EXPLORING SUSTAINABLE MANUFACTURING PRINCIPLES AND PRACTICES

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Abstract

The manufacturing industry remains a critical force in the quest for global sustainability. An increasing number of companies are modifying their operations in favor of more sustainable practices. It is hugely important that manufacturers, irrespective of the subsector they belong to, or their organizational size, implement practices that reduce or eliminate negative environmental, social and economic impacts generated by their manufacturing operations.

Consequently, scholars have called for additional studies concerning sustainable manufacturing practices, not only to address the paucity of related literature, but also to contribute to practitioners’ understanding of how to incorporate sustainability into their operations. However, apart from expanding the knowledge of sustainable manufacturing practices, it is first key to understand the ground set of values, or principles, behind sustainable manufacturing operations. For that reason, the purpose of this thesis is to contribute to the existing body of knowledge regarding sustainable manufacturing principles and practices.

The results presented in this thesis are based on three studies: a systematic literature review exploring sustainability principles applicable to manufacturing settings, and two empirical studies addressing sustainable manufacturing practices.

In general, it is concluded from the literature that there is a little knowledge about sustainability principles from a manufacturing perspective. In relation to the most common sustainable manufacturing practices, it is concluded that these practices mainly refer to energy and material management, and waste management. Similarly, the study of the adherence of sustainable manufacturing practices to sustainable production principles concluded that the principles concerning energy and materials conservation, and waste management were found to create the highest number of practices. Although most manufacturers still engage in reactive sustainable manufacturing practices driven by regulatory and market pressures, some industrial sectors were found to be more prone to develop proactive sustainable manufacturing strategies than others. Furthermore, SMEs were found to lag behind large organizations regarding adherence to sustainable manufacturing principles.

Keywords: Sustainable manufacturing principles, sustainable manufacturing practices
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Claudia Juliana Alayón G.
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List of appended papers

This thesis is based on the following papers, which are referred to in the text by their roman numerals. The contributions made by the authors are described for each appended paper.

**Paper I**


Contribution to Paper I: Alayón carried out the literature review and analyzed the theoretical data, together with Säfsten and Johansson. The co-authors provided comments and checked the quality of the paper. Alayón was the corresponding author and presented the paper.

**Paper II**


Contribution to Paper II: Alayón, together with Säfsten, planned the empirical studies, which were carried out by Alayón. The data collection tool was designed by Alayón. The data collection tool was refined by Säfsten. The analysis was a collaborative effort between all the authors. Säfsten and Johansson provided comments and checked the quality of the paper. Alayón was the corresponding author.

**Paper III**


Contribution to Paper III: All the authors contributed to the planning of the empirical studies. Alayón and Sannö designed the data collection tools and carried out the empirical studies. Säfsten and Johansson provided comments and checked the quality of the paper. Alayón was the corresponding author and presented the paper.
Additional publications by the author, but not included in the thesis


Contribution: Alayón carried out the literature review. Säfsten and Johansson provided comments and checked the quality of the paper. Alayón was the corresponding author and presented the work-in-progress (WIP) paper.


Contribution: Alayón, together with Säfsten, planned the empirical studies, which were carried out by Alayón. The analysis was a collaborative effort between all the authors. Säfsten and Johansson provided comments and the quality of the paper. Alayón was the corresponding author and presented the paper.
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Definitions

**Manufacturing**: The interconnected activities and operations involved in producing a single part, or multiple parts to be assembled to form a final product. In manufacturing, raw materials are transformed with the assistance of technology, physical and chemical processes, labor, and tools, into components or final products within manufacturing industries. Therefore, it is possible to state that while all manufacturing is a type of production, all types of production do not always involve manufacturing (adapted from CIRP, 1990; Bellgran and Säfsten, 2010).

**Production**: The process of transforming a set of input elements into a set of output elements with economic value. Production constitutes the outcome of the industrial work in different fields of activity (e.g. agriculture production, music production, oil production, energy production, manufacturing production). The outcome of the production could be either a tangible, or intangible product (production by service). The research presented in this thesis adopts the notion of production as superior manufacturing, since the term production is associated with a branch of industry or line of business (adapted from CIRP, 1990; Murthy, 2005; Bellgran and Säfsten, 2010).

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

**Sustainable manufacturing practices**: The actions, initiatives, and techniques that positively affect the environmental, social or economic performance of a manufacturing firm, helping to control or mitigate the impacts of the firm’s operations on the triple bottom line.

**Sustainable manufacturing principles**: Fundamental values that guide organizational practices relating to the environmental, social and economic sustainability dimensions, with the aim of attaining sustainable manufacturing operations (adapted from Veleva and Ellenbecker, 2001).

**Sustainability principles**: Deal with moving organizations toward sustainability by changing their vision/mission, their use of natural and
human resources, their production and energy practices, and their products and waste management (Shrivastava and Berger, 2010).

**Sustainable production:** “The creation of goods and services using processes and systems that are non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for employees, communities and consumers; and socially and creatively rewarding for all working people” (LCSP, 1998; Veleva and Ellenbecker, 2001).
CHAPTER 1  
Introduction  
This chapter describes the background and the problem area. Also, the purpose and research questions are presented. The chapter ends with the scope and the outline of this thesis.

1.1 Sustainability in manufacturing operations  
Companies are considered to be “key players on the societal path towards sustainability” (Koplin et al., 2007, p. 1060). In the past, most companies have separated sustainability considerations from their own business strategies and performance evaluation; in this way, economic performance indicators have been the main criteria by which companies have been assessed (Clarkson, 1995). This scenario began to change in the late 1980s when a few manufacturing sectors started adopting practices to help with the minimization or elimination of waste. These were the first signs of sustainable manufacturing (Lazlo et al., 2013; Courtice, 2013).

The growing trend of considering sustainability in manufacturing settings is clearly evident in government initiatives, such as the EU’s growth strategy “Europe 2020”, that calls for joint efforts towards a “resource efficient Europe” (European Commission, 2010). This government initiative is aimed at committing both the EU and its member states to this sustainability agenda, supporting the shift towards a low carbon economy, and promoting an increase in the use of renewable energy sources, without compromising energy efficiency (European commission, 2010). Nevertheless, at present, it is not only the policymakers who are pursuing the establishment of a long-term environmental, economically, and socially sustainable society, but also consumers, whose awareness of sustainability issues along all stages of a product’s life cycle has significantly increased (Vermeir and Verbeke, 2006; UNEP, 2012; Nielsen; 2015). These demanding conditions have driven manufacturers to respond to sustainability issues.

Global economies are strongly influenced by the manufacturing sector. This sector is made up by of a large variety of subsectors, ranging from basic to advanced production practices and techniques, involving different sizes of firm, generating development and employment. Data, provided by the statistical classification of economic activities in the European Community (NACE), placed manufacturing as the second largest
economic sector in the European Union (Eurostat, 2012), with approximately 2.1 million companies employing around 30 million people and thereby contributing to 22.4% of employment within the EU non-financial businesses economy (Eurostat, 2012). These statistics reflect how the industrial sector plays a significant role in the economic well-being of Europe (European commission, 2015). However, this sector is also responsible for a variety of negative impacts on global environmental sustainability. As an example of the key role this sector plays in global sustainability, the industry sector consumes the same amount of energy and emits the same level of greenhouse gases as the transport and construction sectors (IEA, 2012; UNIDO, 2014). Still, the energy demands of the industry sector have been growing faster than in any other sector, contrasting with the continuing efficiency gains (IEA, 2012).

One of the most important events that helped to establish and disseminate the sustainability concept was the publication of “Our Common Future” (Brundtland, 1987), in which the first definition of sustainable development was presented. This report is widely known as the Brundtland report in reference to Gro Harlem Brundtland, who chaired the commission to whom this report was presented. In the Brundtland report, the United Nations, or more specifically, the World Commission on Environment and Development, called on countries around the world to assume the responsibility for the anthropogenic impact on the environment. From that point, sustainable development has formed an essential concept that has shaped the manufacturing scenario. The term sustainable development covers the three dimensions (social, economic and environment) that constitute the triple bottom line (Elkington, 1998).

Aware that the production of every product or service has repercussions on the environmental and social dimensions of sustainability, sustainability demands are assumed to be tackled by all type of manufacturers, regardless of their organizational size and manufacturing subsector. The increase in academic research with a focus on sustainability in operations (Corbett, 2009) is a reflection of the strong sustainability demands on manufacturers. However, in the sustainable manufacturing literature, previous studies have mainly addressed sustainability from its environmental perspective (e.g. Seuring and Müller, 2008; Despeisse et al., 2012), and mainly studied large companies (e.g. Gaughran et al., 2007; Seidel et al., 2009). For example, a study presenting short-term projections of the manufacturing scenario in the United Kingdom (Tennant, 2013) stated that manufacturing strategies largely involve energy and resource efficiency programs. In spite of this bias on focusing on the environmental dimension of sustainability within large organizations, there is an
undeniably increasing interest in sustainability from its triple bottom line perspective, from both practitioners and academics.

Recognizing the outstanding and highly visible participation of the manufacturing sector in global sustainability, stakeholders over the years have developed initiatives for integrating sustainable development approaches at company, supply chain and economy levels. An example of this is the EU’s growth strategy Europe 2020, an effort to guide Europe towards a more sustainable, inclusive and smart economy (European Commission, 2010). The concern of manufacturers regarding the impact of their operations on sustainability is higher than it was 30 years ago (Winroth, 2012) but, to meet the EU’s national targets relating to employment, energy/climate change, innovation, education and social inclusion, manufacturers, irrespective of size or subsector, must take decisive action. Apart from governmental pressures for adopting sustainable manufacturing practices, the literature has reported that organizations engaging in sustainable supply chain management practices are also strongly driven by pressure from consumers, workers, investors and unions (Hall, 2000; González-Benito and González-Benito, 2005; Mollenkopf et al., 2010), compliance with legal requirements (Zhu and Sarkis, 2006; Zhu et al., 2008), improvements in the company’s reputation, cost reduction, improvement of overall performance and the creation and maintenance of competitive advantage (Noori and Chen, 2003; González Benito and González-Benito, 2005).

This broad variety of stakeholder pressures for integrating sustainable development into manufacturing, plus the perceived benefits (i.e. economic savings and positive image) derived from environmental and social initiatives (Petrini and Pozzebon, 2010), has shaped the growing trend in firms worldwide for integrating sustainability into their business practices (Jones, 2003; Bielak et al., 2007; Gunasekaran and Spalanzani, 2012). The consequences of these pressures and drivers for sustainability produce the existing challenging scenario for manufacturers. As the pressures grow, there has been a call to clarify what sustainability is from an operational perspective for manufacturers, as well broaden the understanding about the way in which sustainability might be attained within manufacturing organizations. Increasing the knowledge regarding how organizations can operationalize sustainability constitutes a valuable contribution towards the attainment of national and global sustainability goals.
1.2 Problem area

Sustainability demands are assumed to be tackled by all type of manufacturers. However, some manufacturers such as SMEs still lack knowledge of how to attain sustainable manufacturing (Seidel et al., 2009). A basic starting point to support all type of manufacturers aiming at sustainable manufacturing is to broaden the knowledge about what sustainability is from an operational perspective, and to enhance the understanding about the ways in which sustainability can be incorporated by manufacturers, regardless of their size. Following this line of reasoning, by studying sustainable manufacturing principles and translating these principles into practice, it should be possible to connect the conceptual sustainable manufacturing principles with practice.

From a semantic point of view, principles constitute values that guide actions, conducts and organizational practices (Glavič and Lukman, 2007; Shrivastava and Berger, 2010). In the literature, sustainable manufacturing principles have been defined mainly from a broad and conceptual perspective, and have mostly addressed environmental concerns (e.g. Al-Yousfi, 2004; Tsoufas and Pappis, 2006; Lindsey, 2011). Academics have also called for a better understanding of the empirical reality surrounding the adoption of these sustainability principles among organizations (Shrivastava and Berger, 2010). Furthermore, further studies of sustainability principles from an operative perspective and taking a triple bottom line approach are necessary in order to address this knowledge gap.

Using the manufacturing lens, sustainable production principles have been associated with guiding and moving companies closer to a sustainable production state by addressing aspects such as resource use, energy practice, product and waste management, thereby making companies more responsive to sustainability demands (Shrivastava and Berger, 2010). The literature presents some studies that discuss sustainability principles from an operative perspective (Gladwin et al., 1995; Al-Yousfi, 2004; Tsoufas and Pappis, 2006; Lindsey, 2011; Despeisse et al., 2012). However, only two of these studies introduced sets of sustainability principles addressing the three dimensions of sustainability (Veleva and Ellenbecker, 2001; Despeisse et al., 2012), with none of them including empirical data on the operationalization of the principles from the perspective of both large companies and SMEs.

To this point, it is clear the importance of exploring sustainable manufacturing principles for a deeper understanding of the sustainability demands, as well as taking the opportunity to research the whole manufacturing sector in a more comprehensive manner by including
manufacturing companies regardless of their size. Now, let us consider the other aspect dealt in this thesis: sustainable manufacturing practices.

The study of sustainable manufacturing practices is critical in broadening the understanding of how sustainability might be incorporated into manufacturing operations. According to Roberts and Ball (2014), many sustainable manufacturing practices are being overlooked at a factory level because they are not being reported at all within academic and industry literature. Nevertheless, it would appear from the published body of studies on sustainable manufacturing practices, that further studies of this subject are needed (Despeisse et al., 2012; Roberts and Ball, 2014).

The literature on sustainable manufacturing practices has predominantly focused on the environmental dimension of sustainability (e.g. Montabon et al., 2007; Yüksel, 2008; Despeisse et al., 2012; Schoenherr and Talluri, 2013; Singh et al., 2014; Roberts and Ball, 2014). Most studies have been of large companies (Petrini and Pozzebon, 2010). Consequently, there are a significantly smaller number of studies about sustainable manufacturing practices in small and medium-sized enterprises (SMEs) (e.g. Biondi and Iraldo, 2002; Vives, 2005; Lawrence et al., 2006). The current body of studies also shows how little attention research into sustainable manufacturing practices in SMEs has received among scholars (e.g. Kurapatskie and Darnall, 2013).

Based on the above, and on the evident imbalance of research with respect to organizational size, it can be stated that there is a need for further studies exploring sustainable manufacturing practices from a triple bottom line perspective and using a representative/inclusive empirical sample of the manufacturing sector (i.e. equally involving companies regardless of their size). Correcting this paucity of research into sustainable manufacturing practices is required not only to obtain a comprehensive understanding of how the manufacturing sector is adapting its operations to be more responsive to sustainability demands, but also to help companies achieve sustainability objectives (Roberts and Ball, 2014). As further studies of the operationalization of sustainable manufacturing principles and sustainable manufacturing practices are needed, a way of connecting these two areas may be by exploring how manufacturers’ operations (practices) adhere to sustainable manufacturing principles. Increased knowledge about the connection between sustainable manufacturing principles and sustainable manufacturing practices is needed to show, from an empirical perspective, how high level sustainability concepts might be incorporated into daily manufacturing operations.

Thus, this thesis is based on the need for further studies: (i) of the operationalization of sustainable manufacturing principles; (ii) exploring
sustainable manufacturing practices and (iii) to find a cohesive connection between conceptual sustainable manufacturing principles and sustainable manufacturing practices. Similarly, the small amount of research on sustainable manufacturing practices shows that there is a lack of research involving a triple bottom line approach of sustainability, with such work being limited to large companies. The motivation for this research, coupled with the lack of existing studies, shows that research on sustainable manufacturing practices is still in its infancy, thus constituting a promising and interesting field of research.

1.3 Purpose and research questions

This thesis attempts to address the apparent research gap, or lack of insights, in studies connecting conceptual sustainable production principles (involving the three dimensions of sustainability) with sustainable manufacturing practices (considering all sizes of companies). The purpose of this thesis is to contribute to the existing body of knowledge regarding sustainable manufacturing principles and practices.

To fulfill this purpose, the following research questions were considered:

RQ1. What is the current state in the literature regarding sustainability principles aimed at manufacturing industries?

Answering this question should provide a better understanding of the existing state of the published scientific material, or the existing body of knowledge on sustainability principles that could be potentially implemented within a manufacturing context.

RQ2. What are the main aspects that current sustainable manufacturing practices are responding to?

This research question hopes to provide a better understanding of the main sustainability aspects being addressed though sustainability practices among manufacturers.

RQ3. How do manufacturing practices adhere to sustainable manufacturing principles?
This research question involves the analysis of how manufacturers operations currently adhere to sustainable manufacturing principles.

1.4 Scope of the thesis

The research presented in this thesis explores the existing body of knowledge regarding sustainable manufacturing principles and practices, therefore the unit of study is the manufacturing company. The context of the research is the integration of the fields of operations management and sustainability, which some scholars also refer as the field of sustainable operations management (Kleindorfer et al., 2005; Drake and Spinler, 2013; Gunasekaran and Irani, 2014). This field is relevant to the future of manufacturing as it plays a crucial role in providing mode of actions or solutions for the current sustainability challenges faced by many companies (Kleindorfer et al., 2005). The research follows the triple bottom line approach defined by Elkington (1998), who stated that organizations looking to achieve sustainable development need to work on three dimensions: environment or planet, social or people, and economics or profit. Therefore, all three dimensions of sustainability were considered in order to address the purpose of this research, contrary to the majority of studies within operations management literature that have focused on the environmental issues while overlooking the social dimension of sustainability (Kleindorfer et al., 2005).

Considering the phenomenon to be studied (i.e. sustainable manufacturing practices and principles), the unit of study, and in order to prepare the groundwork for the subsequent theoretical framework, it is pertinent to explain what it is understood by manufacturing. This distinction is relevant, as scholars in both the operations management and the sustainability fields seldom present precise definitions of manufacturing and production, and often use these terms interchangeably (CIRP, 2014). In this research, manufacturing is defined as the interconnected activities and operations involved in producing a single part, or multiple parts to be assembled to form a final product. In manufacturing, raw materials are transformed, with the assistance of technology, physical and chemical processes, labor, and tools into components or final products within manufacturing industries. It is possible to state that while all manufacturing is a type of production, all types of production do not always involve manufacturing. Although this definition is adapted from previous definitions given by CIRP (1990) and Bellgran and Säfsten (2010), it differs from the latter one in the sense that manufacturing is not considered as superior production, but on the
contrary, this research uses the notion that production is superior manufacturing (CIRP, 1990). Thus, the manufacturing definition adopted in this research is consistent with the use of the term within leading sustainability literature in studies addressing the manufacturing industry.

Production is defined as the process of transforming a set of input elements into a set of output elements with economic value. It is the outcome of the industrial work in different fields of activity (e.g. agriculture production, music production, oil production, energy production, manufacturing production). Therefore, by understanding production as superior manufacturing, the term production is associated with a branch of industry or line of business, making the distinction between production related to tangibles (i.e. production by integration or disintegration) or intangible products (i.e. production by service) possible. The former definition was adapted from CIRP (1990), Murthy (2005), and Bellgran and Säfsten (2010).

However, since there is a lack of consensus among academics as to the use of manufacturing and production terms, this research sometimes presents these terms interchangeably but only for citation purposes (e.g. sustainable production principles and sustainable manufacturing principles). The author of this research is aware of the difference between these definitions as stated above.

1.5 Outline of the thesis

The research presented in this thesis is comprised by five chapters and three appended papers.

In **Chapter 1: Introduction**, the background of the research area, the research problem highlighting the motivations for the study, the research purpose and the research questions are presented. This chapter ends with the scope and limitations of the thesis, followed by the thesis outline.

In **Chapter 2: Theoretical framework**, the frame of reference around the two principal topics of this research is introduced. First, it elaborates on the connection between sustainability development and manufacturing. Then, definitions and previous studies about sustainability principles and, more specifically, sustainable manufacturing principles, are presented. This is followed by the introduction of the definition and previous studies relating to sustainable manufacturing practices.

In **Chapter 3: Research methods**, the research design and the research methods are outlined. This is followed by describing the data collection
tools, data analysis, and final considerations about the quality of the research.

In Chapter 4: Summary of the results, the main theoretical and empirical findings from the appended papers with regard to the research questions are described.

In Chapter 5: Discussions and conclusions, the findings presented in the previous chapter are discussed the light of previous research. This is followed by a discussion regarding the methods used. Thereafter, the main conclusions are drawn, where the research questions are answered. The chapter ends by suggesting future studies.

Regarding the three appended papers, Paper I identified research trends from existing empirical studies of sustainable manufacturing, thus presenting a brief view of the current status of published research. Paper II described an overview of how current manufacturing operations, specifically sustainable manufacturing practices, adhere to sustainable production principles. Thus, this connects conceptual sustainable production principles with the sustainable practices reflecting these principles. Finally, Paper III explored the challenges and enablers for implementing sustainable manufacturing in surface treatment SMEs. Thus, insights regarding the needed sustainable manufacturing practices for facing sector specific challenges were extracted from Paper III and presented in this kappa.
CHAPTER 2
Frame of reference

This section presents the theoretical foundation for this research. It is divided into two main blocks: sustainable manufacturing principles and sustainable manufacturing practices.

2.1 Sustainable development and manufacturing

Sustainable development was first defined in “Our common future”, better known as the Brundtland Report (1987). The concept, which is still being used by the European commission, was defined as “meeting the present needs without compromising the ability of future generations to meet their own needs” (Brundtland, 1987, p.15). In regard to this, Brookfield (1987) stated that this environmental report presented a novel focus on the politicization of environmental problems and its connection with social problems such as poverty and inequality. In the same sense, from an enterprise perspective, Elkington (1998) created the triple bottom line concept, stating that organizations looking to achieve sustainable development needed to work on three pillars or dimensions (the triple bottom line): environment or planet, social or people, and economics or profit. However, despite this definition of sustainable development, there is still limited consensus among scholars on the definition of sustainability (Berns et al., 2009).

Based on the definition of sustainable development, the concept of sustainable manufacturing emerged. This term was first mentioned in 1992 during the United Nations Conference on Environment and Development – UNCED. Later, De Ron (1998) defined sustainable production as an industrial activity that generates products which meet the needs and wishes of the present society without sacrificing the ability of future societies to meet their needs and wishes. Alongside De Ron’s definition, the Lowell Center for Sustainable Production – LCSP, University of Massachusetts, Lowell – defined sustainable production as: “The creation of goods and services using processes and systems that are non-polluting; conserving of energy and natural resources; economically viable; safe and healthful for employees, communities and consumers; and socially and creatively rewarding for all working people.” (Veleva and Ellenbecker, 2001, p. 520).
In a similar way, Garetti and Taisch (2012, p.85) defined sustainable manufacturing as “the ability to smartly use natural resources for manufacturing, by creating products and solutions that, thanks to new technology, regulatory measures and coherent social behaviours, are able to satisfy economic, environmental and social objectives, thus preserving the environment, while continuing to improve the quality of human life”.

For many years, large enterprises have made up the visible tip of the iceberg of contributors to global anthropogenic impacts on sustainability. These type of organizations are commonly acknowledged as the usual sources of such impacts resulting from manufacturing operations. On the other hand, SMEs have not been in the spotlight in the ongoing global debate regarding the adoption of sustainable manufacturing. Studies presenting sustainable manufacturing practices seem not to reflect the responsibility of all companies to mitigate or eliminate the negative effects of non-sustainability, as scientific research is still heavily focused on large manufacturers.

2.2 Sustainability principles

According to the dictionary definition, the term “principles” refers to a fixed or predetermined set of policies, ways of action or conducts. For Glavič and Lukman (2007, p.1876), principles “are fundamental concepts that serve as a basis for actions, and as an essential framework for the establishment of a more complex system”. For Shrivastava and Berger (p.248, 2010), principles constitute “sets of values, standards, guidelines or rules of behavior that describe the responsibilities of or proper practices for organizations”. These are some of the many definitions where the term “principles” alludes to guidance for further work. Similarly, principles have been defined as “the key concepts that serve as a basis for action” (Roberts and Ball, p.163, 2014).

One of the first attempts made to publish sustainable principles was by Daly (1990). He defined sustainability principles at a high level with a general approach. Some of the principles proposed by him were: 1) for renewable sources management, the harvesting rates should equal regeneration rates (sustained yield) and waste emission rates should equal the natural assimilative capacities of the ecosystems; 2) the sustainable use of non-renewable sources requires the investment in the exploitation of these type of resources being paired with an equivalent investment in a renewable substitute (e.g. oil extraction paired with tree planting for wood alcohol); 3) technologies that increase resource productivity (i.e. the amount of value extracted per unit of resource) must be prioritized, instead
of those technologies that focus on increasing the resource throughput (Daly, 1990). Two years later, these basic principles were refined and published by Costanza and Dali (1992).

In addition to these attempts at defining sustainability principles, governments in various countries have tried to establish their own sustainable development principles (e.g. The Government of Western Australia, 2004). The establishment of these sustainability principles at a higher level have shaped the way governments, industries and communities approach sustainability. This, as principles are usually introduced into a country’s legislation, forming a starting point for defining governance strategies or public policy (Government of Western Australia, 2004).

Among other studies that reviewed existing sustainability principles, Shrivastava and Berger (2010) worked on organizing the information published about main agreements concerning environment and development problems from 1968 until 2009. According to the authors, the agreements (e.g. the International Conference on Environment and Economics (OECD), Kyoto protocol), had the potential to spawn general sustainability principles, represented as “articulated desired changes” for governments, corporations, financial institutions, and individuals. The study also reviewed industry-specific sustainability principles proposed by several industry associations and national and international institutions. According to Shrivastava and Berger (2010), an increasing number of industries have been realizing that sustainability principles are needed as a guide to operate in the new economy, nevertheless little data published on adoption of these principles.

The principles mentioned above mostly covered defining policies and programs regarding sustainability, falling short when it came to applying these principles to the shop floor, or translating them into an actual transformation process.

### 2.3 Sustainable manufacturing principles

From an organizational perspective, Shrivastava and Berger (2010) defined sustainability principles as a set of basic criteria aimed at mitigating the impact of operations on the triple bottom line. Thus, sustainability principles deal with “moving organizations toward sustainability by changing their vision/mission, their use of natural and human resources, their production and energy practices, and their products and waste management” (Shrivastava and Berger, p.249. 2010).
Among the first attempts at establishing a set of sustainable principles from an operative perspective, Gladwin et al. (1995) presented a set of eight operational principles and their associated techniques of sustainable behavior.

Similarly, Veleva and Ellenbecker (2001) introduced a set of principles linked to corresponding indicators, framed under the concept of sustainable production as defined by the Lowell Center for Sustainable Production. This set of sustainable production principles are based on the following six main aspects that organizations need to tackle in order to make their operations more sustainable: energy and material use, natural environment, social justice and community development, economic performance, workers, and products.

Later, Al-Yousfi (2004) introduced four general principles that organizations implementing clean production approaches had to follow: 1) minimize the use of non-renewable resources; 2) manage renewable resources to ensure sustainability; 3) reduce or eliminate, hazardous/toxic and harmful emissions or waste into the environment; 4) achieve these goals in the most cost-effective manner, emphasizing sustainable development. Nevertheless, this set of sustainability principles was strictly focused on the environmental dimension of sustainability.

Similarly, Tsoulfas and Pappis (2005) described a set of twenty-six environmental sustainability principles with the purpose of guiding the operation and design of green supply chains; however, many of these principles were applicable to the production process. In contrast to the principles described by other authors, this structure was exclusively based on the environmental dimension.

Lindsey (2010) presented a set of three sustainability principles applicable to all segments of society and to all disciplines. These principles were posed with the aim of developing and implementing improved systems.

Finally, Despeisse et al. (2012) defined sustainability principles as a series of “rules”, usually followed by sustainable manufacturing initiatives or practices. The principles presented by these authors focused exclusively on environmental sustainable manufacturing principles.

Most scholars still use the term “sustainability” in “sustainability principles” to refer exclusively to environmental concerns. Indeed, the majority of studies addressing sustainability principles have only described environmental sustainability principles.

Thus, in light of the existing definitions of sustainability principles and considering the above mentioned examples of principles, for the purpose of this research sustainable manufacturing principles are defined as a set of criteria or guidelines to be followed by manufacturing companies in
order to translate a sustainable development policy into the operations required in the transformation processes, with the purpose of improving the environmental, social and economic performance of a company.

2.3.1 LCSP Sustainable production principles

In order to study the empirical adherence by manufacturers to the sustainable manufacturing principles, this research used, as its guiding criteria, the LCSP principles of sustainable production, which adopt a triple bottom line approach and reflect the six main aspects of sustainable production (the LCSP principles were briefly introduced in section 2.3 of this thesis, and are further described in section 4.1). However, although these principles were created to promote a better understanding for companies about what sustainable production actually is, to date there is no scientific literature describing empirical testing of the LCSP principles. Paper II focuses on the sustainability principles from an operative perspective, filling the gap in current literature regarding how manufacturing companies translate sustainability into operative actions.

The LCSP principles can be described as follows: referring to sustainable products, Principle 1 concerns practice such as product design, product efficiency, long-lasting and easily recycled products, and environmentally-friendly and user-friendly product characteristics. Regarding energy and materials, Principle 3 involves energy reduction, non-renewable resources, water and materials consumption and safe material usage for the environment, workers and customers. On the natural environment, Principle 2 addresses reduction or elimination of waste. Principle 4 focuses on hazardous emissions to air and water, hazardous physical agents, technologies or work practices and the use of hazardous substances.

Principles 5, 7 and 8 mostly address aspects relating to workers. Principle 5 mainly deals with the reduction of the risks that workers are exposed to. Principle 7 concerns practices that aim to increase employee efficiency, employee’s improvement suggestions, employee creativity, and reward systems. Principle 8 covers practices that provide opportunities for employee advancement, safety and wellbeing, job satisfaction, training, gender equality, and turnover rate reduction.

Finally, regarding economic performance, Principle 6 encompasses practices aimed at reducing environmental health and safety compliance costs, improving participatory management style, promoting stakeholder involvement in decision-making, and increasing customer satisfaction; all these have the purpose of ensuring company profitability. Referring to community development, Principle 9 deals with increasing employment
opportunities for locals, developing community-company partnerships, and increasing community spending and charitable contributions to local communities.

2.4 Sustainable manufacturing practices

According to Shrivastava and Berger (2010), due to the theoretical or abstract nature of the sustainability principles, practices are originated. Currently, an increasing number of organizations are integrating sustainable practices into their manufacturing operations in order to improve not only their environmental performance but also their social and economic performances.

In scientific literature, often sustainable manufacturing practices are presented centered on the concept of resource productivity, which advocates higher resource efficiency as a means of waste reduction (Lazlo et al., 2013). Thus, sustainable manufacturing practices have mostly been defined from an environmental perspective. Reflecting this, Nordin et al. (2014) viewed sustainable manufacturing practices as aiming to minimize the impacts of manufacturing operations on the environment while optimizing the production efficiency of the company. Taking this definition as a departure point, and considering also the definition of sustainable development (Brundtland, 1987), for the purpose of this thesis sustainable manufacturing practices are defined as the actions, initiatives and techniques that positively affect the environmental, social or economic performance of a firm, helping to control or mitigate the impacts of the firm’s operations on the triple bottom line.

It is worth mentioning that, before the term sustainability was coined, Bowen (1953) introduced the concept of corporate social responsibility (CSR). For Bowen, CSR represented an obligation for companies to take responsibility for the impact of their activities on human, social, ethical and ecological environment over the course of their business activities. Hence, CSR came to be considered as the introduction and implementation of sustainable development within the sphere of management (Kechiche and Soparnot, 2012). Likewise, Perez-Batrez et al. (2010, pp 193) stated that the CSR concept includes the term sustainability. Whilst similar, CSR and sustainability are not identical. Both are voluntary corporate acts which can have different purposes and outcomes. All the sustainability initiatives can be labeled as CSR initiatives, but some CSR initiatives cannot be directly related to sustainability. Conscious of the difference between the two terms, this research focused on sustainability, as CSR is a broader field that is related to policies and practices from a
strategic or business level, while sustainability alludes to practices from an operational level that directly address manufacturing.

The growing importance of sustainable manufacturing over the years has led to an increased interest in the study of sustainability practices. Researchers (e.g. Millar and Russell, 2011; Hurreeram et al., 2014; Habidin et al., 2015) have studied sustainable manufacturing practices within different industry sectors and countries. Nevertheless, the vast majority of studies on sustainability practices have tackled mainly environmental practices, as well as the effects of sustainability practices on company performance, and sustainability practices among countries and sectors (e.g. Montabon et al., 2007; Despeisse et al., 2012; Schoenherr and Talluri, 2013).

The main drivers for undertaking sustainable business practices are both external (government regulations, profit and not-for-profit organizations) and internal pressures (strategic objectives, top management vision, employee safety and wellbeing, cost savings, productivity and quality) (Gunasekaran and Spalanzani, 2012).

Previous studies of sustainable manufacturing practices have described recycling, proactive waste reduction, remanufacturing, environmental design, and market research into environmental issues as the environmental sustainability practices that most strongly affect company performance (Montabon et al., 2007). Similarly, Hurreeram et al. (2014) determined that the most common environmental sustainability practices among large companies were eco-design, renewable energy usage, energy and material optimization, recycling, product life cycle and end of life cycle management, and waste minimization.
CHAPTER 3

Research methods

This chapter starts by describing the research design, and research methods used to achieve the research purpose. Then the description of the data collection, data analysis and insights regarding the quality of the research are presented.

3.1 Research design

Once the research problem is defined, the next stage is usually to plan the research design. The research design aims to describe the methodological decisions taken in regard to the research study. This includes aspects concerning data such as “what” to research, “where” to collect the data, by what means the data are gathered and how the data are analyzed (Kothari, 2004). The purpose of this licentiate thesis was to contribute to the existing body of knowledge regarding sustainable manufacturing principles and practices. In order to fulfill this purpose, three research questions of an exploratory nature were raised. Thus, at the initial stage of this thesis, an exploratory study approach to sustainable manufacturing principles and sustainable manufacturing practices was deemed appropriate to gain familiarity with these two subjects, and also to acquire new insights into them (Kothari, 2004). This agreed with Voss et al. (2002), who stated that exploratory research is mostly used during the early stages of a study in order to contribute to the identification of potential research questions of interest.

The first research question (RQ1) was intended to increase the understanding of the underlying concepts that can be used as a basis for the sustainable manufacturing practices in manufacturing organizations. Therefore, it aimed to identify the sustainability principles that could be potentially implemented within a manufacturing context. In this kappa, the frame of reference, section 4.1 and Paper II contributed to answer the RQ1.

The second research question (RQ2) explored sustainable manufacturing practices in order to identify the main sustainability aspects those practices respond to. Information regarding sustainable manufacturing practices was gathered from literature and empirically. Therefore, Papers I, II and III build upon each other, forming the basis of an answer to RQ2. Paper I explored sustainable manufacturing practices
in published empirical studies. The work described in Paper II added to this research question by presenting current sustainable manufacturing practices commonly carried out within the manufacturing industry. The work described in Paper III partially or indirectly answered this question by presenting the perceived sustainable practices needed to overcome sector-specific challenges for adopting sustainable manufacturing. Hence, Paper III provides insights about the lack of sustainability practices. Papers I, II and III answer this research question by clarifying the main sustainability aspects being addressed though sustainability practices among manufacturers.

The third research question (RQ3) studied how manufacturers’ operations, through their sustainable manufacturing practices, adhere to sustainable manufacturing principles. This research question adds to the general discourse on how industry adopts principles of sustainability and applies them in practice. RQ3 tries to fill the gap in current literature regarding the connection between conceptual sustainable production principles taking a bottom line approach and the sustainable manufacturing practices reflecting these principles. Paper II presents more details to fully answer this research question. Figure 1 shows a graphic representation of how the appended papers, and specific sections of this kappa, contributed to answer the research questions and the research purpose.

Figure 1. Research questions in relation to the research purpose.
3.2 Research methods

Considering that the area of sustainable manufacturing practices is still in its infancy, and few empirical studies have been carried out on this topic involving all types of organizations regardless of their organizational size, an exploratory type of research was suitable for this research. Exploratory approaches are often used during the early stages of researching a phenomenon when looking for insights into a specific problem.

The choice of the research method also depends to a large extent on the form of the research questions (i.e. “what”, “how”, “where” and “why” types of questions) (Yin, 2009). In this research, the first and second research questions address the study problem using a “what” type of question to identify the sustainable manufacturing principles and practices. Similarly, the third research question was framed as a “how” type of question, also implying an exploratory approach.

Table 1 summarizes the main characteristics of the three appended and the non-appended work-in-process papers (WIP) in relation to the research methods used, which helped to contribute to answer the three research questions.

The survey character of the research was appropriate for exploring the sustainable manufacturing practices and principles as the survey methods often involves the use of multiple data collection tools (Kerry, 2002), implying at the same time the collection of data from individuals about them or the social institutions they are part of (Rossi et al., 1983).

3.3 Data collection

The research presented in this thesis used, as its main data collection tools for collecting empirical qualitative data, interviews, focus groups and direct observations (Hancock, 1998). The other way of classifying the data collection tools is by the sources of the data, that is, primary and secondary (Kothari, 2004). Table 1 shows that the data collection tools used in this research were literature reviews (for obtaining secondary data), and semi-structured interviews, direct observations, focus groups and online questionnaires (for obtaining primary data).
Table 1. Overview of the research methods used

<table>
<thead>
<tr>
<th>Paper</th>
<th>Paper 1</th>
<th>WIP paper</th>
<th>Paper 2</th>
<th>Paper 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Research method(s)</strong></td>
<td>Systematic literature review</td>
<td>Literature review</td>
<td>Semi-structured interview</td>
<td>Focus group and online questionnaire</td>
</tr>
<tr>
<td><strong>Purpose</strong></td>
<td>Inquire on sustainable manufacturing practices in published empirical papers</td>
<td>Explore the existing sustainability principles</td>
<td>Explore adherence to sustainable production principles by sustainable manufacturing practices</td>
<td>Enhance the understanding of the adoption of sustainable manufacturing</td>
</tr>
<tr>
<td><strong>Research question</strong></td>
<td>RQ2</td>
<td>RQ1</td>
<td>RQ1, RQ2 and RQ3</td>
<td>RQ2 (indirectly)</td>
</tr>
<tr>
<td><strong>Analysis</strong></td>
<td>Published empirical studies on sustainable manufacturing practices</td>
<td>Published studies on sustainability principles</td>
<td>Sustainable manufacturing practices adhering to sustainable production principles</td>
<td>Challenges and enablers for adopting sustainable manufacturing in surface treatment SMEs</td>
</tr>
<tr>
<td><strong>Type of study</strong></td>
<td>Exploratory</td>
<td>Exploratory</td>
<td>Exploratory</td>
<td>Exploratory</td>
</tr>
<tr>
<td><strong>Data collection</strong></td>
<td>Empirical journal papers</td>
<td>Papers on sustainability principles</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Data analysis</strong></td>
<td>Content analysis</td>
<td>Content analysis</td>
<td>Content analysis</td>
<td>Content analysis</td>
</tr>
</tbody>
</table>

1 The term enabler in Paper III is interpreted and referred to in this thesis as perceived practices needed to overcome sector-specific challenges for implementing sustainable manufacturing.
3.3.1 Paper I

In order to explore the main topics of this research, sustainability manufacturing principles and sustainable manufacturing practices, both traditional and systematic literature reviews were used. A literature review was used in Paper I, to obtain a greater subject knowledge and awareness of how to frame and scope the research by giving an insightful overview of the current state of the study field (Croom, 2009). Knowledge of sustainable manufacturing principles and practices is crucial in the initial stages of licentiate studies. In this sense, a systematic literature review was used to explore the topic (Jesson et al., 2012), while allowing the identification of research gaps, trends and therefore the identification of further studies (Petticrew and Roberts, 2006; Torgersson, 2003).

The systematic literature review carried out in Paper I sought to identify empirical studies and practical initiatives carried out by manufacturing companies. The bibliographic search identified 2897 preliminary papers that were screened for eligibility according to these pre-established inclusion criteria: (i) they had an empirical approach to sustainability within manufacturing companies; (ii) they were published in a peer-reviewed journal between 2000 and 2013, (iii) they were written in English, and (iv) they were carried out within manufacturing industries (assembled products or industrial processes). Empirical papers from process industries were included because this type of industry is closely linked to many discrete manufacturing industries. Additionally, and because the study focus was the transformation process (or production function) within companies, papers dealing with other organizational processes out of this scope were excluded. Thus, papers dealing with topics such as eco-design, end of life product recovery, product-service systems, eco-innovation, sustainable consumption, and remanufacturing were excluded from the sample. After applying the inclusion criteria, the sample consisted of 80 papers; however, after full-text screening was carried out, the final sample was reduced to 25 papers. Thus, the systematic literature review used in Paper I provided a structured and transparent means of gathering, synthesizing and appraising the findings of studies aimed at minimizing the bias inherent in non-systematic reviews (Sweet and Moynihan, 2007). Finally, and in order to extract and organize relevant data from the final sample of journal papers, a matrix sheet in Microsoft Excel was created. The matrix contained key data summarizing each paper (e.g. title, country, year of publication, journal, author, research method, topic, industry, sustainability issue addressed in this dimension and key findings).
3.3.1 WIP paper

The WIP paper sought to gain knowledge about sustainability principles applicable to manufacturing perspective. In order to attain this, a literature review was carried out.

A bibliographic search was done in the citation database Scopus, using the keywords “sustainable manufacturing principles” and “sustainability principles” identified 289 papers. The final sample was constituted by six papers. Some of the reasons for paper exclusion were: duplicated papers, unobtainable full text papers, and papers where sustainability principles were not the main research focus. The papers that dealt with principles and had the higher number of citations were selected for further analysis.

The sustainability principles were extracted and organized in a matrix sheet in Microsoft Excel. The identified set of principles were grouped under the three dimensions of sustainability.

3.3.2 Paper II

Interviews were the main data collection tool used in Paper II. The interview was chosen as it provides important insights into the phenomena under study, helping to identify other relevant sources of evidence (Yin, 2009). A semi-structured interview was the specific type of interview used in Paper II, characterized by open-ended questions, and often used to collect information from individuals knowledgeable of the situation under study (Hancock, 1998).

An interview guide was designed, based on the principles of sustainable production defined by the LCSP, as well as its corresponding indicators for sustainable production (Veleva and Ellenbecker, 2001). The design of the interview guide was important, especially as semi-structured interviews require the interviewer to have previously identified a number of aspects to address (Hancock, 1998). Twelve semi-structured interviews were carried out, within a sample of both large enterprises and SMEs from the following sectors: plastics, metalworking, foundry, engine manufacturers, hydraulic systems and furniture. The exploratory nature of the study made the use of a non-probabilistic purposive sample appropriate. Therefore, Paper II did not attempt to draw statistical generalizations from the results, but presented empirical evidence of adherence to the LCSP sustainable production principles through practices in the manufacturing sector. Respondents interviewed were environmental managers or managing directors. The data were collected by recording the interviews, and by taking handwritten notes. Table 2 shows an overview of the sample studied in Paper II.
Table 2. Paper II sample overview

<table>
<thead>
<tr>
<th>Industry</th>
<th>F1</th>
<th>F2</th>
<th>E1</th>
<th>E2</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>H1</th>
<th>H2</th>
<th>P1</th>
<th>P2</th>
<th>FD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SME</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Large</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>No. Employees</td>
<td>50</td>
<td>500</td>
<td>1400</td>
<td>1535</td>
<td>590</td>
<td>500</td>
<td>9</td>
<td>150</td>
<td>430</td>
<td>200</td>
<td>350</td>
<td>50</td>
</tr>
<tr>
<td>Interviewee role</td>
<td>CEO</td>
<td>EM, EC</td>
<td>PM, EM</td>
<td>PM, EM</td>
<td>EM</td>
<td>CEO</td>
<td>CEO</td>
<td>QSE</td>
<td>EM</td>
<td>CEO</td>
<td>QSE</td>
<td>QSE</td>
</tr>
</tbody>
</table>

*EM: environmental manager; EC: environmental coordinator; PM: production manager; QSE: quality safety and environment manager

The semi-structured interviews were complemented when possible with direct observation (Ghauri and Gronhaug, 2010), carried out during plant tours provided by some of the companies. Direct observation has been used in many disciplines to collect data about processes, organizations, individuals and cultures (Kawulich, 2005). Likewise, direct observation was used in order to gather qualitative data in the form of written field notes about the respondent’s behavior (Papers II and III) and the organizations they belong to (Paper II). According to Dewalt and Dewalt (2002), when direct observation is combined with other data collection tools, the researcher is found to gain a better understanding of the context and phenomenon under study. Therefore, in this research, direct observation was combined with other data collection tools such as semi-structured interviews, an online questionnaire and focus groups.

3.3.3 Paper III

For Paper III, the data were collected using two collection data tools through two stages of empirical studies: focus group discussions and online questionnaire. Both collection data tools had CEOs as their main key respondents.

Focus group discussion is a well-known data collection tool (Morgan et al., 2008), used for gathering large amounts of qualitative data from a moderated interaction between a small group of approximately 6 to 12 individuals (Krueger, 1994; Morgan et al., 2008). A focus group was chosen for the research as it allows the exploration of a topic with little prior knowledge (Williamson, 2002), such as the perceived managerial perception regarding the challenges and enablers faced by SMEs for adopting sustainable production within surface treatment SMEs.
The focus group consisted of two groups of 10 CEOs each, where the discussions were moderated around a few planned questions and lasted 45 minutes each.

The focus group started with the moderator asking about the challenges of attaining environmental, social and economic sustainability within surface treatment SMEs. There were also questions regarding the perceived required practices or enablers that, if implemented, could be helpful in overcoming the sector-specific challenges of adopting sustainable manufacturing.

Regarding the sampling method, a non-probabilistic purposive sample involving CEOs from Swedish surface treatment SMEs was used. The CEO respondents in the sample were chosen based on contacts one of the researchers had with a professional association of surface treatment organizations. Keeping in mind that focus groups are concerned with people perceptions, and therefore it is advised they be carried out in a non-threatening environment (Krueger 1994, p.6), the discussions with CEOs were held in Swedish and in small groups in order to create an appropriate discussion environment where all opinions could be raised. It is worth mentioning that the choice of CEOs as participants in the focus groups was motivated by the holistic knowledge CEOs have of the three dimensions of sustainability within SMEs, knowledge usually lacking in other jobs such as environmental coordinator. In addition, the CEOs’ perceptions were valuable to the study as managers play an essential role in determining the environmental impact of their manufacturing operations through the different decisions they take (Klassen, 2000). The data were collected by recording the discussions and handwriting notes by the moderators. Further, the information gathered during the focus groups was used as input to design an online questionnaire; this increased the validity of the questionnaire as a measurement instrument.

For the second stage of the empirical data collection in Paper III, an online questionnaire was employed. This used a non-probabilistic purposive sample of SMEs’ CEOs in order to discover the perceived importance of the identified challenges and enablers from a broader audience of surface treatment SMEs. Based on this chosen sample technique, the results in Paper III provided an overview about the challenges and enablers identified by CEOs.

The online questionnaire was used as it allowed verification of the data gathered during the focus group stage, by identifying the perceived importance of the pre-identified challenges and enablers within a larger audience of SMEs’ CEOs. Regarding the design of the online questionnaire, Likert scales were used in order to determine the perceived importance of the challenges and enablers within CEOs. Once the
questionnaire was complete, it was pilot tested by surface treatment experts in order to increase not only its clarity, but also to verify its measurement properties and to examine the viability of administering it (Forza, 2009). The link to the online questionnaire was sent out to thirty-six SMEs using the surface treatment professional association as an intermediary between the researchers and the companies. The response rate for this stage was 17% percent, equivalent to 6 responses. Among the measures taken to improve the response rate were two reminders sent by the intermediary professional association to the respondents. In Paper III, the data were collected by recording the group discussions, and handwriting notes.

The data collection tools used reflected the survey character of the research presented in this kappa. This as the survey type of research seeks to collect information from either all, or a part of, a population using a variety of data collection tools, where the most common ones are questionnaires or interviews (Tanner, 2002). This was shown with the collection data tools used in Paper III, where online questionnaire and focus groups were used. It is worth mentioning that focus groups have been defined by scholars as a type of group interview (Morgan et al., 2008).

3.4 Data analysis

According to Neuman (2006), data analysis is about searching for patterns within the data.

Due to the qualitative nature of the data gathered, this kappa, along with the appended papers, followed the process for data analyses proposed originally by Miles and Huberman (1994) and later in Miles et al., (2014). The process in mention analyses the data around three main activities: data condensation, data display and drawing and verifying conclusions. These three types of analysis activities and the activity of data collection in qualitative data analysis, form a non-lineal way, but instead, in interactive and continuous process (Miles and Huberman, 1994).
Figure 2. presents alongside the data collection stage, the three main activities within the data analysis process (data condensation, data display and conclusion drawing and verifying).

Data condensation refers to selecting, focusing, simplifying or transforming the raw data gathered by the data collection tools (Miles et al., 2014). During the data condensation stage in Paper I, the inclusion criteria played an important role in rejecting irrelevant papers. Likewise, important aspects from each of the journal papers in the final sample were grouped and summarized using an Excel matrix to enable easier analysis. The matrix contained information about each paper such as title, country, year of publication, journal, author, research method, topic, industry, sustainability issue addressed in this dimension and key findings.

The condensation stage in the WIP paper was done by extracting the set of sustainability principles into an Excel matrix and organizing them according to the three sustainability dimensions. Similarly, in Paper II, the condensation stage was achieved by transcribing the recorded interviews and written notes into an Excel matrix. Due to the designed interview guide being based on a set of sustainable production principles, this made it easier to classify, categorize and identify specific sustainability aspects and practices mentioned in the interview. Although categorization was easier because of the interview guide being based on the principles, content analysis was used in Paper II for organizing and understanding the data, as it allowed a systematic compression of large chunks of text into fewer categories of content (Montabon et al., 2007).
The condensation stage in Paper III transcribed the large amount of data recorded in the focus groups and written notes into Excel tables. Due to the questions used by the moderators in the focus groups were broad and open-ended, the large amount of data complicated the classification and categorization of the data when trying to identify the challenges and enablers. It is worth mentioning that even while data were being collected in each of these papers, it was unavoidable to start noticing patterns and start drawing potential explanations for some findings. According to Miles et al. (2014), the emergence of these preliminary conclusions is to be expected as qualitative data analysis constitutes a continuous and iterative process.

Data display refers to the activities needed to organize and assemble the information in a manner that allows conclusions to be drawn (Miles et al., 2014). The display of the information in all the appended papers was achieved initially through the use of Excel matrices that facilitated the classification of the data under thematic subcategories and categories. Thus, these matrices also facilitated the understanding of the data. However, Excel matrices were not the only method used for data display: the systematic literature review in Paper I used graphs to visualize characteristics such as distribution of papers by research methodologies, sustainability dimensions addressed in the sample as well as a table presenting the categorization of papers according to sustainability dimensions. In the same way, Paper II used a table for organizing the practices gathered and for grouping them according to sustainable production principles. Due to the continuous and iterative nature of the qualitative data analysis, it was noticed that in the data display stage (i.e. filling up the matrices, tables and graphs), the data still went through an additional condensation, and further preliminary conclusions were drawn.

The last stage in qualitative data analysis corresponds to conclusion drawing. The results from the analyses were contrasted with previous literature, aimed at identifying similarities, contradictions and drawing potential explanations of these findings (Eisenhardt, 1989).

### 3.5 Research quality

Validity and reliability are essential aspects of quality in research. As stated by Miles and Huberman (1994) and Miles et al., (2014) internal validity relates to the credibility and authenticity of the research results. The use of multiple data collection tools constitutes one of the methods for strengthening validity and obtain more valid results (Kohlbacher, 2005; Olausson, 2009).
According to Williamson et al., (2002) and Croom (2009) there are two mayor types of triangulation: methods and data. The internal validity of the research results is increased when data are either collected using several data collection tools (methods triangulation), or from several sources (data triangulation). In this research, the use of multiple data collection tools enabled the method triangulation. Method triangulation aimed to check the consistency of the findings by using several data collection tools (Williamson et al., 2002). Method triangulation was made by collecting data from different collection data tools such as focus groups and an online questionnaire (in Paper III). Similarly, data triangulation aimed to check the consistency of the information from different sources (Williamson et al., 2002). In Paper II, data triangulation was made by gathering data and cross-checking data from several different sources such as individuals (interviewing personal), direct observations, and available information from companies’ websites. The importance of data triangulation for internal validity is explained by Eisenhardt (1989), who stated that qualitative data obtained from several sources contribute to the understanding of the identified relationships in the data, and is thus, crucial for increasing internal validity.

Internal validity concerns also whether the research measures what it intended to measure (Saunders et al., 2012). Thus, internal validity in measurements, according to Williamson et al. (2002), is crucial for research quality because it ensures that the data collection tools were indeed measuring what they were intending to measure. The internal validity in measurements was evidenced in Papers II and III, by pilot testing the semi-structured interview guide with fellow researchers, and pilot testing the online questionnaire among surface treatment experts. These pilot tests sought not only clarity of these instruments, but also verification of the measurement properties of the data collection tools. Similarly, in Paper III, the internal validity of the online questionnaire as a measurement instrument was increased by using the information gathered during the focus groups as input for its design.

External validity is defined as the potential to claim generalizability of research findings, or the extent to which the findings could be generalized (Meredith, 1998; Tanner, 2002). Considering that the exploratory nature of the research did not allow for a wide-ranging data collection involving a larger set of companies (in Papers II and III), statistical generalization of the research findings cannot be claimed. Thus, the findings on how the manufacturing companies adhere to the LCSP principles cannot be extrapolated to the manufacturing sectors involved in Paper II. Similarly, the identified sustainable manufacturing challenges and enablers, or, perceived needed practices for overcoming these challenges identified in
Paper III should not be transferred to the entire population of Swedish surface treatment SMEs. Nevertheless, although these results are not statistically generalizable, the empirical studies presented in this thesis broaden the empirical basis of the small amount of existing research that addresses sustainable production principles and sustainable manufacturing practices.

Reliability constitutes another aspect for judging the quality of a study. Reliability concerns obtaining consistent and stable research results (Powell, 1997; Greenfield, 2002) that can be repeated with the same results by another researcher following the procedures as described in the initial study (Kidder and Judd, 1986; Yin, 2009). Therefore, reliability is closely related to how thoroughly the research is documented (Flick, 2006). In this research, reliability was sought by systematically designing the data collection tools, that is, by designing an interview guide protocol for carrying out the semi-structured interviews (in Paper II), and also, by using the findings from focus groups as input to design the online questionnaire (in Paper III).

To ensure future replicability of this research, scientific rigor in the research was sought. Thus, the systematic literature review (in Paper I) established inclusion criteria for selecting the final paper sample. The data from this final sample of papers were extracted, summarized and visualized in Excel tables. Similarly, the empirical data from the semi-structured interviews and discussions from the focus groups were recorded and transcribed. These efforts to secure reliability, when possible, contributed to the transparency of the study and hence to the replicability of this research.
CHAPTER 4
Summary of results

In this chapter, the main empirical and theoretical results are presented.

4.1 Current state of sustainable manufacturing principles

As was stated in Chapter 2 when referring to the WIP paper, sustainability principles point directions, or act as signposts, along the sustainability journey, for instance through frameworks for decision-making or assessments of progress in sustainable matters. Sustainability principles deal with “moving organizations toward sustainability by changing their vision/mission, their use of natural and human resources, their production and energy practices, and their products and waste management” (Shrivastava and Berger, 2010, p.248). Similarly, Lindsey (2011), referring to (Glavič and Lukman, 2007), claimed that principles are fundamental concepts which act as a basis for actions, and as an essential framework for the establishment of a more complex system.

It was found that some studies discussed sustainability principles from a production perspective (e.g. Gladwin et al., 1995; Veleva and Ellenbecker, 2001; Al-Yousfi, 2004; Tsoulfas and Pappis, 2006; Lindsey, 2011; Despeisse et al., 2012).

One of the first attempts for presenting operative sustainability principles was by Gladwin et al. (1995), who presented a set of principles aimed at blending the concept of sustainability with operational practice. These operative principles covered basic sustainability principles such as waste assimilation, regeneration in terms of harvesting rate and natural regeneration rate, diversification in terms of biodiversity, restoration of ecosystems, conservation referring to energy and material conservation, dissipation referring to the avoidance of energy and material waste, perpetuation referring to the preference of renewable resources over non-renewable resources, and circulation concerning the closed-loop cycle of materials and energy. In short, Gladwin et al. (1995) presented a set of operational principles, derived from general sustainability principles and linked to associated sustainable techniques.

Veleva and Ellenbecker (2001) published a set of indicators based on a set of nine principles of sustainable production proposed by the LCSP. These
principles are: 1) products and packaging are designed to be safe and ecologically sound throughout their life; 2) waste and ecologically incompatible by-products are reduced, eliminated or recycled; 3) energy and materials are conserved, and the forms of energy and materials used are appropriate for the desired results; 4) chemical substances or physical agents and conditions that present hazards to human health or the environment are eliminated; 5) workplaces and technologies are designed to minimize or eliminate chemical, ergonomic and physical hazards; 6) management is committed to an open, participatory process of continuous evaluation and improvement, focused on the long-term economic performance of the firm; 7) work is organized to conserve and enhance the efficiency and creativity of employees; 8) the security and wellbeing of all employees is a priority, as is the continuous development of their talents and capacities; 9) the communities around workplaces are respected and enhanced economically, socially, culturally and physically; equity and fairness are promoted.

Al-Yousfi (2004) further defined a set of four principles derived from the concept of cleaner production, which refers to a proactive environmental strategy seeking to guide organizations towards sustainable development by producing more with less. The principles, or goals, for sustainability defined by Al-Yousfi are: “Minimize the use of non-renewable resources; manage renewable resources to ensure sustainability; reduce, with the ultimate goal of eliminating, hazardous and otherwise harmful emissions/wastes into the environment; and achieve these goals in the most cost-effective manner, emphasizing sustainable development.” (Al-Yousfi, 2004, p.266).

Tsoulfas and Pappis (2006) established a set of environmental sustainability principles with the purpose of guiding the operation and design of green supply chains. The principles were either formulated from the literature describing explicit statements (i.e. guidelines or principles) or inferred from company practices described in the literature. Although these principles mainly concern the design and operation of environmental sustainable supply chains, some of these principles indeed refer to environmental sustainability aspects within the production process. Some of these environmental principles applicable to the production process are: production using a minimum of energy and materials; secondary raw materials being given priority in usage, and use of eco-friendly energy production.

Lindsey (2010) presented a set of three sustainability principles, applicable in all segments of society and in all disciplines. The first principle stipulates that improved sustainability is achieved through reducing wastefulness, the second principles calls for improving quality as
a way for improving sustainability, and the third principle states that sustainability is best achieved through the implementation of better systems. According to Lindsey (2010), applying these set of principles will ensure an optimization of the natural capital utilization (or resource utilization) along all the system components for the entire life cycle of the systems. This will benefit significantly the sustainability of production capabilities, human resources and ecosystems. Finally, although these principles were said by their author to be founded on environmental and social considerations (as these implicitly include the degradation associated with the neglect and overuse of human resources), the formulation or wording of these principles primarily alludes to environmental sustainability.

Recent research carried out by Despeisse et al. (2012) examined the published literature dealing with “rules” defined by previous authors. In their study, they grouped previously published environmental sustainability principles under the following general principle or rules: 1) use less material and energy; 2) shift to biologically inspired production models (e.g. industrial symbiosis, product end of life management, disassembly, remanufacturing etc.); 3) move to solution-based business models s including changed structures of ownership and production (e.g. product service systems and supply chain structure and 4) reinvest in natural capital through substitution of input materials: non-toxic for toxic, renewable for non-renewable.

In order to summarize the results presented in this thesis, Table 3 shows the sustainable manufacturing principles identified, grouped by each of the three dimensions of sustainability.

Table 3. Identified principles of sustainable production

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>Assimilation: waste emissions ≤ natural assimilative capacity</td>
<td>Products and packaging are designed to be safe and ecologically sound throughout their life cycles; services are designed to be safe and ecologically sound.</td>
</tr>
<tr>
<td></td>
<td>Diversification: biodiversity loss ≤ biodiversity preservation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Restoration: ecosystem damage ≤ ecosystem rehabilitation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conservation: energy-matter throughput per unit of output (time 2) ≤ energy-matter throughput per unit of output (time 1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dissipation: energy-matter throughput (time 2) ≤ energy-matter throughput (time 1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Perpetuation: non-renewable resource depletion ≤ renewable resource substitution</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Circulation: virgin / recycled material use (time 2) ≤ virgin / recycled material use (time 1)</td>
<td></td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td>Waste and ecologically incompatible by-products are reduced, eliminated or recycled.</td>
<td></td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td>Energy and materials are conserved, and the forms of energy and materials used are most appropriate for the desired ends.</td>
<td></td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td>Chemical substances or physical agents and conditions that present hazards to human health or the environment are eliminated.</td>
<td></td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td>Workplaces and technologies are designed to minimize or eliminate chemical, ergonomic and physical hazards.</td>
<td></td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td>Management is committed to an open, participatory process of continuous evaluation and improvement, focused on the long-term economic performance of the firm.</td>
<td></td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td>Work is organized to conserve and enhance the efficiency and creativity of employees.</td>
<td></td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td>The security and wellbeing of all employees is a priority, as is the continuous development of their talents and capacities.</td>
<td></td>
</tr>
<tr>
<td><strong>Econo.</strong></td>
<td>The communities around workplaces are respected and enhanced economically, socially, culturally and physically; equity and fairness are promoted.</td>
<td></td>
</tr>
<tr>
<td><strong>Econo.</strong></td>
<td>Minimize the use of non-renewable resources</td>
<td></td>
</tr>
<tr>
<td><strong>Al-Yousfi (2004)</strong></td>
<td>Manage renewable resources to ensure sustainability</td>
<td></td>
</tr>
<tr>
<td><strong>Environ.</strong></td>
<td>Reduce or eliminate, hazardous/toxic and harmful emissions or wastes into the environment</td>
<td></td>
</tr>
<tr>
<td><strong>Econo.</strong></td>
<td>Achieve the sustainability goals in the most cost-effective manner</td>
<td></td>
</tr>
<tr>
<td><strong>Tsoulfas and Pappis (2005)</strong></td>
<td>Design and develop recoverable products, which are technically durable, repeatedly usable, harmlessly recoverable after use and environmentally compatible when disposed</td>
<td></td>
</tr>
<tr>
<td><strong>Environ.</strong></td>
<td>Produce using minimum energy and materials</td>
<td></td>
</tr>
<tr>
<td><strong>Environ.</strong></td>
<td>Secondary raw materials should be given priority in usage</td>
<td></td>
</tr>
<tr>
<td><strong>Environ.</strong></td>
<td>Use eco-friendly energy production, reduce water usage and keep control of pollution sources</td>
<td></td>
</tr>
<tr>
<td><strong>Environ.</strong></td>
<td>Use standardized parts</td>
<td></td>
</tr>
<tr>
<td><strong>Environ.</strong></td>
<td>Provide easy disassembly of the product</td>
<td></td>
</tr>
<tr>
<td><strong>Environ.</strong></td>
<td>Reduce by-products and extract the best from them</td>
<td></td>
</tr>
<tr>
<td><strong>Environ.</strong></td>
<td>Limit packaging to the necessary size</td>
<td></td>
</tr>
<tr>
<td><strong>Environ.</strong></td>
<td>Design packaging for refilling or recycling and use standardized packaging when applicable</td>
<td></td>
</tr>
<tr>
<td><strong>Environ.</strong></td>
<td>Formulate a policy for the recovery of used products</td>
<td></td>
</tr>
</tbody>
</table>
Consider using existing forward supply chain facilities and transportation system for the reverse supply chain
Classify used products as early in the recovery chain as possible
Treat hazardous materials safely
Close the supply loop by recycling effectively and efficiently
Reduce the volume and amount of materials going to landfill and consider alternative uses of used products or wastes
Support the development of markets for recovered components and materials
Locate recycling facilities close to customer markets
Greening the internal and external business environment
Impose higher (and greener) standards on suppliers and cooperate closely with them
Highlight return, reuse and recovery mechanisms, make available the necessary product information concerning recycling and provide adequate safety instructions
Motivate customers and keep records of where they deliver used products or packages
Introduce the eco-objectives to the personnel
Establish flexible manufacturing and management policies
Use effective accounting systems and management tools
Extend service and enhance product function at the usage phase to improve eco-efficiency

<table>
<thead>
<tr>
<th>Lindsey (2010)</th>
<th>Establish product update policies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reduce wastefulness</td>
</tr>
<tr>
<td></td>
<td>Improving quality improves sustainability</td>
</tr>
<tr>
<td></td>
<td>Sustainability is best achieved through implementing better systems.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Despeisse et al. (2012)</th>
<th>Use less material and energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shift to biologically inspired production models</td>
</tr>
<tr>
<td></td>
<td>Move to solution-based business models</td>
</tr>
<tr>
<td></td>
<td>Reinvest in natural capital through substitution of input materials: non-toxic for toxic, renewable for non-renewable</td>
</tr>
</tbody>
</table>

From the group of studies addressing sustainability principles from a production perspective, the principles defined by LCSP in Veleva and Ellenbecker (2001) were the only ones to include consideration of the three dimensions of sustainability, while describing the sustainability principles from a production perspective. The LCSP principles encompass the main aspects of sustainable production: energy and material use, the natural environment, social justice and community development, economic performance, and workers and products (Veleva and Ellenbecker, 2001).
Table 4 shows the LCSP sustainable production principles, whilst considering the holistic perspective of sustainability, according to each of the three dimensions or the triple bottom line.

Table 4. LCSP principles of sustainable production (Veleva and Ellenbecker, 2001)

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Products and packaging are designed to be safe and ecologically sound throughout their life cycles; services are designed to be safe and ecologically sound.</td>
</tr>
<tr>
<td>2</td>
<td>Waste and ecologically incompatible by-products are reduced, eliminated or recycled.</td>
</tr>
<tr>
<td>3</td>
<td>Energy and materials are conserved, and the forms of energy and materials used are most appropriate for the desired ends.</td>
</tr>
<tr>
<td>4</td>
<td>Chemical substances or physical agents and conditions that present hazards to human health or the environment are eliminated.</td>
</tr>
<tr>
<td>5</td>
<td>Workplaces and technologies are designed to minimize or eliminate chemical, ergonomic and physical hazards.</td>
</tr>
<tr>
<td>6</td>
<td>Management is committed to an open, participatory process of continuous evaluation and improvement, focused on the long-term economic performance of the firm.</td>
</tr>
<tr>
<td>7</td>
<td>Work is organized to conserve and enhance the efficiency and creativity of employees.</td>
</tr>
<tr>
<td>8</td>
<td>The security and wellbeing of all employees is a priority, as is the continuous development of their talents and capacities.</td>
</tr>
<tr>
<td>9</td>
<td>The communities around workplaces are respected and enhanced economically, socially, culturally and physically; equity and fairness are promoted.</td>
</tr>
</tbody>
</table>

4.2 Current sustainable manufacturing practices

In order to gain a better understanding of the current sustainable manufacturing practices among practitioners, information on sustainable manufacturing practices was gathered from literature and in practice. The work in Papers I, II and III is used to clarify the main sustainability aspects being addressed through sustainable manufacturing practices among manufacturers.

4.2.1 Exploration of sustainable manufacturing practices published in the literature

The systematic literature review in Paper I presented insights collected from empirical papers, regarding how the manufacturing industry has
approached, and is currently working towards, attaining sustainability in its business operations. It was found that despite existing reviews on sustainable manufacturing practices, none of these reviews were specifically focused on empirical studies of sustainable manufacturing.

Similarly, the number of empirical studies about sustainable manufacturing only started increasing from 2009, where survey and case studies constituted the most popular research methods used. Figure 3, shows the distribution of papers addressing with respect to the addressed sustainability dimension in the depicted practices.

![Figure 3 Dimensions of sustainable development addressed in the sample (presented in Paper I)](image)

As seen in Figure 3, the systematic literature review indicated that the majority of empirical published studies addressed practices that concerned the environmental dimension of sustainability, followed by papers addressing the three dimensions (i.e. sustainable category) and the studies addressing the environmental and social dimension. The studies presenting industrial practices that addressed economic sustainability had the least number of papers in the sample, while papers exclusively concerned with social sustainability were absent.

Furthermore, Paper I identified that the most common environmental aspects studied were energy efficiency, solid waste, water use, and greenhouse gas emissions. Likewise, other environmentally-related topics such as emissions to water, air pollutants, hazardous waste, reuse and recycling and use of non-renewable natural resources were also popular to a lesser extent. Similarly, the review showed that environmental management systems (EMSs) were not popular in the sample. This last finding contrasts with the results in Paper II, where twelve manufacturing companies used ISO 14001 EMS, and highlighted the standard as a driver.
for adopting sustainability (Yüksel, 2008; Alshuwaikhat and Abubakar, 2008).

Regarding social sustainability, studies of employee’s health and safety conditions, education and training, and general working conditions were the most popular topics. Fair wages and benefits, or employee satisfaction, were also commonly studied, but to a lesser extent. However, social equity, fairness, or anti-discrimination constituted some of the issues not present in this sample. In relation to practices concerning economic sustainability, manufacturing costs and profitability were the issues most addressed. As a way of summarizing the different sustainability concerns found in the final sample of empirical journal papers, Table 5 shows the most common sustainability aspects addressed through sustainable manufacturing practices. The papers are presented according to common categories and subcategories within each of the three dimensions of sustainability.

Table 5. Categorization of reviewed papers by sustainability aspects that were addressed (presented in Paper I)

<table>
<thead>
<tr>
<th>Environmental dimension of sustainability</th>
<th>Category</th>
<th>Subcategory</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy</td>
<td>Clean energy use</td>
<td>Vinodh (2011); Jiang et al., (2012)</td>
</tr>
<tr>
<td></td>
<td>Natural resources</td>
<td>Use of non-renewable resources</td>
<td>Taplin et al., (2006); Morrow et al., (2007); Vinodh (2011); Jiang et al., (2012)</td>
</tr>
<tr>
<td>Category</td>
<td>Subcategory</td>
<td>References</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>----------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Natural resources</td>
<td>Water use</td>
<td>Erol and Thöming (2006); Morrow et al., (2007); Hahn et al., (2007); Pusavec et al., (2010); Law (2010); Fore and Mbohwa (2010); Menzel et al., (2010); Jiang et al., (2012)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air pollutants</td>
<td>Hahn et al., (2006); Fore and Mbohwa (2010); Vinodh (2011); Gimenez et al., (2012); Jiang et al., (2012)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Emissions to water</td>
<td>Erol and Thöming (2006); Morrow et al., (2007); Fore and Mbohwa (2010); Vinodh (2011); Jiang et al., (2012)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hazardous substances</td>
<td>Morrow et al., (2007); Fore and Mbohwa (2010)</td>
<td></td>
</tr>
<tr>
<td>Environmental management systems</td>
<td>Implementation of EMS (ISO 14001, EMAS etc.)</td>
<td>Burke and Gaughram (2007); Pusavec et al., (2010)</td>
<td></td>
</tr>
<tr>
<td><strong>Social dimension of sustainability</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stakeholders</td>
<td>Stakeholder involvement</td>
<td>Vinodh (2011)</td>
<td></td>
</tr>
<tr>
<td>Employee life quality</td>
<td>Fair wages and benefits</td>
<td>Pagell and Gobeli (2009); Vinodh (2011)</td>
<td></td>
</tr>
</tbody>
</table>
### 4.2.2 Exploration of sustainable manufacturing practices in a practical context.

Papers II and III described empirical evidence about the main sustainability aspects being addressed through sustainable manufacturing practices among manufacturers.

Paper II presented an overview of the current sustainable manufacturing practices commonly carried out within the manufacturing industry. The majority of sustainable manufacturing practices identified in Paper II focused on improving the environmental performance of the studied organizations, followed by socially-related practices, and economic-related practices. Thus, the growing trend in environmental sustainable manufacturing practices evidenced in the systematic literature in Paper I, was confirmed by the results in Paper II.
Referring to the environment, the identified practices addressed energy management, resource usage, and hazardous substances. Regarding social sustainability, the practices concerned the improvement of working safety conditions to minimize exposure to hazardous substances, improvement of employee efficiency and creativity, employee competence development, job satisfaction and employee wellbeing as well as practices referring to the development of local communities. Practices referring to economic sustainability addressed the economic and strategic performance of the company. Table 6 shows the practices identified in Paper II, grouped according to different subject categories within the three sustainability dimensions.

Table 6. Sustainable manufacturing practices

<table>
<thead>
<tr>
<th>Category</th>
<th>Sustainable manufacturing practices</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environment</strong></td>
<td>Employee training on energy savings&lt;br&gt;Mapping energy consumption to identify energy savings&lt;br&gt;Renewable energy&lt;br&gt;Bio-oil based central heating&lt;br&gt;Heat recovery and recycle using heat exchangers&lt;br&gt;Ventilation systems upgrade&lt;br&gt;Equipment upgrades for improving efficiency&lt;br&gt;Preventive equipment maintenance&lt;br&gt;Energy-efficient building automation systems&lt;br&gt;Energy audits&lt;br&gt;Prevention and correction of leakages&lt;br&gt;Energy metering&lt;br&gt;High efficient lamps and motion sensors&lt;br&gt;ISO 14001&lt;br&gt;Design for the environment&lt;br&gt;Design of energy efficient products</td>
</tr>
<tr>
<td><strong>Resources usage</strong></td>
<td>Material recycle and reuse&lt;br&gt;Material substitution for better efficiency&lt;br&gt;Material usage optimization&lt;br&gt;Process optimization&lt;br&gt;Monitoring of fresh water use&lt;br&gt;Recirculating water for cooling&lt;br&gt;Closed-loop water systems&lt;br&gt;Storm water usage for cooling processes&lt;br&gt;Operational performance indicators&lt;br&gt;Minimization of unnecessary packaging&lt;br&gt;Design for the environment</td>
</tr>
</tbody>
</table>
| **Environmental** | Hazardous substances substitution or elimination  
Tracking chemicals in processes and products  
Materials usage according to REACH and ROHS  
Training on hazardous substances  
Solvents substitution  
Air filtration and cleaning systems  
Heavy metals filtration  
Closed-loop process water systems  
Biologically-based wastewater treatment  
Oil leakage prevention  
Standard safety procedures  
Design for the environment  
Operational performance indicators |
|---|---|
| **Waste management** | Component and product design optimization  
Substitution of hazardous materials  
Redesigning of components for solid waste reduction  
Non-conforming products reduction  
Reuse and recycle of direct and indirect waste  
Employee training on sorting and waste reduction  
Process water and emulsions closed-loop systems  
External and on-site recycling  
Biological process for processing waste waters  
Donation of waste and by-products to other industries or institutions  
Minimization of unnecessary packaging  
Operational performance indicators  
Design for the environment  
ISO 14001 |
| **Social** | Robotic automation in hazardous activities  
Internal safety inspections  
External work environment audits  
Mechanical lifting aids  
Employees rotation between work stations  
Process modifications to reduce noise and vibrations  
Employee training on hazardous risks  
Key performance indicators |
| **Efficiency and creativity development of employees** | Work standardization  
Work accountability  
Employee improvement suggestions goals  
Rewards for applicable improvement suggestions  
Team work  
Improvement meetings  
Key performance indicators |
Thus, the empirical results from Paper II support the results from the systematic review about sustainable manufacturing practices presented in Paper I, as findings showed that the most popular type of sustainable manufacturing practices adopted among the participant companies were those addressing energy and waste management.

As stated in the research design of this thesis (section 3.1) Paper III answers indirectly and partially, RQ2. Paper III does not present direct results from commonly adopted sustainable manufacturing practices (as in Papers I and II), but instead describes the sustainable practices perceived by managers that are needed to overcome sector-specific challenges for adopting sustainable manufacturing.

Paper III starts by identifying the challenges identified by managers from surface treatment SMEs for improving the sustainability of their operations. Further, Paper III identifies the enablers needed to assist these companies on their way towards sustainable manufacturing. The enablers are interpreted as practices perceived to be needed to overcome sector-specific challenges, and hence contribute to making their operations more sustainable.

| Competence development, job satisfaction and wellbeing for employees | Health and safety management system  
Training plans  
Career development programs  
Employee rotation  
Scholarships  
Subsides for health and wellbeing purposes  
Job satisfaction assessment  
Performance appraisal  
ISO 9001 supporting training and competence  
Key performance indicators |
|---|---|
| Community development | Job opportunities for locals  
Collaborations with educational institutions  
Periodical meetings with local authorities  
Volunteering work within local communities  
Sponsoring local associations |
| Economic and strategic performance | Strategic sustainability and functional goals display  
Technology investments prioritization considering environment, safety, quality and economic aspects  
Communicating with employees about strategic plans, targets and results  
ISO 9001 for managerial continuously evaluation  
Financial key performance indicators |
Table 7 shows the identified challenges and the perceived practices needed to overcome the challenges for sustainability, grouped according to the sustainability dimension the challenges mainly refer to.

Table 7. Challenges for sustainable manufacturing and manufacturing practices needed to overcome them

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Description</th>
<th>Perceived practices needed for overcoming challenges for sustainable manufacturing.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economic sustainability</td>
<td>Economic profitability</td>
<td>• Investments to develop and improve employee skills</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Marketing promoting customer preference towards national companies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Improvement of company’s internal flow (i.e. changing factory layout, internal facility logistics)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Engage in activities that aim to increase customer awareness of these SMEs’ economic struggle (i.e. price adjustments to meet environmental and social regulation)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Lead time reduction (improve operations)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Strengthen the collaboration in the cluster of surface treatment SMEs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reduce energy consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Reduce waste generation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Technology investment (automation for material handling)</td>
</tr>
<tr>
<td>Technology development</td>
<td>Lack of technologies to streamline operations. Lack of technology suppliers. Lack of alternative chemicals.</td>
<td></td>
</tr>
<tr>
<td>Social sustainability</td>
<td>Working procedures</td>
<td>• Prioritize health and safety issues within the company</td>
</tr>
<tr>
<td></td>
<td>Problems attracting workers and maintaining competence</td>
<td>• Improve knowledge management</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Improve recruitment process</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Improve the development of employee talents and skills</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Invest in modern, attractive and clean plant facilities</td>
</tr>
</tbody>
</table>
Change resistance | Adapting to international competition.  
| • Technology investment (automation for material handling)  
| • Increase collaboration with schools and academics

Environmental sustainability

Meeting Environmental Requirements | Difficulties in understanding and applying environmental requirements (e.g. chemicals legislation and Best Available Technology - BAT)  
| • To work with active, engaged and collaborative technology suppliers  
| • Engage in activities aimed at increasing customers’ awareness of additional environmental regulation compliance costs  
| • To be financially capable of investing in new equipment.  
| • Increase the knowledge of understanding and implementing legislation  
| • Engage in activities aiming to increase customer awareness of costs of environmental sustainability  
| • Government subsidized investments.  
| • Increase collaboration with schools and academics

The identified challenges for sustainability within the surface treatment SMEs are: 1) economic profitability; 2) working procedures that streamline operations; 3) meeting environmental requirements; 4) ensuring a long-term workforce, and 5) technology development.

Regarding the perceived practices needed for attaining sustainable operations, the majority of these practices were found to correspond to the challenges related to economic sustainability.

The fact that the majority of sustainable manufacturing practices needed in Paper III were associated with economic sustainability indicates that, at present, these organizations are facing significant difficulties in achieving economic sustainability. This shows that more effort needs to be applied to design and implement sustainable manufacturing practices that improve the economic performance of these companies.

Likewise, this predominance of the sustainable manufacturing practices needed identified in the sample might indicate that, at present, environmentally and socially sustainable manufacturing practices are being carried out to a higher extent.

Finally, this noticeable trend of environmental sustainability practices agrees well with the results on sustainable manufacturing practices identified in Papers I and II, where the majority of sustainability practices
were concerned with the mitigation, reduction or elimination of the environmental risks associated with the operations.

4.3 Adherence of sustainable manufacturing practices to sustainable manufacturing principles

Paper II fully answers RQ3 by providing insights into how manufacturers within different industry sectors carry out sustainable manufacturing practices that adhere to LCSP sustainability production principles.

Results showed that, from all the LCSP sustainable production principles, the principles referring to energy and materials conservation (Principle 3), and waste management (Principle 2) rendered the highest number of sustainable manufacturing practices mentioned by the respondents. This finding also indicated that the studied companies are currently focusing most on improving the environmental performance in their operations, something evidenced by the large number of environmentally sustainable manufacturing practices mentioned.

Results showed that the studied companies associated product safety with safe material use approved by the European Union legislation, and adoption of life cycle considerations early in the product design stage (but the latter only within large organizations). Similarly, safe and ecologically friendly packaging was linked with environmental and quality considerations in packaging decisions.

Regarding waste management (Principle 2), the respondents mentioned source reduction practices associated with prevention, minimization and reuse of waste. Product redesign and material reuse also constituted a common source reduction practice. Similarly, operational performance indicators – OPIs – were used by these companies to quantify waste, carry out quality assurance, and reduce the use of non-conforming products. Also, most of the companies tried to reduce the amount of solid waste sent to landfills through recycling and reusing waste practices. There was a common perception among the companies about waste being perceived as a burden with high economic impact. When considering the role of employees in waste management, most of the respondents stressed the importance of training in waste sorting, as employees are vital for succeeding in waste sorting initiatives. Further, the role of environmental management systems (EMS), specifically ISO 14001, was highlighted by most of the companies which consider ISO 14001 an enabler to continuously reduce waste, set environmental goals, and keep track of safe materials, chemical and oils.
Regarding energy management (Principle 3), all companies reported that they measured and tracked energy consumption, and had energy saving goals supported, in most cases, by their environmental management systems. Employees were acknowledged as critical to saving energy. Referring to renewable energy, most of the companies used district heating from waste incineration. Relating to energy efficiency, LED lighting, heat recovery and the use of energy-efficient machines were common practices. Energy-related job roles were not common among respondents. Further, when considering the conservation and reduction of materials, the majority of companies associated it as a responsibility for R&D. In relation to fresh water, most of the companies monitored fresh water use and installed closed-loop water systems to reduce fresh water consumption, allowing multi-purpose water usage within processes, and a reduction in wastewater generation.

Referring to hazardous substances (Principle 4), the tracking of chemical use in products and processes conforming to the European Union legislation REACH, as well as standard safety procedures for work practices, were found to be common practice within all the studied companies. Substitutions of potentially hazardous chemicals were approached proactively by most of the large companies, that also mentioned having a good deal of experience in reducing their use of volatile organic compounds (VOCs) and carbon dioxide (CO2).

In relation to the reduction of the risks workers are exposed to (Principle 5), all companies kept statistics to assess the extent to which employees were protected from work-related hazards. Similarly, all respondents stressed the importance of internal workstation risk assessment on health and safety. Robotic automation was also very common for eliminating ergonomic and safety risks. Further, all companies mentioned that they carried out internal inspections and controlled noise, vibration, and lighting conditions. Companies highlighted the critical role in risk reduction played by continuous employee training in hazardous risks identification, as well as in the reporting of accidents and incidents. Most companies stated that sustainable manufacturing practices helped to ensure that workplaces were being kept safe in accordance with the requirements set by the Work Environment Authority in Sweden.

Among the practices related to sustainable economic performance (Principle 6), follow-up of financial indicators, provision of high quality products satisfying customer specifications, and reducing company costs were associated by most of the companies with having long-term economic viability. Thus, the use of financial key performance indicators – KPIs – to measure, monitor and assess was mentioned by all the companies.
Another common practice was the integration of sustainability elements within the strategic planning. Likewise, management review, within ISO 9001, was mentioned by many companies to support the continuous evaluation of the company in respect of economic, environmental, quality and safety aspects. Similarly, all respondents emphasized the importance of continuously sharing information, at all levels of the company, concerning the strategic plan, goals, targets and performance, thus helping to increase employee awareness and commitment towards achieving its goals.

Regarding Principle 7, respondents associated employee efficiency with work standardization, and hence, formalization of processes. Teamwork, as well as encouraging, quantifying and setting goals for the number of employee improvement suggestions were common practices among companies to promote employee creativity. Operator knowledge and expertise were mentioned as critical for generating improvement suggestions.

Regarding Principle 8, companies highlighted the role of health and safety management systems for assessing and monitoring risks as a way of ensuring employee security. Referring to the continuous development of talents and capacities, all respondents highlighted the importance of training plans, job rotation, and employee performance evaluation. ISO 9001 was acknowledged by many respondents as a tool for systematically working with employee training and competence. Likewise, ISO 9001 (specifically the managerial review meetings) was acknowledged to promote the discussion at a managerial level about concerns on industrial safety, training needs, work environment, and environmental issues.

In relation to community development addressed by Principle 9, respondents mentioned that their companies enhanced local communities by providing job opportunities, collaborating with educational institutions, and providing fair wages and good working conditions. Among common practices mentioned related to this principle were participation in research projects with local universities, summer job and thesis opportunities, as well as regular meetings with the local authorities. Large companies were found to contribute economically to volunteering work, as well as by providing sponsorship for local events and some sports teams.

A summary of the identified sustainable manufacturing practices showing empirical adherence to the LCSP production principles is given in Table 8. Full results are presented in the appended Paper II.
Table 8. List of sustainable manufacturing practices (described in Paper II)

<table>
<thead>
<tr>
<th>LCSP principles</th>
<th>Sustainable manufacturing practices</th>
</tr>
</thead>
</table>
| 1. Products and packaging are designed to be safe and ecologically sound through their life cycles; services are designed to be safe and ecologically sound. | Material usage according to REACH and ROHS in processes and products  
Hazardous substances substitution or elimination in products and processes  
Consideration of disassembly, reuse and recycling during product design  
Eco-design assisted by customers  
Recyclability and reuse of incoming materials’ packaging  
Design of energy efficient products  
Minimization of unnecessary packaging  
Design for the environment (DfE) |
| 2. Waste and ecologically incompatible by-products are reduced, eliminated or recycled. | Component and product design optimization  
Substitution of hazardous materials  
Redesigning of components to reduce solid waste  
Non-conforming products reduction  
Reuse and recycle direct and indirect waste  
Employee training in sorting and waste reduction  
Process water and emulsions closed-loop systems  
External and on-site recycling  
Biological process for processing waste water  
Donation of waste and by-products to other industries or institutions  
Operational performance indicators  
ISO 14001 |
| 3. Energy and materials are conserved, and the forms of energy and materials used are most appropriate for the desired ends. | Employee training in energy saving  
Mapping energy consumption for identifying energy saving  
Renewable energy  
Bio-oil based heating centrals  
Heat recovery and recycle using heat exchangers  
Ventilation systems upgrade  
Equipment upgrades to improve efficiency  
Preventive equipment maintenance  
Energy-efficient building automation systems  
Energy audits  
Prevention and correction of leakages in compressed air systems  
Energy metering  
High-efficiency lamps and motion sensors  
Material recycle and reuse  
Material substitution for better efficiency  
Material usage optimization |
<table>
<thead>
<tr>
<th>Process optimization</th>
<th>Hazardous substances substitution or elimination in processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitor fresh water use</td>
<td>Tracking chemicals in processes and products</td>
</tr>
<tr>
<td>Recirculating water for cooling</td>
<td>Materials usage in processes and products</td>
</tr>
<tr>
<td>Closed-loop water systems</td>
<td>according to REACH and ROHS</td>
</tr>
<tr>
<td>Stormwater usage for cooling processes</td>
<td>Training in hazardous substances</td>
</tr>
<tr>
<td>Operational performance indicators</td>
<td>Solvents substitution</td>
</tr>
<tr>
<td>ISO 14001</td>
<td>Air filtration and cleaning systems</td>
</tr>
<tr>
<td></td>
<td>Heavy metals filtration</td>
</tr>
<tr>
<td></td>
<td>Closed-loop process water systems</td>
</tr>
<tr>
<td></td>
<td>Biologically-based wastewater treatment</td>
</tr>
<tr>
<td></td>
<td>Oil leakage prevention</td>
</tr>
<tr>
<td></td>
<td>Standard safety procedures</td>
</tr>
<tr>
<td></td>
<td>Operational performance indicators</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4. Chemical substances or physical agents and conditions that present hazards to human health or the environment are eliminated.</th>
<th>Work places and technologies are designed to minimize or eliminate chemical, ergonomic and physical hazards.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robotic automation in hazardous activities</td>
<td>Internal safety inspections</td>
</tr>
<tr>
<td></td>
<td>External work environment audits (regulation authorities)</td>
</tr>
<tr>
<td></td>
<td>Mechanical lifting aids</td>
</tr>
<tr>
<td></td>
<td>Employee rotation between workstations</td>
</tr>
<tr>
<td></td>
<td>Process modifications to reduce noise and vibrations</td>
</tr>
<tr>
<td></td>
<td>Employee training in hazardous risks</td>
</tr>
<tr>
<td></td>
<td>Key performance indicators</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>6. Management is committed to an open, participatory process of continuous evaluation and improvement, focused on the long-term economic performance of the firm.</th>
<th>Strategic sustainability and functional goals display throughout the plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology investments prioritization (considering environment, safety, quality and economic aspects)</td>
<td>Communicating with employees about strategic plans, targets and results</td>
</tr>
<tr>
<td></td>
<td>ISO 9001 for continuous managerial evaluation</td>
</tr>
<tr>
<td></td>
<td>Financial key performance indicators</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>7. Work is organized to conserve and enhance the efficiency</th>
<th>Work standardization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Work accountability</td>
<td>Employee improvement suggestions goals</td>
</tr>
<tr>
<td></td>
<td>Rewards for applicable improvement suggestions from employees</td>
</tr>
</tbody>
</table>
and creativity of employees.

<table>
<thead>
<tr>
<th>Teamwork</th>
<th>Improvement meetings</th>
<th>Key performance indicators</th>
</tr>
</thead>
</table>

8. The security and wellbeing of employees is a priority, as is the continuous development of their talents and capacities.

<table>
<thead>
<tr>
<th>Health and safety management system</th>
<th>Training plans</th>
<th>Career development programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Employee rotation</td>
<td>Scholarships</td>
<td>Subsides for health and wellbeing purposes</td>
</tr>
<tr>
<td>Job satisfaction assessment</td>
<td>Performance appraisal</td>
<td>ISO 9001 supporting training and competence</td>
</tr>
<tr>
<td>Key performance indicators</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9. The communities around workplaces are respected and enhanced economically, socially, culturally and physically.

<table>
<thead>
<tr>
<th>Job opportunities for local residents</th>
<th>Collaboration with educational institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regular meetings with local authorities</td>
<td>Volunteering work within local communities</td>
</tr>
<tr>
<td>Sponsoring local associations</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER 5
Discussion and conclusions

This chapter starts with a general discussion of the research results followed by a discussion of the methods used. Thereafter, conclusions are drawn and the three research questions are answered. Finally, the academic and industrial contributions, as well as future research, are presented.

5.1 Discussion

At the beginning of this kappa, a research gap was identified, the filling of which required additional studies exploring sustainable manufacturing practices (Despeisse et al., 2012; Roberts and Ball, 2014), that took into account the three dimensions of sustainability. Similarly, the scientific literature also identified the need for additional studies addressing the operationalization of conceptual sustainability principles (Shrivastava and Berger, 2010). Sustainable manufacturing practices and sustainable manufacturing principles constituted the two main elements of study in this research, and therefore the purpose of the research presented in this thesis has been:

“to contribute to the existing body of knowledge regarding sustainable manufacturing principles and practices.”

In order to fulfill this purpose, the following three research questions have been addressed:

RQ1. What is the current state in the literature regarding sustainability principles aimed at manufacturing industries?

RQ2. What are the main sustainability aspects that current sustainable manufacturing practices are responding to?

RQ3. How do manufacturing practices adhere to sustainable manufacturing principles?

The first research question was aimed at identifying the current state of sustainability principles that could be potentially implemented within a
manufacturing context. As the research adopted an exploratory approach to study sustainable manufacturing principles, a literature review was useful to identify and provide an overview of the published sustainability principles applicable to manufacturing settings. The outcome of this study was taken from a WIP paper (not appended), with the main findings briefly introduced in this kappa (section 2.3), and described in more detail later in the results section (4.1) and in Table 3.

The overview of sustainability principles described in section 2.2 showed that, in operations management and sustainability management literature, sustainability principles have been seldom described or explored in a practical context. Interestingly, the majority of sustainability principles have been designed at a policy or governmental level, or directed towards a specific industrial sector as an attempt to address sustainable development in these contexts. Most of these principles were found to fall short when it came to applying sustainability principles to the shop floor, or in other words, to apply these sustainability principles to the actual production process.

Among the set of studies published that introduced sustainability principles from an operative perspective (e.g. Gladwin et al., 1995; Al-Yousfi, 2004; Veleva and Ellenbecker, 2001; Tsoulsas and Pappis, 2006; Lindsey, 2011; Despeisse et al., 2012), only the LCSP sustainable production principles by Veleva and Ellenbecker succeeded in involving the three dimensions of sustainability, and also encompassing the main aspects of sustainable production (i.e. energy and material use, the natural environment, social justice and community development, economic performance, workers and products).

Although some sustainability principles claimed to be operationally prescriptive, most of them failed to include the three dimensions of sustainability clearly. For example, despite the fact that Al-Yousfi (2004) referred to economic considerations in one of the four principles, consideration of social sustainability was not clearly explicit in these set of principles, showing that they still seemed heavily focused on environmental sustainability. Likewise, the principles described by Tsoulsas and Pappis (2006) did not include in its formulation consideration of the social and economic dimensions of sustainability. Furthermore, despite that Lindsey’s principles are grounded on pollution prevention techniques, repercussions on the social and economic sustainability dimensions were referred to emerge from these postulates.

In addition, the broad character of some principles (e.g. Gladwin et al., 1995; Al-Yousfi, 2004; Lindsey, 2011; and Despeisse et al., 2012) might potentially create an issue when it comes to operationalize the conceptual principles, especially by companies with little expertise in sustainability.
Due to the wording or formulation of the above mentioned set of principles, they are not specific enough and do not make a straightforward guide of actions that manufacturing companies might follow when aiming to have sustainable operations. This broad character contrasts with the principles of Velleva and Ellenbecker (2001) and Tsouflas and Pappis (2006), which were more explicitly formulated and operationally prescriptive. It could therefore be said that these principles are more likely to be operationalized by organizations.

There may be several reasons why, among the few studies discussing sustainability principles from an operative perspective, only the LCSP principles by Velleva and Ellenbecker (2001) succeeded in involving the three dimensions of sustainability, while prescriptively formulating the principles from an operational perspective. First, it could be an indication that the research field of sustainable manufacturing principles is still in its infancy. This idea is supported by conclusive remarks done by Despeisse et al. (2012, p.360), who stated “the translation of sustainable manufacturing principles into an operational activity is still a blind spot”. Second, it could be a sign that environmental aspects are the most relevant and crucial ones from the triple bottom line to be addressed not only because of the associated environmental impacts, but also because of the potentially damaging repercussions on the social and economic dimensions. Third, the environmental focus of the principles might be a consequence of the researchers or institutions addressing such principles coming from an environmental background.

The second research question first identified sustainable manufacturing practices, so that how sustainability is reflected in operations could be analyzed later. Thus, this part of the study explored current sustainable manufacturing practices. The research in Paper I (see Table 5) and Paper II (see Table 6) helped to answer RQ2 by identifying the main sustainability aspects being targeted by the adoption of sustainable manufacturing practices. The work in Paper III indirectly addressed this question by presenting sustainable practices that the surface treatment SMEs needed to adopt in order to overcome sector specific challenges.

In operations management and sustainability literature, sustainable manufacturing practices have been mostly defined from an environmental perspective, and currently are not being addressed from a triple bottom line perspective. This research’s findings were seen to be consistent with both the findings from the systematic literature review (Paper I) and the empirical data (Paper II). This is in agreement with previous authors stating that the majority of sustainability manufacturing practices refer to
The predominance of environmentally-related manufacturing practices might be due to several reasons. One reason could be the strong practitioner’s association of the term sustainability to environmental issues, thus producing a strong bias towards the environmental dimension of sustainability. This reason agrees with the common understanding of sustainable development as being “one dimensional” and often being reduced to environmental improvements (Seuring and Müller, 2008). Likewise, the strong association of the term sustainability to the environment could be rooted in the lack of consensus among scholars on the definition of sustainability (Berns et al., 2009). Another reason could be that such environmental bias could be a consequence of economic and work organizational issues being constantly addressed in the literature ahead of research on environmental considerations in manufacturing. This is, as economic performance was for many decades, the traditional bottom line for assessing companies (Clarkson, 1995). Therefore, environmental issues have been considered as “the new thing”, creating an increasing interest in researching these issues. Thus, the bias might have a logical basis. A final reason may be because of increased public awareness of the environmental problems the world is facing and a realization that, without action, there could be irreversible consequences for the planet (Vermeir and Verbeke, 2006; UNEP, 2012; Nielsen; 2015).

Specifically, from the empirical findings presented in Paper II, it can be seen that the most common sustainable manufacturing practices referred to energy and material management, and waste management. This finding might be motivated by the economic savings, increased competitiveness and higher productivity resulting from improved energy efficiency (Yüksel, 2007; Thollander et al., 2013). In a similar way, the identified popularity of waste management-related practices among practitioners agrees with previous studies (Montabon et al., 2007) which have stated that recycling and waste reduction practices are acknowledged as one of the practices having the greatest effect on a firm’s performance. The economic motivations behind the findings in this research also agree with a mainstream idea suggested by Castro (2004), who stated that sustainable development is still mostly associated with its development component. This idea implies that environmental considerations within companies are taken only if they are compatible with the firm’s main goal of promoting economic growth. This means that the mainstream view of sustainable development is that it is primarily concerned with sustaining development, instead of developing sustainability.
The results in the papers appended to this *kappa* also supported each other’s findings. Paper I identified an imbalance of published empirical research between the three sustainability dimensions with a significant bias towards the environmental perspective, specifically towards energy efficiency and solid waste. Thus, the results in Paper I agree with the empirical results from Paper II, where the majority of sustainable manufacturing practices mentioned addressed energy efficiency and solid waste management aspects.

Sustainable manufacturing practices addressing the economic dimension of sustainability have not been thoroughly analyzed in comparison to the volume of mentioned practices regarding environmental sustainability. This was observed both in Paper I and Paper II. The systematic literature review in Paper I identified that, within economic sustainability, the studies relating to manufacturing costs (e.g. Foulds et al., 2006; Tan et al., 2006; Solding et al., 2009; Vinodh, 2011; Gimenez et al., 2012) and profitability (e.g. Menzel et al., 2010; Vinodh, 2011; Wolf, 2013) formed the most addressed topic in this dimension. Nevertheless, the empirical data in Paper II showed that the majority of practices focused on financial key performance indicators, displays of strategic sustainability and functional goals, environmentally and socially responsible investment decisions, and ISO 9001 for continuous managerial evaluation. Among sustainable manufacturing practices, none were mentioned that referred to tools or techniques related to finance, or internal and external reporting (Cerf and Savage, 2009).

The third research question required the analysis of how manufacturers operations currently adhere to sustainable manufacturing principles. The results from Paper II fully answered this research question by exploring adherence to the LCSP sustainable production principles in practice, involving both large and SME manufacturing companies, and addressing the three dimensions of sustainability.

For this research question, again the results confirmed the predominance of the environmental dimension of sustainability, evidenced by the large number of environmentally sustainable manufacturing practices mentioned in relation to the sustainable manufacturing principles. This is not a surprising finding, as the results that answered both RQ1 and RQ2 indicated the majority of sustainable principles and practices in the literature relate to environmental matters.

The principles referring to energy and materials conservation, and waste management represented the highest number of practices. This results alike the findings from the RQ2, might be due to the cost reduction benefit implicit in energy, material efficiency, and waste elimination, increased company competitiveness, improved productivity, and because
of the limited availability of energy and material resources (Yüksel, 2007; Thollander et al., 2013). The popularity of waste management-related manufacturing practices might have also been motivated by economic reasons, as waste generation is usually associated with production process inefficiency. Previous studies, such as Montabon et al. (2007), have also identified the high demand for waste management-related practices, where recycling and waste reduction practices are acknowledged as some of those having the strongest effect on a firm’s performance.

Similarly, the adoption of environmentally sustainable manufacturing practices was found to be driven by pressures from customers and stakeholders (González-Benito and González-Benito, 2005; Mollenkopf et al., 2010). It is relevant to highlight the pressure large companies, as customers, exert on SMEs for improving environmental sustainability performance. Dependency on these customers, and fear of losing market share, were mentioned as motivation for SMEs to adopt sustainable manufacturing practices in order to fulfill the requirements of large companies.

The relationship between the main focus on sustainable manufacturing practices related to energy, materials and waste minimization, and the influence exerted by the implementation of Lean production and environmental management systems – EMS – was discussed in Paper II. In line with previous studies (Yuksel, 2008; Alshuwaikhat and Abubakar, 2008; Giunipero et al., 2012), the research presented in this thesis identified that ISO 14001 EMS is a significant driver for sustainability, by encouraging organizations to implement more environmental manufacturing practices. The importance given by companies to environmental management systems when complying with environmental sustainability is based on the fact that ISO 14001 considers the policies, strategies, procedures and practices that organizations use as a response to the environmental impact produced by their operations (Lazlo et al., 2013).

As with Paper II (RQ3), the results of the literature review in Paper I (RQ2) indicated that the majority of published empirical studies concerned the environmental dimension of sustainability, where practices addressing energy efficiency, solid waste, water use and greenhouse gas emissions were the most popular. These findings indicate that the most common sustainability practices in scientific literature are heavily connected to the sustainable production Principles 2 and 3, addressing waste management, and energy and materials management and waste management (as with the empirical results obtained in Paper II). This predominance of manufacturing endeavors related to energy and material conservation, and waste reduction might be rooted in the inclusion of environmental
considerations within manufacturing systems, also known as green production systems (Kruszewska and Thorpe, 1995), or integrated lean and green production systems (Kurdve, 2014). The later as lean and green production systems are paradigms sharing a common goal of waste elimination (King and Lenox, 2001). Nevertheless, as stated by Kurdve (2014, p.90), “a green lean production system may be one important step towards attaining sustainable production system”.

Another discussion point is the recognition of the Swedish environmental and social regulations as a common method by which manufacturers comply with environmental and socially-related manufacturing principles. In Papers II and III, it was shown that environmental and socially-related sustainable manufacturing practices were perceived by manufacturers to be driven by the environmental and social regulations established by the Swedish government, the Swedish environmental agency, and the Swedish work environment authority. This finding is consistent with previous research (Zhu and Sarkis, 2006; Jones, 2010) which has highlighted the role of national regulation as an important driver influencing firms’ environmental responsiveness, as well as the acknowledgement of national regulation as the sustainability component with the strongest impact on businesses (Berns et al., 2009). Considering the role of Swedish regulation as a sustainability driver, and also as a common way for compliance with environmental and socially-related principles, it can thus be argued that, for the majority of studied companies, the adherence to the sustainable manufacturing principles might be caused by reactive behaviors (Azzone and Noci, 1998) to meet regulatory and market pressures. In this context, reactive behaviors are those whereby a firm’s intention is only to comply with regulations or customer requirements, while proactive behaviors are those that go beyond regulation or anticipate competitors’ concerns (Azzone and Noci, 1998).

However, in some exceptional cases, specific manufacturing sectors (e.g. foundries, metalworking and engine manufacturers) are apparently engaged in more proactive sustainable practices than others. This might be as the industries supplied by these sectors (automotive and transport) have spent a longer time working on sustainability along all stages of the product’s life cycle.

Likewise, Quality Management systems (ISO 9001) were perceived by some companies as another common mechanism by which manufacturers complied with social and economically-related sustainability principles. Although ISO 9001 standard systems emphasize conformity of procedures within organizations, there may a reason why companies mentioned to use this standard when complying with social and economic principles. The reason is that while ISO 14001 is widely
associated with environmental concerns, ISO 9001:2000 improves companies by integrating a process focus and systems approach for continuous management evaluation, and by supporting training and competence. Not only are ISO standards easy to integrate with each other, but they are also highly regarded by their users. Other authors have also mentioned that these standards in general have been praised for helping companies to move towards sustainable manufacturing (Lazlo et al., 2013). Apart from quality and environmental management systems, some production systems (specifically within large organizations), have acted as important tools for putting some sustainability principles into practice.

The adherence to LCSP principles varies not only according to industrial sector but also according to organizational size, as was shown in Paper II. Empirical findings showed that while SMEs rarely complied with the LCSP sustainability principles, large companies often exhibited more proactive practices which anticipated or exceeded regulation. This finding is supported by previous research suggesting that a firm’s size explains proactive behaviors, as large enterprises are more proactively engaged in environmental management initiatives (Singh et al., 2014), and usually employ a higher number of sustainability practices compared to SMEs. (Brower and Mahajan, 2013).

Regarding management, leadership, as presented in Paper III, was found to have a relevant role in attaining the firm’s sustainability goals. This agrees with Courtice (2013), who stated that in order to embed sustainable manufacturing principles into practices, organizations should invest in integrating sustainability into their mainstream leadership and management development programs. This is closely connected with a successful integration of the sustainability principles into the firm’s values, vision and strategy.

Among other drivers of undertaking sustainability practices in SMEs, pointed out and discussed in Papers II and III, were the role of the requirements of large companies who are customers, market dependency, and employee retention.
Finally, another point to consider is that the empirical results presented in Paper II support the findings from the systematic literature review of the common sustainability practices in Paper I. It can thus be said that the practices identified from Paper I reflect the solid adherence of the sustainable manufacturing practices to the sustainable production Principles 2 and 3 which address waste management, and energy and materials, and waste management.

5.2 Discussion of the research method used

As is well known, the choice of research method used for answering the three research questions has implications for the scope of the conclusions (Yin, 2009).

Considering that RQ1 explored the current state of sustainable principles applicable to manufacturing settings, this exploratory question was answered by using a traditional literature review (WIP paper, not appended), and semi-structured interview (Paper II).

When researching what the main sustainability aspects are that current sustainable manufacturing practices respond to (RQ2), the timescale used in the systematic literature review for identifying empirical papers describing sustainable manufacturing initiatives could represent a limitation to identifying a broader range of sustainability practices. The fact that only journal papers published between 2000 and 2012 were included could have left out some relevant sustainable manufacturing practices from 1987, the year when sustainable development was first defined.

Complementing the literature reviews, semi-structured interviews, focus groups, and online questionnaires were used for answering the exploratory questions RQ2 and RQ3. These data collection tools reflect the survey character of the research presented in this study. This as survey type of research tries to collect information from either all or a part of a population, using a variety of data collection tools, where the most common ones are questionnaires or interviews (Tanner, 2002).

Regarding the generalizability of the findings, although Paper II describes results from 12 companies in five different manufacturing sectors, the results about the adherence of sustainable manufacturing practices to the principles do not attempt to draw statistical generalizations to these five sectors, but instead, the results are only valid for the particular studied companies. The same logic applies to the results from Paper III, which provide an overview of the challenges and enablers perceived by
surface treatment SMEs, rather than interpreting the results as generalizations within the SMEs surface treatment sector.

An additional aspect that might have affected the results was the choice of key respondents participating in the semi-structured interviews (Paper II), focus groups and online questionnaires (Paper III).

It is relevant to discuss the impact of the low response rate to the online questionnaire (Paper III) on this research. The low response rate particularly affected the results in Paper III about the perceived importance of the challenges and enablers for adopting sustainable production in SMEs. However, although the low response rate might raise questions of the validity of the results for this paper, the use of multiple data collection tools in Paper III lessened the impact on the results’ validity to an extent. Finally, it is worth to mention that despite that a measure was taken to correct this low response rate (i.e. reminders sent to respondents), the impact that the low response rate had on the general results presented in this kappa was not significant, due to the results from Paper III contributed to answer only partially the RQ2.

5.3 Conclusions

This research aimed to contribute to the existing body of knowledge regarding sustainable manufacturing principles and practices, providing empirical evidence about the connection between sustainable manufacturing principles (involving the three dimensions of sustainability) and sustainable manufacturing practices (including large enterprises and SMEs).

With regards to the current state of sustainability principles that could be potentially implemented within a manufacturing context, the systematic literature review concluded that currently there is only a small body of knowledge introducing and discussing sustainability principles from an operative or manufacturing perspective. The number of studies discussing the three dimensions of sustainability in a manufacturing setting is even smaller.

Results showed that the majority of studies addressing sustainability principles refer mostly to policies and programs addressing sustainable development. Few discussed applying sustainability principles to the shop floor, or using these sustainability principles within actual production processes. Thus, it was found that only the LCSP sustainable production principles described by Veleva and Ellenbecker (2001) involved the three dimensions of sustainability and also encompassed the main aspects of sustainable production. It can also be concluded that relatively few studies
have examined the operationalization of sustainable production principles, as well as the connections between sustainable manufacturing principles and practices.

With respect to sustainable manufacturing practices, it is possible to conclude that the most common practices refer to energy and material management, and waste management, possibly motivated by improved energy efficiency which results in economic savings, increased competitiveness and higher productivity.

In relation to how manufacturers’ operations currently adhere to sustainable manufacturing principles, it can be concluded that the majority of practitioners still engage in reactive sustainability practices driven by regulatory and market pressure, with the exception of specific manufacturing sectors (e.g. foundries, metalworking and engine manufacturing) that apparently engage in more proactive sustainable practices than others (to be further investigated).

Concerning the adherence to sustainable manufacturing principles, it can be concluded that the sustainable production principles concerning energy and materials conservation, and waste management were linked to the highest number of practices. This clearly shows that sustainable manufacturing practices are still predominantly focused on the environmental dimension of sustainability. As the majority sustainable manufacturing practices responded to improve performance of the environmental sustainability dimension.

Also, LCSP principles were found to be described well enough to be used by any size or type of organization. This is because they are prescriptive, specific and address the most relevant sustainability-related aspects from an operative viewpoint.

The adherence to LCSP principles was seen to vary according to organizational size: while SMEs rarely complied with principles, large companies used more proactive practices, anticipating or exceeding regulations. The requirements of large companies as customers, market dependency, and employee retention were seen to drive sustainability practices in SMEs.

It was also identified that suppliers of the automotive and transport industries (foundries, metalworking and engine manufacturing sectors), that generate large environmental and social impacts along all stages of their product's life cycle (Koplin et al., 2007), were found to undertake more proactive sustainable initiatives.

Finally, the research’s findings indicate that there is still a clear imbalance of sustainable manufacturing practices between the three sustainability dimensions, with a significant bias towards the
environmental perspective, specifically towards practices related to energy efficiency and solid waste.

5.4 Scientific and industrial contribution of the research

The research presented in this thesis contributes to expand the body of knowledge of sustainable manufacturing practices by presenting both literature and empirical evidence of how manufacturing industry has approached and implemented sustainability in its business operations.

This research makes an academic contribution in the area of sustainability management. Based on analysis of both empirical data gathered from large Swedish enterprises and SMEs using sustainable manufacturing practices (Papers II and III), and also from a traditional literature review (Paper I), the research has aimed at providing insights regarding the operationalization of sustainable manufacturing principles, and the sustainable manufacturing practices reflecting these principles.

Furthermore, by shedding light on the operationalization of conceptual sustainable manufacturing principles, this research constitutes a rare effort to explore the adherence to sustainable production principles through the adoption of sustainable manufacturing practices involving both large companies and SMEs, while addressing the three dimensions of sustainability.

The research not only explores the sustainability principles from an operative perspective, filling the gaps in current literature regarding how manufacturing companies translate sustainability into sustainable manufacturing practices. But, it also adds to the general discourse on how industry adopts principles of sustainability and applies them in practice.

Considering that further studies are needed to promote theoretical and practical advances in the research area of sustainable manufacturing practices, the research presented in this thesis specifically contributes to the sustainable manufacturing literature and improves the understanding of how sustainability issues are being addressed within the manufacturing industry.

With regard to the industrial contribution of the research, the empirical results presented in this thesis indicate that the LCSP principles can be used by manufacturers as a guiding aid for companies to work towards sustainable production. This might help firms to face some of the challenges encountered when incorporating into their business strategy not only environmental considerations (Tsoulfas and Pappis; 2006), but also sustainability considerations (a triple bottom line approach).
Furthermore, the identification of several sustainable manufacturing practices (RQ2 and RQ3) might serve as examples of how the conceptual LCSP sustainable production principles can be put into practice by companies and, also, might be used as a checklist of relevant sustainable manufacturing practices. Hence, the sustainable manufacturing practices identified are valuable as a benchmark of such practices for companies aiming at either implementing the LCSP principles, or having holistic sustainable operations.

In addition, increasing the knowledge of how organizations can operationalize sustainable manufacturing principles constitutes a valuable industrial contribution, especially for those SMEs with little knowledge of sustainable manufacturing practices, and where current research on those practices is still in its infancy (Seidel et al., 2009). In this order of ideas, it can be stated that this research might represent a small-scale contribution to the attainment of national and global sustainability goals, when the cumulative impact of SMEs on global sustainability is taken into account.

5.5 Suggestions for future research

One of the conclusions of the research was that SMEs lag behind large manufacturing companies regarding adherence to sustainable manufacturing principles. Therefore, it would be interesting to study manufacturing SMEs further with regard to sustainable production principles and practices. Some future research could include the exploration of the differences regarding awareness and adoption of sustainable manufacturing principles and practices in manufacturing SMEs within other countries or between SMEs and large organizations.

In this research, some manufacturing sectors were found to be more likely to develop proactive sustainable manufacturing practices than others, therefore future research could be to carry out in-depth studies connecting conceptual sustainable production principles and their implementation within different contexts (e.g. specific industries, at a national or global scale).

In addition, as most of the results of the research presented in this kappa refer to environmental manufacturing practices, future research could focus on exploring sustainable manufacturing practices with a stronger emphasis on the social dimension of sustainability. This research could examine social sustainable manufacturing practices, as well as analyze the managerial perception about the benefits of these practices.

Finally, another way to expand the topic of this research might be in relation to production systems. Further studies might explore how
organizations include sustainability considerations when developing production systems (sustainable production systems) and the challenges presented when doing so.
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