material efficiency (e.g., Allwood et al. (2011) and Watkins et al. (2013)), particularly in the manufacturing context (e.g., Abdul Rashid (2008)). Exacerbating 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, this study considered generic barriers to general environmental sustainability strategies, e.g., barriers to environmental strategy implementation in the hotel industry (Chan, 2008); barriers to cleaner production in the metal producing industry (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 in the fastener industry (Al Zaabi et al., 2013); barriers to recycling in the apparel industry (Larney and Aardt, 2010, Zhu et al., 2011, Östlund et al., 2015); and barriers to sustainability in operating IT software solutions (Seidel et al., 2010).

Finding relevant papers related to Sweden's manufacturing industry was also problematic. Numerous studies limited their investigations to industries in specific countries, including 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 Aardt, 2010), Malaysia (Amrina and Yusof, 2012) and Finland (Pajunen et al., 2013).

Many barriers to general environmental sustainability strategies were identified through the consideration of generic barriers; however, irrelevant barriers were excluded. Selection was based on the relevancy of the barrier to material efficiency and the number of citations. Other barriers were excluded because they were very specific to a particular industry, e.g., the apparel industry. Based on an extensive study of the literature and a workshop discussion among industrial experts and academicians, the identified barriers were first categorised into six groups (Technological, Social, Informational, Legal, Organisational and Economic) both to facilitate an understanding of material efficiency and to effectively mitigate the barriers. Barriers within each category were clustered further to ease prioritisation and eradication. Because it is difficult to eradicate all barriers in the initial stages, this categorisation and clustering helps companies prioritise their goals of realising improved material efficiency, increasing recycling rates and climbing the waste hierarchy.

Table 8 - Barriers that impede material efficiency improvement at manufacturing companies (presented in Paper III)

Barriers		Associated issue	References
Technological	Engineering	Engineering barriers, e.g., layout	(Shi et al., 2008), (Murillo-Luna et al., 2011), (Ammenberg and Sundin, 2005)
		Technical and detailed knowledge, e.g., waste material awareness	(Post and Altma, 1994), (van Hemel and Cramer, 2002), (Bey et al., 2013), (Pajunen et al., 2013), (Simpson, 2008)
		Trade-offs and difficulty in balancing	(Mittal and Sangwan, 2013), (Bey et al., 2013)
	Technology, machine and equipment	Lack or scarcity of advanced technology and equipment with lower-environmental impacts	(Murillo-Luna et al., 2011), (Luken and Van Rompaey, 2008), (Zhu et al., 2011), (Simpson, 2008), (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)
		Aversion to innovation and technological change	(Murillo-Luna et al., 2011), (van Hemel and Cramer, 2002), (Seidel et al., 2010)
		Difficulties and technological risks	(Sarkis et al., 2007), (Mittal and Sangwan, 2013), (Post and Altma, 1994)
	Environmental tools	Lack of relevant/suitable tools for environmental initiatives	(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)
Economic	Budgetary	Limited financial capability for environmental investments	(Post and Altma, 1994), (Hillary, 2004), (Shi et al., 2008), (Chan, 2008), (Rashid and Evans, 2010), (Moors et al., 2005), (Bey et al., 2013), (Pajunen et al., 2012), (Allwood et al., 2011), (Simpson, 2008), (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, 2013), (Zhu et al., 2011), (Luken and Van Rompaey, 2008)
		High short-term costs and low short-term economic benefits	(Mittal and Sangwan, 2013), (Zhu et al., 2011)
	Material and product cost	Difficulty in simultaneously adapting and maintaining competitive prices of products	(Murillo-Luna et al., 2011), (Bey et al., 2013)
		High purchasing cost of environmentally friendly materials and packaging	(Zhu et al., 2011), (Al Zaabi et al., 2013)
		High cost of collection and segregation	(Allwood et al., 2011)

Organisational	Management	Limited environmental awareness of directors	(Murillo-Luna et al., 2011), (Rashid and Evans, 2010), (Zhu et al., 2011), (Moors et al., 2005), (Simpson, 2008)
		Limited top management commitment and support for sustainability initiatives	(Shi et al., 2008), (Zhu et al., 2011), (Post and Altma, 1994), (Moors et al., 2005), (Amrina and Yusof, 2012), (Sarkis et al., 2007), (Mittal and Sangwan, 2013), (Koho et al., 2011), (Seidel et al., 2010), (Zhu et al., 2011), (Al Zaabi et al., 2013), (Johansson, 2002), (Bey et al., 2013)
		Higher priority of other issues or requirements, e.g., production expansion/market share	(Shi et al., 2008), (Murillo-Luna et al., 2011), (Simpson, 2008), (Seidel et al., 2009)
		Management resistance to change	(Shi et al., 2008), (Murillo-Luna et al., 2011), (Amrina and Yusof, 2012), (Sarkis et al., 2007)
	Supplier	Poor partnership formation and management	(Sarkis et al., 2007), (Simpson, 2008)
		Limited development of environmental supply sector	(Murillo-Luna et al., 2011)
		Uncooperative supplier	(Abdul Rashid and Evans, 2012), (Bey et al., 2013)
		Lack of demand from supplier	(Koho et al., 2011)
	Vision and culture	Company culture	(Pajunen et al., 2012), (Ammenberg and Sundin, 2005), (Allwood et al., 2011), (Chan, 2008), (Rashid and Evans, 2010)
		Lack of focus on corporate image and social responsibility	(Bey et al., 2013), (Pajunen et al., 2012), (Seidel et al., 2010), (van Hemel and Cramer, 2002), (Rashid and Evans, 2010), (Moors et al., 2005)
		Unclear/weak strategic and business goals, capabilities and planning, and the existence of misalignment of short- and long-term strategic goals	(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, 2008), (van Hemel and Cramer, 2002), (Seidel et al., 2009)
		Lack of vision, lack of environmental goals and corporate values, lack of specific goals for specific processes/products	(Amrina and Yusof, 2012), (Bey et al., 2013), (Pajunen et al., 2013), (Johansson, 2002)
	Employees	Negative employee attitudes, limited environmental motivation and awareness among employees	(Amrina and Yusof, 2012), (Post and Altma, 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)
		Lack of human resources and time	(Hillary, 2004), (Chan, 2008), (Bey et al., 2013), (Zhu et al., 2011), (Shi et al., 2008), (Ammenberg and Sundin, 2005), (Seidel et al., 2009)

		Resistance to organisational change and operational inertia	(Amrina and Yusof, 2012), (Post and Altma, 1994), (Murillo-Luna et al., 2011), (Sarkis et al., 2007)
		Insufficient technical and environmental training, education and reward systems	(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)
		Lack of support and guidance, limited in-plant expertise/capability	(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)
Legal	Legislation and regulation	Difficulties associated with the process of applying/complying with legislation and/or EMS	(Hillary, 2004), (Chan, 2008), (Murillo-Luna et al., 2011), (Amrina and Yusof, 2012), (Pajunen et al., 2013)
		Lack of or low environmental enforcement	(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, 2013), (Zhu et al., 2011), (Seidel et al., 2009), (Bey et al., 2013)
	Methodology and measurement	Lack of clarity, know-how, methodologies and processes	(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, 2013)
		Lack of effective approaches and measures to evaluate sustainability, difficulties in quantifying sustainability	(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)
Informational	Communication	Poor communication	(Post and Altma, 1994), (Murillo-Luna et al., 2011), (Ammenberg and Sundin, 2005), (Pajunen et al., 2012)
		Limited intra-organisational cooperation and interaction	(Sarkis et al., 2007), (Simpson, 2008)
	Uncertainty and risk	Uncertainty about potential results, market benefits, performance impact and environmental benefits	(Hillary, 2004), (Shi et al., 2008), (Zhu et al., 2011), (van Hemel and Cramer, 2002), (Post and Altma, 1994), (Murillo-Luna et al., 2011), (Mittal and Sangwan, 2013), (Luken and Van Rompaey, 2008), (Koho et al., 2011), (Moors et al., 2005), (Pajunen et al., 2013), (Simpson, 2008)
		Uncertainty regarding future legislation	(Mittal and Sangwan, 2013)
	Information	Lack of information, e.g., environmental legislation or collection and disposal options	(Shi et al., 2008), (Murillo-Luna et al., 2011), (Ammenberg and Sundin, 2005), (Post and Altma, 1994), (Bey et al., 2013), (Pajunen et al., 2013), (Luken and Van Rompaey, 2008), (Seidel et al., 2009), (Allwood et al., 2011), (Simpson, 2008), (Mittal and Sangwan, 2013), (Zhu et al., 2011), (Moors et al., 2005)

Social	Preference and demand	Lack of market preference and customer demand	(Shi et al., 2008), (Rashid and Evans, 2010), (Mittal and Sangwan, 2013), (Koho et al., 2011), (Zhu et al., 2011), (van Hemel and Cramer, 2002), (Pajunen et al., 2012), (Seidel et al., 2009), (Bey et al., 2013)
		Low public pressure, lack of demand from shareholders, investors and community	(Mittal and Sangwan, 2013), (Shi et al., 2008), (Seidel et al., 2009), (Pajunen et al., 2012), (Koho et al., 2011), (Bey et al., 2013), (Post and Altma, 1994)
	Understanding and perception	Inaccurate perceptions of EMS, material value and reused/recycled material	(Pajunen et al., 2012), (Hillary, 2004), (Chan, 2008), (Seidel et al., 2009), (Allwood et al., 2011), (Simpson, 2008)
		Lack of awareness, understanding, knowledge and experience with environmental issues	(Post and Altma, 1994), (Ammenberg and Sundin, 2005), (Seidel et al., 2009), (Koho et al., 2011), (Zhu et al., 2011), (Moors et al., 2005), (Amrina and Yusof, 2012), (van Hemel and Cramer, 2002)

The literature review further revealed that environmental barriers range from general issues, such as "financial and economic barriers" or "limited intra-organisational 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.

The most-cited barriers (and associated issues) 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) low commitment and support from top management; (5) unclear/weak strategic and business goals; (6) employee attitude, motivation and awareness; and (7) lack or scarcity of advanced technology and equipment with lower environmental impacts. The majority of the cited barriers are internal, i.e., they are dependent upon each organisation’s characteristics. The most influential barrier clusters related to material efficiency of residual material in manufacturing are *Budgetary*, *Information*, *Management* and *Employees*.

4. Empirical findings

This chapter presents findings from the case studies on material efficiency practices in manufacturing industry in Sweden. First, implementation of material efficiency strategies within manufacturing industry is analysed. Then, empirical results related to existing state of material efficiency, particularly with regards to waste segregation are presented, followed by related barriers. This chapter ends with results concerning environmental and economic perception regarding material efficiency.

4.1. Implementation of material efficiency strategies

In empirical study B, thirteen interviewees from five companies identified the material efficiency strategies that are being implemented at their respective companies (see table 7). Numerous employees were interviewed, including environmental coordinators/environmental management, operators, manufacturing engineers, plant directors and production managers. The extent of the strategies' implementation is described in table 9, as presented in Paper III.

Table 9 - Implemented material efficiency strategies (presented in Paper III)

Familiarity	Not known at all	Known by one or two interviewees	Implemented at two or three companies	Implemented at all five companies
Strategy	• Product stewardship • Reverse logistics	• Industrial ecology • Material flow cost accounting • Eco-efficiency	• Eco-design • Cleaner production • Eco-mapping • Waste hierarchy • Closed-loop • Life cycle assessment • Resource efficiency	• Environmental management system • Best practice • Waste minimisation

According to these results, there are few material efficiency strategies that are being practiced by all five case 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 Minimisation* activities are undertaken primarily to comply with legal requirements, which is not a proactive step. In general, *Waste Minimisation* is the first step towards material efficiency due to its simplicity and its explicit goal of waste reduction (Abdul Rashid et al., 2008).

The participating companies have mature practices characterised by lean implementation and elimination of the seven Muda. As stated by the interviewees, lean philosophy not only helps improving the delivery performance, reducing the 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 include waste elimination - primarily referring to wasted time, not material waste (Kurdve et al., 2014) - the involvement of all employees in continuous improvement, visualisation and "go to Gemba". Thus, the companies' existing practices might have affected the results.

The results indicate that these companies can still consider and/or implement additional material efficiency strategies. Based on this empirical finding, two hypotheses are proposed. First, there is insufficient implementation of material efficiency strategies in Sweden's manufacturing industry. This insufficiency is probably due to the lack of hands-on, easy-to-use and easy-to-visualise strategies for the operational level. This hypothesis is also consistent with the results presented in section 5.1, which clearly demonstrate the lack of hands-on, easy-to-use and easy-to-visualise strategies for the operational level. This hypothesis does not necessarily mean that Sweden's manufacturing industry does not take material efficiency into account at all; rather, it simply implies that material efficiency is not the top priority in manufacturers' environmental activities, goals and visions. Second, industry and academia use completely different terminology to discuss material efficiency activities. This hypothesis might indicate a lack of sufficient collaboration and cooperation between industry and academia with respect to material efficiency.

The results also suggest that strategies with certain attributes and criteria (e.g., easy-to-use, hands-on, and having clearly defined and direct goals) are the most-implemented strategies. Therefore, a lean company is most likely to have the potential for material efficiency improvements because a company culture of continuous improvement, engagement and waste elimination already exists.

4.2. Industrial waste and material efficiency assessment

This section presents results from observations, interviews and deployment of Waste Flow Mapping (for details, see Papers III and IV). Waste Flow Mapping has proven to be a valuable tool both for analysing the existing state of material efficiency and industrial waste management and for identifying potential improvements in material efficiency at manufacturing companies.

The results presented in this section rely on a multiple case study (empirical study A) conducted at four Swedish manufacturing companies. The purpose of this study was to obtain a clear picture of the existing state of material efficiency and industrial waste management in Sweden's manufacturing industry.

1. At each case company, waste streams and waste generation points were eco-mapped; figure 8 is an example of that eco-mapping.

2. Data were gathered regarding the number and type of waste bins and fractions, man-hours dedicated to waste management services, visualisation and related 5S activities, and internal waste handling from operations to environmental stations. Additional information regarding off-site transportation of waste fractions and segments by waste-handling contractors was also investigated. However, detailed information about the costs of operations and waste handling activities- -including

segregation, internal and external transportation, and in-house and off-site disposal - was not fully collected due to confidentiality concerns.

Figure 8 - Example of an eco-map performed as a part of Waste Flow Mapping (adapted from Paper IV)

3. An initial (overall) segment sorting rate was calculated for the non-hazardous waste segment to determine what proportion of the material was segregated into high quality fractions. Figure 9 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). Both hazardous and fluid waste were excluded from further study. The metals segment primarily included aluminium, 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.

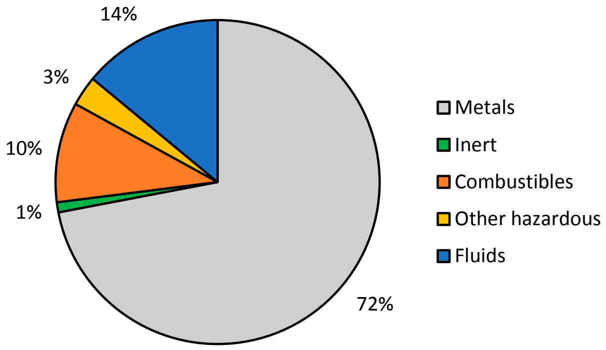

Figure 9 - Volume of waste by segment (presented in Paper IV)

The segment sorting rates were calculated by dividing the segregated portion of each waste segment by the total waste generated in each segment, including both sorted and mixed waste.

$$\text{Segment sorting rate (\%)} = \sum \text{sorted} / (\sum \text{mixed} + \sum \text{sorted})$$

4. Waste sorting analyses were performed to investigate the potential for segregating more high-quality fractions from the mixed- or low-quality fractions. The analyses showed that the segregation rate varied among both the companies and the materials. The volumes of inert materials at the investigated operations were low and therefore were omitted from further analysis.

Table 10 - Overall segment sorting rates (appended Paper III)

Segment sorting rate	**Metals**		**Inert**		**Non-inert/Combustible**	
	sorted	mixed	sorted	mixed	sorted	mixed
Company CC1	31%	69%	100%	0%	60%	40%
Company CC2	97%	3%	0	100%	57%	43%
Company CC3	96%	4%	100%	0%	94%	6%
Company CC4	68%	32%	96%	4%	41%	59%

5. Based on the eco-maps and following the waste sorting analyses, random waste bins from different operations within the case companies were closely examined. The waste contained inside each analysed bin was weighed to calculate the proportions of different material fractions. Initial observations showed that the majority of industrial waste fractions are being segregated by the case companies in accordance with local standards; although some incorrectly segregated fractions were observed, only a few were rated as important. Some of the pure segregated bins were also contaminated with an incorrect fraction/material. According to personnel and observations, the primary reasons for incorrect waste segregation were technical problems, specific circumstances, inadequate information sharing, the presence of different functions and actors, weak 5S activities and visualisation (i.e., incorrect or hidden labels or incorrect bin locations), and operator unwillingness to contribute due to a lack of incentives, exhaustion, indolence and/or weariness.

The results of the detailed analysis of the contents of twenty-three waste bins are summarised in table 11. The numbers inside each cell represent the percentage of that fraction in the respective bin. The data in this table indicate that on average, only approximately 43% of the content in the combustible bins comprised materials that were required to be segregated as combustible and household waste according to standards; 16% of the content could have been segregated as biodegradable material. Approximately 26% of the materials in the combustible bins were plastics; therefore, there is significant potential to segregate plastics, a practice that has both economic and environmental benefits. In addition, approximately 8% and 6% of the content in the combustible and household bins were paper and cardboard, respectively, which

Table 11 - Waste sorting analysis

Type of bins	**Company CC1**								**Company CC2**					**Company CC3**				**Company CC4**					
	Combustible	Combustible	Combustible	Combustible	Household waste	Household waste	Combustible	Metal **scraps**	Combustible	Metal **scraps**	Combustible	Combustible	Combustible	Combustible	Plastic	Combustible	Combustible	Combustible	Combustible	Metal **scraps**	Combustible	Combustible	Combustible
Cardboard		4	8	17			13		23		1			27		11	8	3			36	1	3
Metal scraps								99		98	1		5	12		6		2		94	7	1	
Hard plastic	26	22					8		27		38	12	66		21		4	3	71		10	10	
Soft plastic	67	8	22	28				0.2	4			25		3	73		4	40	17		4	4	1
Hazardous material		35	54	32				0.4		2	35			4			3						
Household waste		20	4	3	10	91			31		2	13	8	24		8	20	28				3	94
Combustible	4	11	12	20	90	9	79	0.4	5		20	33	18	30	5	43	37	22	12	6	13	66	1
Paper	3								7		3	17	3		1	28	24	2			30	15	1
Wood																4							
Landfill									3														
Total Percentage	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Total weight (kg)	2.3	8.3	1.1	1.2	1	3.5	2	144	38	95	7.8	1	3.4	3.7	4.5	5.1	3.8	16	8.1	325	12	7	25

could have been segregated further. Small portions of other types of waste - including wood, tin, metal scraps, metal chips, coffee grounds and hazardous waste - were also found in the bins labelled for combustible and household waste, accounting for an average of 17% of the content in the bins labelled for combustible and household waste. There are both economic and environmental benefits to be gained from segregating the aforementioned materials from combustible bins.

Despite the errors found in some combustible bins, it was generally found that hazardous waste was treated in compliance with internal company rules, primarily as a result of legislation and legal reporting. It was also apparent that metal fractions were handled appropriately. In general, the justification for the high degree of metal segregation and recycling is increased demand for recycled metals because of quantitative shortages and scarcity, increasing metal prices, severe environmental pollution and large carbon footprints resulting from the extraction and provision of metals, and substitution difficulties (Norgate and Rankin, 2002). In addition, the studied companies use metals as their main product material; understandably, the metal segment is relatively important to them and thus the segregation and recycling rates for metals were higher than those for residual material.

Nevertheless, the results pinpointed improvement opportunities in further segregation of waste material, particularly, mixed-metal waste and mixed-plastics. A waste sorting analysis on a bin at one of the case companies is presented in figure 10. As shown, only 28% of the bin is truly mixed scrap; 34% is cast iron, and 7% is aluminium, both of which can be segregated into separate fractions.

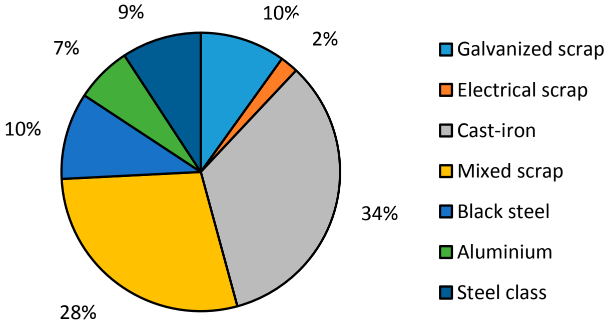

Figure 10 - Waste sorting analysis of the contents of a mixed-metal scrap bin (appended Paper III)

Plastics can also be further segregated as polystyrene (PS), polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP), polytetrafluoroethylene (TPFE) and rubber. Figure 11 shows the total proportions of different types of plastics in the performed waste sorting analysis. 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. 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 bit more expensive, complex and energy consuming compared to metal recycling processes.

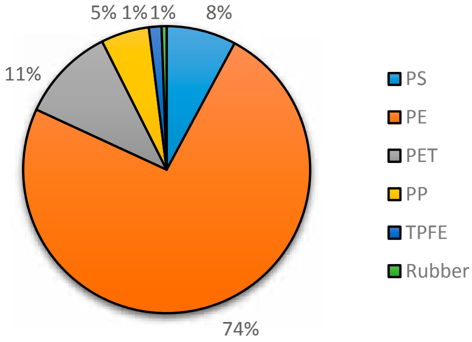

Figure 11 - Proportions of different types of plastics based (appended Paper III)

4.3. Barriers for improved material efficiency

Section 3.6 presents the theoretically identified generic barriers to environmental sustainability strategies. In this section, those generic barriers are narrowed down to include only the barriers to material efficiency that were identified through empirical studies and interviews. The results are presented in table 12. During empirical study D, eleven semi-structured interviews at three manufacturing companies were conducted. The interviewees included environmental managers, plant directors, production leaders and operators. Interviewees were questioned about existing barriers to waste generation reduction, increased homogeneity of residual material and reduction of total virgin material input. Each interviewee answered according to his or her own experience and current position related to industrial waste management and material efficiency; as a result (and as intended), a broad perspective was obtained.

Table 12 - Barriers identified in empirical study D (See Paper III)

Barriers		Evidence from empirical studies
Technological	Engineering	Insufficient waste volume Contamination of waste Incorrect ordering system Insufficient number of bins Engineering barriers, e.g., layout Low volume of new material Design constraints, e.g., quality versus environment for packaging or function versus environment for products Material substitution
	Technology, machine and equipment	Old technology, machines and equipment and nonconformity with new techniques

	Environmental tools	Lack of relevant/suitable tools for environmental initiatives
Economic	Budgetary	Economic limitations and inadequate economic incentives
	Material and product cost	---
Organisational	Management	Higher priority of other issues or requirements, e.g., production expansion/market share
		Limited top management commitment and support for sustainability initiatives
		Limited environmental awareness of directors
		Lack of support and guidance, limited in-plant expertise/capability
	Supplier	Different plant involved in outsourcing
		Supplier quality
		Packaging standardisation
		Overseas supply chain constraints
		Uncooperative supplier
	Vision and culture	Unclear/weak business model
		Lack of vision, lack of environmental goals and corporate values
	Employees	Lack of resources (time and human)
		White-collar oversight
		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 low environmental enforcement
		Lack of assistance from government agencies
		Lack of sufficient ambition to go beyond regulations and legislation
	Methodology and measurement	---
Informational	Communication	Lack of or incorrect visualisation and 5S, e.g., incorrect or hidden labels, incorrect bin locations
		Lack of communication
		Lack of eco-design and communication with product development
	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

4.4. Environmental and economic perceptions

This section presents the results of empirical study C, the purpose of which was to assess individuals' intuitions and perceptions regarding the environmental and economic impacts of industrial waste fractions, segregation and recycling (Papers VI and VII). Thirty-one people involved in environmental research were asked to rank the following common industrial waste types: mixed plastics, sorted soft plastics, sorted hard plastics, aluminium, mixed metal scraps, glass, cotton, steel, wood, cardboard, paper, compostable, mixed combustibles and electronic waste. The respondents were first asked to rank these waste fractions according to their environmental impact and then to rank them according to their (economic) cost per weight. Complementary information and pictures relating to each industrial waste type were provided to the respondents (figure 12).

Figure 12 - Common industrial waste fractions

Understanding individuals' waste segregation and management behaviour provides insight into both why degrees of waste segregation differs among individuals and companies and why more waste is not recycled. The results are particularly interesting because they indicate both that materials are perceived very differently by different individuals and that certain materials are perceived as more or less important than they actually are. These discrepancies can be further analysed to enable more-effective targeting of waste management efforts. These results can be used primarily to indicate the need for specific educational and encouragement efforts and to show environmental alignment and misalignment for specific waste fractions.

The Homogeneity of industrial waste is directly connected to environmental behaviour during operations. Homogeneity of industrial waste is also directly connected to awareness, clear instructions, visualisation, and waste management activities that are sufficiently convenient for personnel. Intuition and knowledge regarding waste handling, segregation, and treatment operations are the most important factors (Oskamp et al., 1991, Barr and Gilg, 2007).

Figures 13 and 14 depict the environmental and economic ranking results, respectively, for participants' perceptions of the five most important material fractions for segregation and further recycling. The ranked waste materials were given a score from 1 (for the most important) to 5 (for the fifth-most important); materials that were ranked lower than fifth were given a score of zero (i.e., materials that were ranked lower than fifth-most important were excluded from the graph). The x-axis depicts colour-coded material fractions; the y-axis shows the scores between 1 and 5 (based on importance); and the bubbles' sizes represent the number of scores. For example, figure 13 (environmental perception) demonstrates that three fourths of the participants (23 participants) ranked aluminium as the most important fraction (given a score of 1) to be segregated and recycled, whereas cotton was ranked as the most important fraction (given a score of 1) by only one participant.

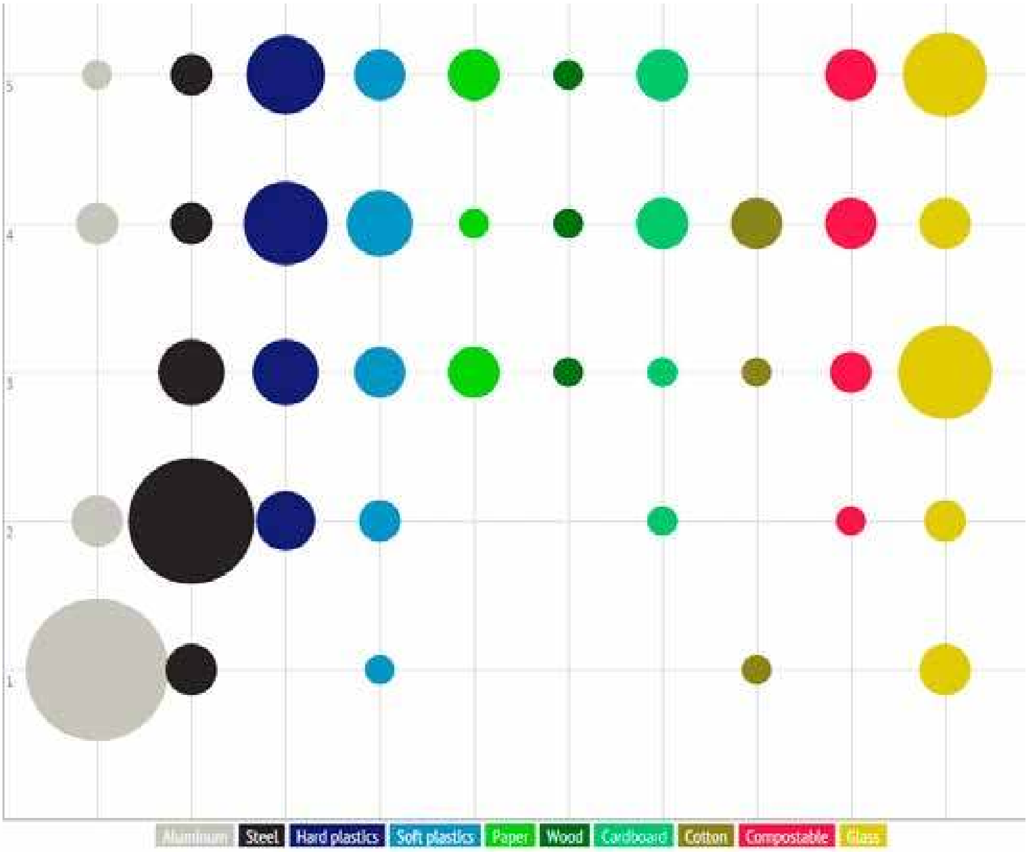

Figure 13 - Environmental ranking results

As shown in figures 13 and 14, the rankings are scattered and the responses vary greatly among the various individuals and groups (see also Shahbazi et al. (2014) and Bjelkemyr et al. (2015)). Ranking all of the material fractions within the top-five fractions indicates that there is no understanding or certainty about the prioritisation of fraction segregation and recycling. In other words, one can conclude that the environmental and economic benefits of recycling are non-intuitive and that the knowledge level is low.

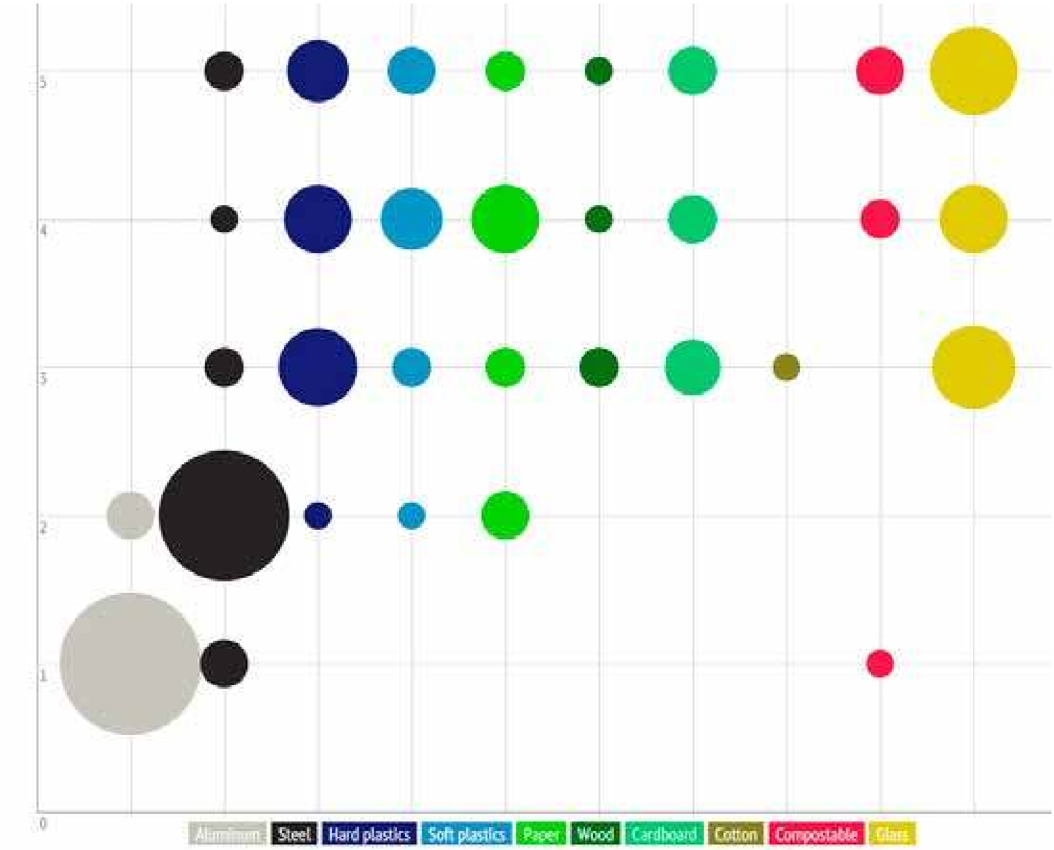

Figure 14 - Economic ranking results

However, a consensus does exist regarding the ranking of metal-based fractions; the segregation and recycling of metal-based fractions was ranked very high in terms of both environmental and economic benefits. Furthermore, the results show a correlation between the perceived environmental and economic benefits of metal-based fractions.

On the other hand, no clear pattern regarding residual material could be detected in either of the graphs. Among the residual materials, hard plastics and glass have a clearer pattern from both environmental and economic perspectives, where more than half of the participants ranked them as the top five most important. The correlation between the environmental and economic benefits of fractions is not well established. The results indicate that the participants' lack of understanding regarding environmental benefits is more severe than their lack of understanding regarding economic benefits.

Figure 15 illustrates the CO_2 equivalent environmental impact of the selected fractions, calculated by life cycle assessment (Simapro software). In the analysis of CO_2 equivalents, cotton has the highest environmental impact; however, only five respondents have included cotton on their top-five list. In contrast, respondents considered glass as the third most important material, but the environmental assessment (figure 15) shows that it has a lower impact than hard and soft plastics.

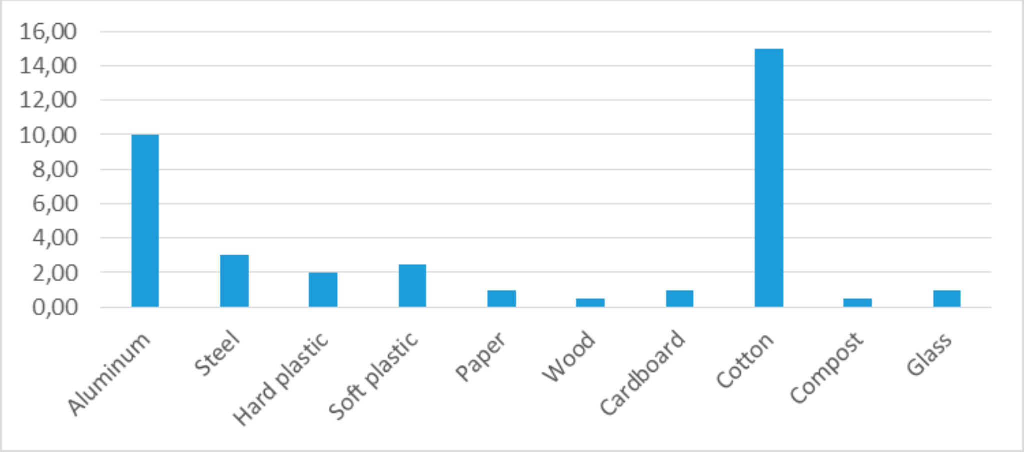

Figure 15 - CO_2 equivalent for the ten waste materials

To sum, the environmental and economic benefits of recycling are non-intuitive and the knowledge level is low. A consensus exists regarding the ranking of metal-based fractions; both in terms of environmental and economic benefits, however, no clear pattern regarding residual material could be detected. The data and the analysis show that plastics are generally underestimated, and the rank of both cotton and glass do not correlate with the LCA analysis. Moreover, the study shows that there is a limited difference between the perceived environmental and economic impact.

5. Analysis and discussion

This chapter discusses the theoretical and empirical results in the context of the research questions. First, the identified material efficiency strategies are compared and discussed (RQ1). Then, based on the empirical results, the existing state of material efficiency in Sweden's manufacturing industry is discussed, and improvement potentials are pinpointed (RQ2). This chapter concludes with a discussion of barriers to material efficiency (RQ3).

5.1. Comparison of material efficiency strategies

In the manufacturing industry, there are various environmental sustainability strategies to improve material efficiency. However, as noted in previous research, these strategies are insufficiently clear in terms of scope, requirements, product life cycle, contribution and end-of-life stage. Research question 1 thus relates to environmental sustainability strategies that support material efficiency, taking into account different criteria. Table 13 presents the identified material efficiency strategies and compares them using various criteria (for more detail, see Papers I and III). The categorisation of strategies in terms of the different criteria was based on subjective assessments made after the pilot study and literature review A, both of which address environmental sustainability strategies in manufacturing.

The *Scope criteria* simply indicate the extensiveness and organisational level of the strategy. Strategies at the managerial level embrace broader dimensions, whereas strategies at the operational level focus more on actions related to daily routines, operations and production. The majority of material efficiency strategies are discussed and decided at the managerial level and filter down to the operational level if necessary. Operational-level strategies also relate to management issues, but their contribution and application have a greater impact on operations. In general, management-level strategies are more difficult to implement, measure and evaluate because they encompass a broader perspective and their indicators are both elusive and difficult to define.

The *Material efficiency contribution criteria* relate to the effects of strategies. Material efficiency in manufacturing aims to reduce the total consumption of virgin raw material in the manufacturing industry, reduce the waste generated by manufacturing companies, and enhance the homogeneity of generated industrial waste (i.e., increase waste segregation). Material efficiency goals are connected to one another 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. Thus, these criteria reflect the contributions of various material efficiency strategies to specific goals.

Table 13 - Comparison of material efficiency strategies (presented in Paper III)

	Material Efficiency Strategies	Cleaner production	Waste minimisation	Eco-efficiency	Life Cycle Assessment (LCA)	Best practice (including lean)	Closed-loop	Industrial ecology	Reverse logistics	Resource efficiency	Product stewardship	Environmental management system (EMS)	Eco-mapping	Waste hierarchy	Material Flow Cost Accounting (MFCA)
Scope	Management			✓	✓		✓	✓	✓	✓	✓	✓		✓	✓
	Operation	✓	✓			✓							✓		
ME contribution	Increase homogenous quality of waste		✓		✓	✓	✓	✓					✓		
	Decrease waste volume	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Decrease total raw material consumption	✓		✓	✓		✓	✓	✓	✓	✓	✓		✓	
Requirements	Technological	✓	✓					✓		✓				✓	
	Management/decision making		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓
	Process improvement	✓	✓			✓	✓	✓	✓	✓		✓	✓	✓	✓
	Raw material substitution	✓	✓		✓		✓			✓		✓		✓	
	Mindset		✓		✓	✓				✓				✓	
	Political action/legislation			✓					✓	✓	✓				
Product life cycle	Design			✓	✓					✓					
	Material extraction and processing	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	
	Manufacturing	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓
	Use/consumption			✓	✓				✓	✓					
	End of life			✓	✓		✓	✓	✓	✓	✓			✓	
End-of-life	Landfill				✓									✓	
	Energy recovery				✓			✓						✓	
	Recycling		✓		✓		✓	✓	✓	✓	✓	✓	✓	✓	
	Reusing		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
	Reduction	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓
	Prevention	✓	✓	✓	✓	✓				✓		✓		✓	✓

The *Requirements criteria* address each strategy's prerequisites. Strategies might be based on technological shifts towards more advanced, cutting-edge machines and equipment or better (environmental) management and decision making. Some strategies might focus on process improvement and modifications to production systems (Wiktorsson et al., 2008), whereas others might address substitutions of materials whose extraction, processing, manufacturing and use phases have less environmental impact. Certain strategies challenge existing mindsets and encourage new ways of thinking (for instance, life cycle thinking), whereas others promote new, more concrete legislation.

The *Product life cycle criteria* show the direct link between a strategy and a specific product life cycle phase. A product's life cycle includes the following stages: product design, extraction and processing of virgin material, manufacturing, product consumption and, ultimately, end-of-life and disposal.

The *End-of-life criteria* relate to various disposal options. The disposal options encouraged by each strategy vary. In general, LCA and waste hierarchy strategies promote prevention, reduction, and avoiding landfills.

According to the results, most material efficiency strategies are suitable for the management level. Bearing in mind that managerial-level strategies embrace broader dimensions and are difficult to implement, measure and evaluate precisely, it is not practical to implement them at the operational level, where raw material is consumed and the waste is generated. The lack of hands-on strategies for the shop floor and operations is obvious; although some operational strategies do exist.

The results also indicate that there is no strategy that either incorporates all possible material efficiency contributions or covers all product life cycle phases. Consequently, material efficiency strategies must be integrated to not only include the entire product life cycle but also contribute to reductions in total virgin raw material consumption and waste volumes and enhance the homogeneity of waste.

Various types of prerequisites are necessary to achieve material efficiency goals. Each single prerequisite plays a small part in material efficiency improvement, although the roles of management and process improvement are more significant than other prerequisites. Nevertheless, all prerequisites must be implemented simultaneously to improve material efficiency. Increased management commitments to environmental goals, continuous process improvements, substitution of environmentally friendly materials for hazardous materials, more concrete (material- and waste-related) legislation and increased enforcement, more widespread environmental and/or life cycle thinking, and minor technological improvements must work together to enable higher levels of material efficiency among manufacturing companies.

Most strategies focus on *recycling*, *reusing* and *reduction* (see the waste hierarchy depicted in figure 6). Although such strategies indicate a positive trend, achieving a zero waste vision and the complete elimination of environmental impact require material efficiency activities to be moved further up in the hierarchy, towards the *prevention* of using ever more resources. The dominance of waste *reduction* among these strategies is to be expected because waste reduction has a direct effect on manufacturing activities and reduces the volume, cost and complexity of waste. Therefore, non-environmental benefits might provide an incentive for manufacturing companies to focus more on reduction.

Overall, achieving material efficiency goals requires a structured approach that incorporates the best use of existing strategies to address all aspects of each criterion to prevent waste in the first place. The implementation of a single strategy to achieve material efficiency goals is not recommended; on the contrary, manufacturers must integrate multiple strategies to cover all criteria. Corporate environmental managers should achieve material efficiency targets by implementing hands-on strategies at the operations level. Integrated strategies should be deployed on the shop floor to motivate companies to formalise and follow their material efficiency and waste management plans. Most of these actions are not primarily technology driven; instead, material efficiency improvements in the short term might focus on operational improvements, management commitments and the transformation of mindsets (towards life cycle thinking). The re-examination of production processes and operations and the redesign of material flow and production systems are necessary to identify material efficiency opportunities and to enable the remanufacturing, recycling and reuse of waste materials, along with the reduction and prevention of material usage and waste generation. Moreover, taking advantage of other facilities' experiences relating to material efficiency and encouraging relevant communication among stakeholders, staff members, customers and suppliers will facilitate material efficiency.

5.2. The existing state of material efficiency

This section addresses the existing state of material efficiency, i.e., the second research question. Relevant data were collected through empirical studies of four large global manufacturing companies in Sweden. Providing a clear picture of material efficiency will enable manufacturing industries to recognise the potential in material efficiency improvement and recycling activities.

Waste Flow Mapping is a collection of methods based on material efficiency strategies including reverse logistics, cleaner production, the waste hierarchy, material flow cost accounting, environmental management systems, eco-mapping and best practice. It also follows lean principles, including continuous process improvement, and is intended to be hands-on, easy to use and easy to visualise. Along with systematic problem solving and communication, Waste Flow Mapping's incorporation of lean principles is designed for the operational level to improve collaboration and information sharing while covering scattered material efficiency responsibilities (see Paper IV).

According to empirical studies on the existing state of material efficiency among Swedish manufacturing companies, the improvement potential of material efficiency is high, particularly with respect to the segregation of residual material. This improvement potential not only provides environmental benefits but also yields economic advantages. The results indicate that manufacturing companies must ensure the correct segregation of their residual materials. Although residual material derived from productive material (mainly metals) and hazardous material is handled correctly, residual materials derived from non-productive (process) materials, such as packaging from assembly lines, are not segregated in the optimal manner. This deficiency is due to relatively low knowledge and economic incentives related to recycling residual and non-productive material. As illustrated by the empirical results presented in section 4.4, individuals have varied and uncertain perceptions of the environmental impact and economic benefits of common waste fractions in the manufacturing industry. The results also revealed that individuals' understanding of the environmental benefits of segregating industrial waste was less clear than their understanding of the economic advantages.

In addition to waste generation reduction efforts, the avoidance of blending and the correct segregation of different waste fractions are essential steps towards an effective material efficiency strategy. Employee awareness of both correct waste segregation practices and economic/environmental alignments and misalignments, in addition to adequate education, monitoring and visualisation, will facilitate success. Another vital step towards an effective material efficiency strategy is to improve the value of waste fractions, i.e., to have more specific cost-effective fractions. Depending on the industrial operation and its residual and packaging material, more specific segregation can be achieved; for example, mixed metals can be further divided into aluminium, galvanised steel, cast iron, steel and mixed-metal scrap. In general, higher costs are associated with mixed-waste fractions compared with pure segregated fractions; the latter often recoup a larger portion of the original material value (see Paper IV). The differences in value correspond to the cost of segregating valuable material from mixed-waste material. The performed waste sorting analysis in figures 10 and 11 are good examples of the improvement opportunities in further segregation of mixed-metal and mixed-plastics. As shown in figure 10, only 28% of the bin was truly mixed scrap; 34% was cast iron and 7% was aluminium, both of which can be segregated into separate fractions. Figure 11 illustrates that 74% of the plastics were PE and 11% were PET, both of which could potentially be separated into improved/new fractions.

It is necessary both to separate waste flows and to monitor each segment, not only to understand the flow of materials and their ultimate disposal as waste but also to set relevant targets. As suggested in Paper IV, waste can be segmented into metals, inert materials, combustible material, fluid waste and other hazardous wastes. These segments can be further divided into more precise fractions. Table 14 suggests suitable performance measurements for material efficiency to be calculated; (P) represents the produced unit, and (C) and (W) represent cost and weight, respectively.

Table 14 - Suggested performance measurements for waste segments (presented in Paper III)

Segments		**Example of fractions**	**Segment sorting rate (%)**	**Weight per produced unit (ton/#)**	**Average segment treatment cost (SEK/ton)**
Non-hazardous material	Metals	Aluminium, copper, steel, cast iron	Σ segregated / (Σ mixed + Σ segregated)	$W_{\text{(segment total)}} / P$	$C_{\text{(segment total)}} / W_{\text{(segment total)}}$
	Combustible	Paper, cardboard, biodegradable, wood, plastics	Σ segregated / (Σ mixed + Σ segregated)	$W_{\text{(segment total)}} / P$	$C_{\text{(segment total)}} / W_{\text{(segment total)}}$
	Inert materials	Sand, glass, landfill waste	Σ segregated / (Σ mixed + Σ segregated)	$W_{\text{(segment total)}} / P$	$C_{\text{(segment total)}} / W_{\text{(segment total)}}$
Hazardous material	Fluid waste	Oils, chemicals, solvents, glycols, emulsions	Not applicable	$W_{\text{(segment total)}} / P$	$C_{\text{(segment total)}} / W_{\text{(segment total)}}$
	Other Hazardous waste	Electronic waste, fluorescent waste, batteries	Not applicable	$W_{\text{(segment total)}} / P$	$C_{\text{(segment total)}} / W_{\text{(segment total)}}$

In sum, the empirical results from multiple case studies in different manufacturing industries in Sweden indicate that the improvement potential of further waste segregation, in terms of both economic and environmental benefits, is high. The determination of different waste segments and their respective fractions and the calculation of material efficiency performance measures will facilitate operational, waste management and material efficiency. These material efficiency performance measures are consistent with legal requirements and environmental management standards related to the observation and control of waste flows.

5.3. Material efficiency barriers

Empirical studies A and D reveal that manufacturing companies in Sweden encounter several barriers to material efficiency. The identified barriers to material efficiency hinder the achievement of increased homogeneous waste segregation, reduced waste generation and reduced total virgin raw material consumption. To address this issue, the third research question focused on barriers that prevent manufacturing companies from achieving greater material efficiency improvements.

Most of the barriers that were identified empirically are the same as the generic 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 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 of the generic barriers to environmental sustainability strategies, although some additional, specific barriers related to process and residual materials should be added, e.g., detailed knowledge of material science and recycling processes.

Material efficiency in relation to waste management depends both on correct waste segregation and on achieving fractions that are as close as possible to being completely homogeneous. As residual material homogeneity increases, price volatility and opportunities to sell also increase, which yields both economic and environmental benefits. In general, metal fractions are separated and handled appropriately at the studied manufacturing companies, and related recycling is mature. The primary issue is with respect to residual materials, such as plastics, packaging and cardboard, etc., which are not part of the main product and that are less valuable. As raw material costs increase and recycling technologies improve, process and residual materials become more and more valuable. The acquisition of sufficient information, correct segregation, the use of up-to-date technology and the identification of localised markets will increase the recycle or reuse potential of residual material. The primary empirically identified barriers to improved waste segregation are insufficient volume of waste fractions, waste contamination, incorrect visualisation and labelling, 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, due primarily to indolence, weariness and lack of awareness and/or information.

Uncertainty about investment payoffs, market potential, likely results, impact on performance and environmental benefits are other barriers encountered by manufacturing companies. These barriers relate directly not only to a lack of information and knowledge sharing but also to inadequate communication and awareness. More support and guidance by experts, environmental training and education, government financial assistance or tax reductions, and the deployment of life cycle thinking are some factors that will help manufacturers overcome these barriers. With respect to life cycle thinking, the integration of the major elements of LCA into organisational practice remains relatively immature.

Another major barrier to material efficiency is the inability to identify market demand. The majority of recycling/waste management contractors 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. Compounding 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.

Collaboration among companies - i.e., suppliers, customers, retailers and waste contractors - 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 the potential for material efficiency improvement and recycling to facilitate waste segregation, minimise waste and reduce total consumption of virgin raw materials. Lack of information and uncertainty regarding payoffs, alternative disposal options, unrealised material value and potential markets could be resolved through increased interaction within the supply chain.

Swedish manufacturing companies' lack of ambition and motivation to improve their waste segregation and material efficiency activities beyond what is legally required is obvious from the results. 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 and stay a step ahead of the legislation. In other words, manufacturing companies comply with current legislation only to protect themselves from legal penalties. In addition, manufacturing companies have insufficient experience with the implementation of material efficiency strategies. Given manufacturers' past failure to implement material efficiency strategies and the lack of any current motivation for manufacturers to adopt material efficiency strategies, the government should intervene (Allwood, 2013). Note that an idealised, 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 are more likely to enhance material efficiency potential (Allwood et al., 2013). Regardless, increased environmental enforcement is also necessary because companies tend to flout legislation if it is not adequately enforced.

It is crucial to consider all barriers, their effects and their linkages when implementing material efficiency improvements. As illustrated in figure 16 and in Paper III, 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 are linked to insufficient communication, visualisation, education and training; employee oversight; and inadequate time and human resources. A lack of environmental targets and corporate environmental values are associated with limited top management commitment and awareness, a lack of support and guidance throughout the organisation, supplier issues, a weak business model, etc.

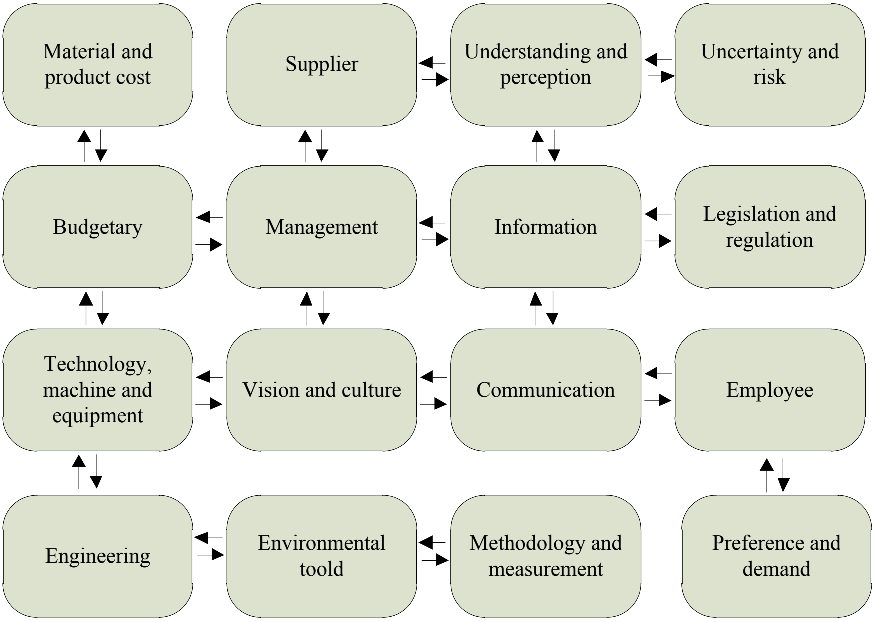

Figure 16 - Linkage between material efficiency barriers clusters (See Paper III)

Clearly, it is not possible to suppress all barriers simultaneously. Therefore, it is necessary for manufacturing companies to prioritise the most significant barriers. The barrier clusters cited most often in the literature are *Budgetary*, *Information*; *Technology*, *Management*, *Vision and culture*, and *Employees*. The empirical results and interviews indicate that the most significant material efficiency barriers in the studied Swedish companies are the same, excluding *Technology* and *Vision and culture*. The reason that *Vision and culture* is not a barrier for Swedish companies is likely that Sweden is an environmentally conscious country, and most companies, particularly those that participated in this research, include environmental care as a core corporate value applicable to their production systems, targets and visions.

Management plays an important role in the implementation of a material efficiency strategy. Personal environmental commitments and/or a brand name associated with environmental management can simulate and effectuate material efficiency strategies. In addition, material efficiency-related regulations can be introduced in decision making discussions both to increase awareness and to present possible potentials.

Most of the identified material efficiency barriers appear to be internal. Internal barriers originate within the company itself and depend on the manufacturing company’s characteristics, whereas external barriers originate outside of the company and are to some extent beyond the company’s control. External barriers relate primarily to (1) suppliers; (2) legislation and legal issues; and (3) market preference and customer demand. A manufacturing company can to some extent directly or indirectly influence or suppress supplier-related barriers. The barriers that prevent manufacturing companies from improving material efficiency exist mainly within the company and thus can be eliminated given sufficient resources (human, time and financial) and better management. This result is inconsistent with the conclusion reached based on the performed literature study, as it conforms with the finding of Post and Altma (1994) and Murillo-Luna et al. (2011). In summary, managerial and employee attitudes, environmental knowledge and motivation, internal company communication and information sharing, and a company’s core values and vision facilitate material efficiency improvement.

6. Summary and conclusions

This chapter begins by summarising the research's findings, followed by a discussion of the research objective fulfilment. 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. Summary of research findings

Population growth, increasing wealth, key resource consumption, higher prices for products and raw materials, and the scarcity of raw materials suggest that more virgin raw materials will be extracted in the coming years. The environmental burden of such an increase will be considerable in terms of waste generation, energy consumption, emissions generation and global warming. A key approach both to prevent and control this future dilemma and to contribute to sustainable development is improving material efficiency, which can help both to reduce (or ideally to prevent) the production of new materials and to reduce total material demand.

Various strategies that support material efficiency in the manufacturing industry were identified. These strategies must be integrated to address different criteria. In addition, the strategies must be hands-on, easy to use and easy to visualise to effectively support process improvements, visualisation, simplicity, communication, collaboration, and information sharing while fulfilling scattered material efficiency responsibilities.

Empirical results from the case studies conducted in different manufacturing industries in Sweden reveal the improvement potential of further waste segregation in terms of both economic and environmental benefits, particularly with respect to the segregation of residual material. Through material efficiency, the value of process and residual materials and their improvement potentials are taken into consideration. Determining different waste segments and their relative fractions and calculating material efficiency performance measures will facilitate material efficiency and operational and waste management.

In addition to efforts to reduce waste generation, avoiding blending and correctly segregating residual and productive material are essential steps towards material efficiency improvement. Although residual materials derived from productive materials (mainly metals) and hazardous materials are handled correctly, residual materials derived from non-productive (process) materials, such as packaging from assembly lines, are not segregated in the optimal manner. This deficiency is due to the generally lower knowledge levels and economic incentives related to the recycling of residual and non-productive material. Employee awareness regarding correct segregation and economic/environmental alignment and misalignment, along with sufficient education, monitoring and visualisation, are some possible facilitators of material efficiency improvements. Improving the value of waste fractions, i.e., creating more specific, cost-effective fractions, is also vital. In general, higher costs are associated with mixed waste fractions instead of with pure segregated fractions, which often recoup a larger portion of their original material value. The differences in value correspond to the costs of segregating valuable material from the mix.

Numerous barriers to material efficiency were identified. The identified barriers are related to one another and thus cannot be considered or eradicated separately even though it is impossible to overcome all barriers simultaneously. The empirical results indicate that the most important barriers to material efficiency are within the clusters *Budgetary*, *Information*, *Management* and *Employees*. The literature study on barriers to environmental sustainability identifies the same barriers, along with *Technology* and *Vision and culture.* The majority of identified barriers to material efficiency are internal and originate within the company itself; these barriers thus relate to each manufacturing company's characteristics. Internal barriers can be eliminated with both sufficient resources (including human, time, and financial resources) and better management. Management and employee attitudes, environmental knowledge and motivation, internal communication and information sharing, and companies' core values and vision are the characteristics that will enable material efficiency improvement.

6.2. Review of the research objective and questions

The objective of this thesis was to *contribute to the existing body of knowledge regarding material efficiency in manufacturing* by increasing understanding, describing the existing situation and developing support for improvement. This thesis primarily focused on the value of process and residual materials, with a particular concentration on increasing the homogeneous quality of generated waste through higher segregation rates, decreasing the amount of generated waste material and reducing virgin raw material consumption without influencing the function or quality of a product or process. To fulfil the research objective, the following research questions were formulated:

> *RQ1: What environmental sustainability strategies support material efficiency, considering different criteria?*

Industrial waste and the depletion of virgin material pressure manufacturing companies to find new, viable strategies consistent with environmental, social, and economic sustainability. In recent years, a multitude of environmental sustainability strategies have been developed in both academia and industry to facilitate material efficiency improvement. However, these strategies are insufficiently clear regarding different material efficiency criteria. This research question was formulated to help companies overcome the identified challenges by presenting and comparing relevant environmental sustainability strategies related to material efficiency.

An extensive structured literature review on material efficiency strategies was conducted in the pilot study and literature study A, the theoretical results of which are presented in section 3.5. In addition to empirical study A, empirical study B, regarding existing material efficiency strategies and practices at manufacturing companies in Sweden, was conducted; the results are presented in section 4.1. The identified strategies are compared, and their differences and respective application areas are discussed in section 5.1. The comparison of strategies is based on material efficiency criteria, i.e., scope, product life cycle, requirements, contributions and end-of-life phase.

Appended Paper I contributes to answering this research question and compares the various strategies. However, the results presented in this thesis are slightly different than the results presented in Paper I, primarily due to complementary data collection and knowledge development that occurred later in the research process. Paper III also partially contributes to answering this research question. The main conclusion regarding material efficiency strategies is as follows: to achieve material efficiency goals, the deployment of a single strategy is not recommended; on the contrary, multiple strategies must be integrated by manufacturing companies to address all of the criteria. The empirical investigation also revealed that waste minimisation, environmental management systems and best practice are the most common strategies implemented at manufacturing companies in Sweden; however, these strategies are only the first steps towards material efficiency improvement.

RQ2: What is the existing state of material efficiency in manufacturing?

Because this licentiate thesis involves exploratory research on material efficiency, it was necessary to understand the existing state of material efficiency in the Swedish manufacturing industry to identify improvement potential and existing barriers.

Empirical studies A and C and literature studies B and C contribute to answering this research question. The application of Waste Flow Mapping at multiple manufacturing sites, real-life observation of operations and processes, and interviews of different functions helped to provide a transparent picture of material efficiency in Sweden’s manufacturing industry. The results relevant to this research question were presented in section 4.2 and discussed in section 5.2.

Empirical study C directly contributes to answering this research question by investigating individuals’ perceptions of economic and environmental benefits; the relevant results are presented in section 4.4. Papers VI and VII are also relevant to this study by investigating individuals’ perceptions of the economic and environmental benefits of common industrial waste fractions.

In addition, Papers III and IV contribute to answering this research question. Paper IV relates more to the implementation and development of the Waste Flow Mapping method but is included in this thesis to illustrate the existing state of material efficiency at manufacturing companies in Sweden. Paper III partially addresses the existing state of material efficiency in Swedish industry. The main conclusions regarding this research question are as follows: a lack of knowledge among individuals regarding waste segregation and recycling still exists, and material efficiency improvement potentials remain high, especially concerning the homogeneity of residual materials.

RQ3: What barriers prevent manufacturing companies from achieving higher material efficiency improvement?

After analysing the existing state of material efficiency, barriers that hamper material efficiency improvement must be identified both to increase industrial waste segregation and to reduce waste generation and virgin raw material consumption.

Literature study D and empirical studies A and D contribute to the identification of material efficiency barriers. The theoretical results are presented in section 3.6, and the empirical results are provided in section 4.3. The identified barriers are discussed in section 5.3. The main conclusions regarding this research question are as follows: various barriers to material efficiency have been identified, and the most-cited barrier clusters are *Budgetary*, *Information*, *Technology*, *Management*, *Vision and culture*, and *Employee*. According to the empirical results, the most significant material efficiency barriers in the studied companies are *Budgetary*, *Information*, *Management*, and *Employee*. In addition, most of the identified material efficiency barriers are internal.

Paper III can to some extent be considered a summary of the performed research because it addresses all three of the research questions, particularly the question regarding barriers to material efficiency.

6.3. Scientific and industrial contributions

The ability of material efficiency to improve the recyclability, reusability, reduction and prevention of industrial waste is under-researched despite its contributions to reduced carbon emissions, industrial waste and virgin raw material requirements. This research contributes to science and extends the body of knowledge regarding material efficiency by increasing understanding and describing the existing situation in the manufacturing context, particularly with respect to (1) residual and process material and (2) Sweden's large automotive industry. First, relevant environmental sustainability strategies developed in academia and industry that support material efficiency improvement have been identified, and their characteristics (criteria) have been highlighted. Second, manufacturing companies' current practice of material efficiency management has been described. Third, barriers that hamper the implementation and improvement of material efficiency strategies in the manufacturing industry have been identified. As a result, a better understanding of material efficiency in the manufacturing context has been framed.

The European Commission (2011a), the World Economic Forum (2012) and Mistra (2011) have emphasised that a circular economy and resource efficiency 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.

Exploring material efficiency enhances waste segregation and recyclability and can help the manufacturing industry to climb the waste hierarchy. Understanding the existing state and improvement potentials of material efficiency 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 (the EU baseline target is 20% by 2020), solid industrial waste, the demand for virgin raw material and total energy consumption. There is significant potential in industrial processes to retain high-quality residual material; however, the waste must comply both with legal requirements and with quality demands from recycling companies 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. As a result, suboptimal system solutions are implemented. The full potential benefits of material efficiency can only be realised if the characteristics and barriers that influence its implementation are identified. Improving material efficiency not only provides environmental benefits but also yields both short- and long-term economic advantages.

6.4. Review of the applied methodology

The main aspects of the research quality, including internal and external validity and reliability, were discussed in section 2.3. However, because the research methodology and knowledge evolved throughout the research process, several comments regarding the quality of the research are warranted.

First, the performed research was explorative in nature and thus, material efficiency was broadly investigated. Consequently, sundry paths were occasionally taken. For instance, the literature study in chapter 3 includes aspects beyond the specific scope of the research; however, this literature study was consistent with both the exploratory study and the initial steps of DRM. Nevertheless, in retrospect, the research process could have been more focused (at least in certain respects).

To avoid any bias and errors from the data source side (i.e., companies and interviewees), the interviews and the majority of communications that transpired throughout the empirical studies were conducted in Swedish. Moreover, 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 terms. Furthermore, this research primarily describes the situation at Swedish automotive companies, which use metal as their primary product material and generate common types of waste, e.g., plastics, aluminium, steel, cardboard, wood, hazardous waste and combustibles. Thus, the results may not be generalised to other industries, to similar manufacturing companies outside of Sweden, or to SMEs in Sweden. In addition, most of the studies focused on answering research question two. Better correlation among the research questions is necessary in the future. Although the research was exploratory in nature and different aspects of material efficiency were necessarily addressed, the scattered topics and discrete research questions made it difficult to assemble the pieces.

6.5. Future research

This research was exploratory and aimed to understand material efficiency within the manufacturing context. Therefore, many opportunities exist for further research.

The participating case companies are predominantly large companies in Sweden that are the lead manufacturers in their respective industries. Their products are manufactured, assembled and sold worldwide, and their international reputations and success have forced them to maintain tighter control of environmental issues, including material flows. Thus, there are sets of factors that might be changed in future research, e.g., future researchers might include either SMEs (which generally have less control over environmental issues) or other 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 material or industries that use different primary product materials, such as plastics. In sum, future research might focus on case studies with different variables relating to, for example, company size, industry type product type, and process materials.

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). A lean company is most likely to have material efficiency improvement potential because the adoption of a lean paradigm indicates that a culture of continuous improvement, engagement and waste elimination already exists within 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. 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 a lack of implementation of material efficiency strategies; thus, further study of both the reasons for the lack of implementation and actual implementation processes would be helpful. In addition, further development of strategies to address more criteria and resolve barriers would be fruitful for practitioners and academics alike. For example, further research on both quantitative and qualitative material efficiency performance measures or integration into eco-design of packaging and other supplied material and new business models would be valuable.

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 behaviours. Thus, more detailed research analysing 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 functions are involved in material efficiency management. These scattered responsibilities, their linkages to each other, their respective roles, and communication and information sharing could be further investigated, e.g., within the company itself or between the company and local recyclers and waste management contractors. 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.

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