THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Towards a framework for enabling sustainable production systems: a life-cycle perspective

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Abstract

This thesis contributes to scientific knowledge by offering the foundation of a framework that helps stakeholders such as managers and engineers to enable sustainability over the entire lifecycle of the production system, from planning to re-use. In this thesis sustainability can be assessed through performance indicators and is understood through its triple bottom line of: economic, environmental and social sustainability. Within the framework, the requirements for designing a sustainable production system drove the choice of methods and key performance indicators (KPIs) used to assess sustainability performances of the production system in object. The methods employed to assess sustainability were: novel energy KPIs, a set of social sustainability KPIs, life cycle assessment, and discrete event simulation. The framework has been applied to the case of an automatic piece of sorting equipment for electronic waste, with the aim of foreseeing the sustainability impacts of its implementation in a facility run by manual labor. For the case study of production systems using machine tools, the use of newly developed energy efficiency KPIs proved to enable more effective energy management and saving. Possible lack of commitment to sustainability from companies and lack of necessary data can hinder the applicability of the framework.
All in all, the framework and the methods can offer decisional support for the stakeholders who want to foster sustainable production.

Keywords: sustainability, triple bottom line, manufacturing, e-waste, decision support, KPI, discrete event simulation, energy efficiency.

This thesis includes:

- Literature's state of the art methods that enable sustainable production systems.
- A framework made up of requirements and methods to help managers and engineers develop and operate sustainable production systems.
- Four research papers containing results from two studies. One study dealt with an automotive facility and the other dealt with an electronic waste sorting facility.
- Lessons learned and next steps of this research.

ACKNOWLEDGEMENTS

There’s no end to studying…luckily!
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I give thanks to those whom gave me resources, knowledge and chances to drive my work forward over these three years at Chalmers.
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APPENDED PAPERS

The list of papers is given in a chronological order, from the oldest date of publication to the latest date of publication.

Paper I:
May, G., Barletta, I., Stahl, B., and Taisch, M. (2015). Energy Management in Production: A novel Method to Develop Key Performance Indicators for Improving Energy Efficiency. *Applied Energy* 46-61.

Contribution:
Ilaria Barletta established the research framework, designed the method and developed the results on a theoretical and practical level. She contributed to the writing of the manuscript.

Paper II:
Barletta, I., Johansson, B., Reimers, J., Stahre, J. and Berlin, C. (2015b). Prerequisites for a High-level Framework to Design Sustainable Plants in the E-waste Supply Chain. *Procedia CIRP*, *29* 29 633-638.

Contribution:
Ilaria Barletta designed the framework and implemented it on a case study. She took care of the writing of the manuscript mainly.

Paper III:
Taghavi, N., Barletta, I. and Berlin, C. (2015). Social Implications of Introducing Innovative Technology into a Product-Service System: the Case of a Waste-Grading Machine in Electronic Waste Management. APMS International Conference Advances in Production Management System, Tokyo, Japan, Springer.

Contribution:
Ilaria Barletta designed the industrial case study for testing the method being proposed and was responsible of the data collection.

Paper IV:
Barletta, I., Larborn, J., Mani, M. and Johansson, B. (2016). Towards An Assessment Methodology to Support Decision Making for Sustainable Electronic Waste Management Systems: Automatic Sorting Technology. *Sustainability* 8(1).

Contribution:
Ilaria Barletta designed the study and conducted the analyses. She took care of the writing of the manuscript mainly.

ADDITIONAL CONTRIBUTIONS

Paper A:
May, G., Taisch, M., Prabhu, V. V. and Barletta, I. (2013). Energy Related Key Performance Indicators - State of the Art, Gaps and Industrial Needs. *Advances in Production Management Systems: Sustainable Production and Service Supply Chains, Pt 1* 414 257-267.

Contribution:
Ilaria Barletta designed a consistent part of the study, collected the data from secondary literature and conducted the analyses.

Paper B:
Barletta, I., Johansson, B., Cullbrand, K., Björkman, M. and Reimers, J. (2015a). Fostering sustainable electronic waste management through intelligent sorting equipment. Gothenburg, Sweden, IEEE International Conference on Automation Science and Engineering (IEEE CASE 2015).

Contribution:
Ilaria Barletta collected the data from secondary literature and wrote the paper.

DEFINITIONS

This list reports definitions of the main concepts which have to be known in order to contextualize this research. Further definitions of such kind are provided within the thesis' chapters.

Performance indicator	A performance measure that “tells you what to do” (Parmenter, 2007)
Key performance indicator	A performance measure that “tells you what to do to increase performance dramatically” (Parmenter, 2007) “A set of measures focusing on those aspects of organizational performance that are the most critical for the current and future success of the organization” (Parmenter, 2007)
Stakeholders	“A stakeholder in an organization is (by definition) any group or individual who can affect or is affected by the achievement of the organization's objectives” (Freeman, 1994).
Decision making	“The thought process of selecting a logical choice from the available options” (Business Dictionary)
Energy efficiency	“[Energy efficiency] refers to using less energy to produce the same amount of services or useful output” (Patterson, 1996).
Life cycle assessment	“A tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle” (UNEP).

ABBREVIATIONS

CSR	Corporate social responsibility
DES	Discrete event simulation
e-KPI	Energy-related key performance indicator
EMS	E-waste management system
Eq	Equation
GDP	Gross domestic product
ICT	Information and communication technology
KPI	Key performance indicator
LCA	Life cycle assessment
RQ	Research question
SBD	Sustainable business development
SCADA	Supervisory Control and Data Acquisition
SDG	Sustainable development goal
SOTA	State of the art
UN	United Nations

PREFACE

I came to know the relationship between "production systems and sustainability" when I attended the master programme of manufacturing management at the Politecnico di Milano, Italy, in 2010.

Within the courses I took at that time, talking about energy efficiency meant taking as a given that sustainability was addressed.

Moreover, as Italy is one of the major European producers of machine tools, many applications and thesis projects addressed machine tools and how to make them more energy efficient.

In my master thesis I developed indicators to monitor machine tools' energy consumption: I wanted to improve the energy efficiency performances of manufacturing facilities by spotting and tackling energy inefficiencies.

Many technological and environmental changes have occurred since then. A more pervasive artificial intelligence presence in our daily life and scarcer reserves of drinkable water are just a few worthy of mention.
A point was reached where I was compelled to stop merely witnessing such changes and actually do something about them. Correspondingly, I drastically changed my diet, I walked more, I recycled carefully. But this was still not enough: how could I have an impact if I was only focusing on myself? How could I disseminate the message to others?
On top of this, I wanted to fully develop my critical thinking skills and work within an international, diverse working environment.
So, after one year as a junior consultant in Milan I landed my job as a PhD student in Chalmers University of Technology, within the department of Product and Production Development.

When I arrived in Chalmers, in January 2014, I was impressed by the strong focus that the university gave to sustainability all over its programmes. "The motto Avancez!" rings true, I thought, "How advanced they are in sustainability education!"
I did find a good place to develop both new and existing skills and to network with people who were committed to the sustainability cause in the same way I was.
Here in Chalmers I extended the scope of my original analysis, from machine tools to manufacturing and recycling facilities. I could look at the way they worked and evaluate whether and how technological advancements to them could have secured a sustainable future, not only for the factory as such but for the ecosystem around it.

This thesis marks the halfway milestone of my journey towards the doctoral of philosophy. Getting things done has been difficult at times and it will also be so in the future. However, as I am studying what I am passionate about I am grateful for each hurdle and setback, as I am for each moment of excitement and revelation. I hope this work will contribute, even marginally, to making manufacturing play an honest, substantial role in making this world a greener, healthier and more prosperous place for everybody.

Doing what needs to be done may not make you happy, but it will make you great.

George Bernard Shaw

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1. Introduction

This chapter introduces why making production systems more sustainable is of a paramount importance for the well-being of current and future generations. It then reports on the challenges that production systems face in the future, maps the addressees of this research and illustrates the outline of the thesis.

1.1 The challenges of a sustainable future

The change of Earth's physical systems – involving climate, chemistry and biology – caused by the massive impact of the world economy is so dramatic that scientists have given our age a new scientific name: the Anthropocene (from *Anthropos*, meaning humankind and *Cene*, meaning epoch) (Sachs, 2015). Climate change and resource scarcity are tangible examples of such a negative disruption. Moreover, the world population is projected to exceed 9 billion inhabitants by 2050. Such a scenario implies the feeding of a growing number of people while preserving environmental resources and biodiversity (Billen, Lassaletta et al., 2015). This demands long-term, sustainable behaviors and business models from society and industry. For now, sustainability will be defined through the most adopted definition of it, issued from the World Commission on Environment and Development's report on 1987 (Brundtland, 1987). The commission referred to the concept of sustainable development, defining it as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". To help secure a bright future for society, on September 2015 the United Nations (UN) issued seventeen Sustainable Development Goals (SDGs) (United Nations, 2015b). Among the SDGs, "responsible consumption and production", "climate action", and decent work and economic growth", are examples of goals where industry can play a relevant contribution. But how to make sure that these goals are achieved? The United Nations are currently working on the building of a framework of indicators related to the SDGs "to monitor progress, inform policy and ensure accountability of all stakeholders" (United Nations, 2015a). On an organizational scale, this implies that companies or organizations should be able to collect data and use indicators that can guide them towards the achievement of sustainability goals.

1.2 The challenges for manufacturing

First, why does this thesis focus on manufacturing above other sectors? Beyond my personal interest in this sector, manufacturing has considerable relevance for the economy too. In 2014 the manufacturing sector had an contribution of 15% to the gross domestic product (GDP) of Europe and Central Asia (The World Bank Group, 2014). For this reason, it is important to sustain an economy resulting from manufacturing, while at the same time fostering healthy human-ecology systems in which manufacturers operate.

In addition to the global-scale, Anthropocene-related trends, the manufacturing sector has started to face numerous future technology-driven challenges. Many of these challenges are brought by digitalization strategies of businesses. To exemplify, Esmaeilian, Behdad et al.

(2016) have extensively described the new manufacturing paradigms that have originated from data analytics (e.g., smart manufacturing, cloud manufacturing, cyber-physical systems). Wang, Wan et al. (2016) have given an engineering-based outlook of the smart factory envisioned by Industry 4.0, the fourth industrial revolution. Here the authors have claimed that the smart factory will help sustainable production face the global challenges of the future, although implementation aspects are still technically difficult to solve.

Different ways to produce products exist within the manufacturing sector. This research looks specifically at the discrete manufacturing industry, which is dedicated to the production of distinct items. The resulting products are easily identifiable, unlike products from process manufacturing, like oil and natural gas. The automotive or electronics industry, where the case companies of this thesis come from, are examples of discrete manufacturing industries.
Moreover, from a system-engineering standpoint, I have tackled sustainability in manufacturing by looking at production systems on a shop-floor level. Within systems engineering education, a production system is usually conceived of as a transformation system, which is a system that transforms inputs and uses resources to produce goods.

The first assumption being made in this thesis is that sustainability in production systems can be partially[1] explained by a set of output performances, which are measured through key performance indicators (KPIs[2]) (*assumption 1*). KPIs that measure sustainability-related performances are defined in this work as sustainability KPIs. Sustainability KPIs are seen as control tools which secure the achievement of goals related to sustainability, such as the SDGs. However, KPIs cannot foster sustainability by themselves, as production systems need to be designed and operated in a way that allows them to perform according to expected targets. To exemplify, the capabilities of production systems come from the fulfillment of certain functional requirements. Specific design parameters, which stem from the production strategy, are the means by which functional requirements are fulfilled (Herrmann, Bergmann et al., 2009). Therefore, from a methodological standpoint, sustainable production systems are enabled by methods that identify those requirements, design parameters and KPIs which support sustainability goals. To conclude, methods that enable sustainable production systems should be adopted within each life-cycle stage of the production system, from the design of the system to its end of life.

1.3 Problem statement

From what has been illustrated before, it becomes clear that production engineers must be aware of current economic, environmental, and social issues, as well as methods and tools to address them, as also pointed out by Zhang and Haapala (2015). On top of that, these methods should be able to give decision stakeholders of the manufacturing industry (such as managers and engineers) valid and trustworthy information that supports decision making in a way that

[1] Sustainability can be expressed through elements that are different from KPIs, such as production strategies, initiatives, investments, etc.
[2] Within the literature about performance management systems, several names related to indicators coexist, such as KPIs, performance indicators, metrics and measurements. The name chosen for this thesis is KPI. The difference between performance indicator and KPI is clarified in the section “Definitions”.

promotes sustainability. This boils down to assessing the impacts of decisions related to production development and operations management on sustainability through proper methods and KPIs. In this way, production systems can turn into sustainable (or even more sustainable) production systems. A specific problem that this research aims to explore is posed through the following question: do these stakeholders have methods that support them in the challenges of sustainable manufacturing?

1.4 Research questions

In order to address the problem stated above, I have generated two research questions: RQ1 and RQ2, listed below.

- **RQ1:** what are the currently available methods for decision-making support that help design, operate, and maintain sustainable production systems?
- **RQ2**: what typical requirements, methods, and KPIs enable the design of sustainable production systems and the assessment of their sustainability performances?

A response to RQ1 requires a definition of what a sustainable production system means to this thesis, and an exploration of methods for decision support within the academic literature that aim to enable sustainable production systems.
A response to RQ2 requires the development and use of a framework of research methods through case studies to enable sustainable production systems, or make them more sustainable than they currently are. Therefore, these methods are meant to enrich existing scientific knowledge reported within the answer to RQ1.

1.5 Stakeholders of this research

This section describes two types of stakeholders to whom this research is important. The first are stakeholders who affect the degree of development or implementation of the results from this research. The second are stakeholders who are affected by the implementation of this research. The first type of stakeholder is described in Table 1.

Table 1: Stakeholders of this research and the potential benefits they get from the outcome of this research.

Stakeholder	Description	Benefits
Academia	Researchers in the area of sustainable production, green manufacturing, production design and development, decision support systems for manufacturing.	A framework of tested methods to assess and enable sustainability performance in business environments. Advancement in the field of study.
Manufacturing Industry	Decision stakeholders in manufacturing and recycling companies represented by the	Improvement of sustainability performance of facilities

Stakeholder	Description	Benefits
	top and middle management, such as CEOs, production and environmental engineers.	through research-based decision making support. Results of assessments being disclosed through specific KPIs.
Consulting firms	Consultants and experts in production development, operations management, sustainability management and sustainability transitions.	A framework of tested methods to assess and enable sustainability performance improvements at customers. Baseline for the development of digital decision support tools for companies.
Institutions	National governments, international organizations, municipalities.	Inputs for the development of policies and regulations tailored for manufacturing industry (e.g., data and KPIs requirements).

Further, this thesis maps the degree of influence and interest of the identified stakeholders (see Figure 1). In order to do so, the influence-interest matrix model developed by Reed, Graves et al. (2009) is used.

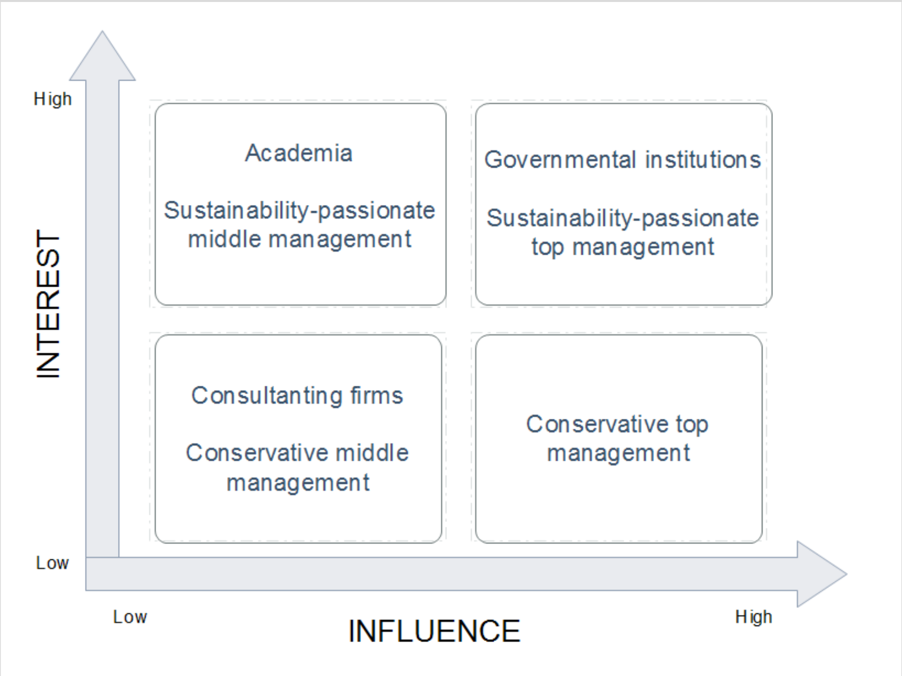

Figure 1: Influence - interest matrix of the stakeholders of this research.

In particular, in Figure 1 the interest means the interest in the development and the application of the results of this research, whereas the influence refers to the power that an actor has in

fostering the application of the results of this research. In Figure 1, “conservative” represents stakeholders who are not interested in the cause of sustainability and/or do not grasp its importance in their business. Conversely, sustainability-passionate stakeholders are sustainability-drivers within their company.
The stakeholders affected by the outcome of this research (beyond those mapped in Figure 1,) are operators and local communities around the production system which is being analyzed. Nonetheless, such stakeholders can play an active role if the primary company establishes a participative working culture.

1.6 Research scope and delimitations

The research scope of this thesis, its delimitations and further assumptions are described as follows:

1. **Unit of analysis: production system as discrete manufacturing facility**

   In this research a production system is seen as a single location, which coincides with a specific factory or facility within the discrete manufacturing sector. Such a system represents the unit of analysis of this research. The factory level has been considered suitable for studying sustainable production systems from an industrial-engineering point of view. Choosing a lower level as a unit of analysis like single transformation processes, was also possible. However, such an angle entails research on technological advancements in production processes that are outside of the scope of this thesis.

2. **Only certain changes to the production system’s configuration are within the scope of analysis**

   As explained before, production systems will go through numerous changes in the future. In particular, changes within the design or operations of production systems are to be evaluated by a group of decision stakeholders.
   Potentially, the scope of this research encompasses any change on production systems which affects:
   - equipment and assets configuration
   - layout configuration
   - material and energy flows balances
   - labor operational procedures.

   These hold relevance as long as decision stakeholders deem that they can have an effect on sustainability performances.
   These changes have to be assessed through KPIs, which can be both quantitative and qualitative, in order to be evaluated from a sustainability point of view. Accordingly, it is assumed that reliable data is available in order to calculate or estimate such KPIs (*assumption 2*).

3. **The system boundaries of the assessment methods are flexible all over the manufacturing supply chain and case-dependent**

   Despite what was stated in point 1 of this list, the system boundaries of each assessment method being employed in this research (e.g., life cycle assessment) will inevitably vary from case to case and may go beyond the boundaries of the facility. The definition of the system boundaries depends on the goal of the analysis and stakeholders' needs. In fact, the stakeholders might want to adopt a life-cycle thinking approach in order to understand what factors within the supply chain affects production system's sustainability performance and vice versa.

4. **Interconnections among product design and production development are not explored**

   Because of point 1 and point 2 of this list, this thesis does not intend to explore the interconnections among product design and production development. Simply put, this thesis does not explore how product design affects a production system's sustainability performance and how product-design changes for sustainability purposes affect the production system. Therefore, the product is considered as a given within the system. This delimitation holds within the case studies shown in this thesis: in fact, the application of the developed methods did not lead to product design changes. Nevertheless, such interconnections should be taken into account in the real management of production systems. In this regard, the research by Michaelis, Johannesson et al. (2015) has proposed an integrated platform model for a concurrent management of product and manufacturing systems.

5. **This research does not provide decision support tools but methods that can potentially be part of them**

   This thesis does not aim to build a decision support tool or to deliver a decision support system for sustainability. It provides instead an organized set of established and novel methodologies and methods to support decision making for sustainable production systems. In this research, implementation aspects (e.g., demos, prototypes) and user experience-related aspects are therefore excluded. However, the outcome of this research is the first step to forming decision support tools and systems for sustainability or improving the existing tools. Naturally, some of the methods provided in this research can be implemented only through the use of existing computing tools like simulation software packages and excel sheets (*assumption 3*), because they are able to process the collected data and extract results to be presented to stakeholders. Moreover, the part of this research focusing on sustainability KPIs has the purpose of only informing the decision stakeholders on the ultimate value of the KPIs. This research does not want to suggest to the decision stakeholders specific ways to handle results afterwards, such as Pareto optimizations or objective-weighting procedures. Also because of this choice, this research does not explore knowledge on change-management and leadership in sustainability projects.

1.7 Structure of the thesis

The thesis is structured as follows: Chapter 2 shows the research design strategy being adopted, Chapter 3 frames this research and defines its state-of-the-art literature, Chapter 4 illustrates the results, Chapter 5 discusses them and Chapter 6 outlines the conclusions and future developments of this research.

2. Research design

A research design "represents the structure that guides the execution of a research method and the analysis of subsequent data" (Bryman and Bell, 2011). The purpose of this chapter is to explain the research design being adopted. The first section showcases which elements have contributed the most to answering the RQs and how these elements were connected with each other functionally. The second section reports on the research methodology being adopted, which comprises the methods for data collection and data analysis.

2.1 Research framework

This section frames the context and the areas of application of this research in a greater detail, compared to what was stated in the introductory chapter. It does so by describing the studies my co-authors and I have performed over this research from a functional perspective. In the end the main steps of the research process are showcased.

In order to engage with the RQs, I performed two research studies.
The first study, *Study 1*, stemmed from my master thesis project and looked at a simplified model of a discrete manufacturing factory, where energy consumption from machine tools could have been reduced by cleverer energy management, accomplished through energy-related KPIs. *Study 1* aimed to develop such KPIs and propose guidelines to implement them.
The second study, *Study 2*, stemmed from the VINNOVA-funded WEEE ID project[3]. In WEEE ID the production system being analyzed is an e-waste sorting facility that is to be re-configured with a novel automatic piece of sorting equipment, the *e-grader*, shown in Figure 2.

Figure 2: E-grader demonstrator: an automated piece of sorting equipment for e-waste (courtesy of ReFind technologies AB).

Study 2 aimed to understand the impacts on sustainability performances that would have come from the future implementation of the *e-grader* in facilities for e-waste treatment.

[3] See Barletta, I., et al. (2015a) (*Paper B*) for a description of it.

Figure 3 on the next page showcases a visual representation of the research process, ranging from a clarification of the research focus to the achievement of findings.

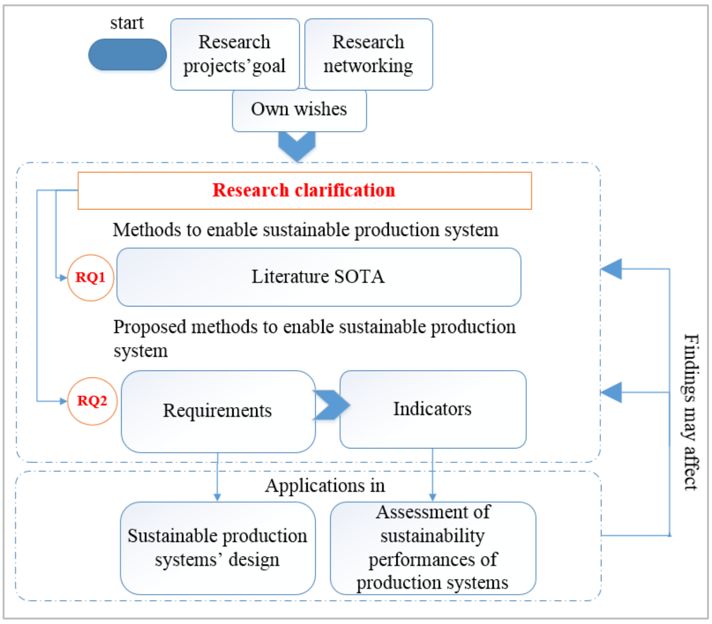

Figure 3: Research process.

After clarifying the foundation of this research (research clarification in Figure 3), I was able to formulate RQ1 and RQ2. RQ1 is to investigate methods within the literature state of the art (SOTA) to assist decision-making. RQ2 is to develop and apply these kinds of methods to case studies, defined within *Study 1* and *Study 2*.

The methods being proposed are either novel methods or existing methods within a novel structured methodology.

The application of the methods to case studies generated results that could affect the formulation of such methods in light of future studies.

Results from *Study 1* and *Study 2* contributed primarily to answering RQ2, and to some extent RQ1.

The findings enriched the literature SOTA (see feedback arrows in Figure 3) but may also affect the formulation of RQ2 for several reasons, such as the reconsideration of the relevance of some KPIs originally included in RQ2.

From the description of *Study 1* and *Study 2*, it is possible to see how this research is both empirical and applied. It is empirical because is based on observed phenomena from which it derives knowledge. It is applied because it aims to develop methods in order to intervene and alter phenomena (in other words, to enable sustainable production systems).

Study 1 and *Study 2* resulted in the research papers that are appended in this thesis and that will be described in Chapter 4. *Study 1* resulted in *Paper I* whereas *Study 2* resulted in *Paper II*, *Paper III* and *Paper IV*.

At this stage it is useful to introduce what the underpinning methodological paradigm of this research is. A paradigm in research "dictates what is considered to be studied, how research should be done, and how results should be interpreted" (Bryman, 1988).
Production research and sustainability research require an approach that looks for long-term achievements that at the same time solves industry and society's problems at hand. In such a context, the research problem and "what-and–how" type of research questions are at the center of the research. These characteristics comply with the definition of pragmatic research, whose paradigm has been described by (Feilzer, 2010).
From a philosophical standpoint, pragmatism, when considered as a paradigm, sidesteps the issues of truth and reality and accepts that there are multiple realities that can be the subject of empirical inquiry (Feilzer, 2010). Pragmatism is the underpinning methodological paradigm of this research.

2.2 Research methodology

According to Kothari (2004), research methods are all those methods/techniques that are used for conduction of research, whereas research methodology is a way to systematically solve the research problem, not excluding the adoption of research methods.
Study 1 and *Study 2* utilized qualitative and quantitative data in order to best fulfill the goals of the study. In fact, sustainability performances of production systems can be translated into indicators that are built from qualitative data (e.g., work satisfaction of employees) but also from quantitative data (e.g., production costs, CO2 emission per kWh of electricity). The same goes for the requirements for the design of sustainable production systems: some may be oriented towards quantitative aspects (e.g., level of efficiency required from a piece of equipment) and others may be oriented towards qualitative aspects (e.g., well-being of operators). It can be said that such research is what Johnson, Onwuegbuzie et al. (2007) call mixed method research" or "mixed research". The authors have stated that "mixed research started with researchers and methodologists who believed qualitative and quantitative viewpoints and methods[4] were useful as they addressed their research questions". This quote does not attempt to provide a definition of mixed methods research (several definitions of it have been explored by Johnson, Onwuegbuzie et al. (2007)), but to clarify that the research methodology chosen is neither wholly qualitative nor qualitative, but indeed mixed. In mixed methods research there are several possible ways to combine findings from qualitative studies and quantitative studies. Creswell and Plano Clark (2011) have illustrated prototypes versions of the six mixed methods designs they identified. Among them, the one that related to my research design was the convergent parallel design. It "occurs when the researcher uses concurrent timing to implement the quantitative and qualitative strands during the same phase of the research process, … keeps the strands independent during analysis and then mixes the results during the overall interpretation". This kind of design resulted when the production system was being assessed according to economic and environmental criteria (that involved quantitative results) along with social criteria (that involved qualitative results).

[4] The definition of qualitative research and quantitative research is given by Creswell and Plano Clark (2011).

When *Study 1* and *Study 2* were carried out there was no solid preliminary knowledge to properly understand problems, ask the right questions and find support solutions. Therefore, a close-up knowledge of the case study was needed in order to understand the complexity embedded in each study. This was primarily achieved through what it is called the "case study research method".
The case study as research method aims to derive a close, in-depth understanding of a single or small number of cases set in their real-world contexts (see Bromley (1986)). Yin (2013) defines the case study research method as "an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used" [5].
But what defines our understanding of "case"? A case represents a bounded situation or system and can exist on different levels of analysis: a single organization, a single location, a person or a single event (Bryman and Bell, 2011). The type of case chosen for this research has already been defined by the first and second point of the section 1.6 "Research scope and delimitations".
A case study can be designed in different ways in order to tackle a research question. In this research the case studies have been designed as follows:

- Comparative, as a to-be production system is evaluated against a baseline or possible alternatives of production systems
- Prospective (ex-ante), because the evaluations are done before the to-be production system is implemented
- In some case longitudinal, as the production system's performances were evaluated by considering a future time horizon.

According to Yin's definition of case study, "multiple sources of evidence are used" in order to investigate the phenomenon.
Creswell (2009) has used his own view on pragmatism, coupled with those views of Cherryholmes (1992) and Patton (1990) to draw a set of connection points between pragmatic research and mixed methods research. One of them states that pragmatism provides a philosophical basis for which "researchers are free to choose the methods, techniques and procedures that best meet their needs and purposes". Naturally, as pointed out by Denscombe (2008) "this is not an excuse for sloppy research and pragmatic should never be confused with expedient", but rather the concept demands a good understanding of quantitative and qualitative methods and analyses, so that transparency and replicability are guaranteed as much as is possible (Creswell, 2009, Feilzer, 2010).

2.2.1 Data collection methods

Observations and interviews were the main methods used for data collection. Study visits to two recycling facilities in Sweden allowed the observation of their physical layout and their existing operative procedures, so that it was possible to outline an as-is state of the facility. During the study visits, the opportunity was taken to capture photos and record the explanations

[5] Yin (2013) defined the case study as "research method". However, from the definition he gave the case study seems to comply with the definition of research methodology instead, with which this section started.

given by the company representative was giving. In one instance a translation from Swedish to English was necessary.
Both semi-structured and structured interviews were utilized as a guide for collecting data that could best serve a specific aspect of investigation. I contributed to the design of most of the interview questions in *Study 1* and designed and delivered the interviews in *Study 2* myself.
The semi-structured interviews were done face-to-face in some cases and by phone in others. Structured interviews were used in order to obtain quantitative data about the configuration of the production system (e.g., material and energy flow rates, cycle times, buffer sizes, number of operators per line). This was necessary for *Study 2* in order to acquire data for quantitative analyses that were run through discrete event simulation[6] (DES). Here also, a structured interview was used to collect data of the bill of material of the *e-grader*. This was necessary for *Study 2* in order to acquire input data for the life cycle assessment[7] (LCA) of the piece of equipment. Structured interviews were carried out through pre-filled excel sheets sent to the experts of the production system. The interview subject returned the file complete with values and notes. Some additional information was given via phone calls from the experts and included in the excel sheets. A questionnaire was used in *Study 2* to foresee the usefulness of a decision support methodology being proposed. The questionnaire was sent via email to top-management representatives of five companies within e-waste recycling in Sweden and Finland. The Appendix contains the data collection forms that were used in this research.

2.2.2 *Data analysis methods*

The qualitative data needed for analysis came from notes taken from the interviews and the contents were classified manually according to an inductive coding[8].
Quantitative data in input to the DES model in *Study 2* was obviously analyzed by the DES software itself. AnyLogic software (Version 7.1.2–University) was used for this purpose. I did not build the model in AnyLogic personally but I took care of the data fed to it, launched the simulation runs and then reported the results. In particular, DES was employed when the goal of the assessment was to estimate the throughput and energy consumption rates of a modeled, simplified facility. In fact, DES can be used to estimate, without a certain range of variability, certain production-related KPIs (e.g., throughput) of a modeled production system without doing tests on the real one.
Quantitative data needed for the life cycle assessment (LCA) of the *e-grader* in *Study 2* was analyzed by the software OpenLCA software (version 1.4.1) which used data from the EcoInvent database (version 3) as a life cycle inventory database.
Table 2 reports the specific research methods adopted within each study.

[6] See Dooley, K. (2002).for more insight on DES.
[7] The LCA followed the ISO standard ISO14044 (2006).
[8] See Thomas, D. R. (2006) for insights about qualitative data analysis.

Table 2: Research methods for each study and desired type of knowledge.

Study	Desired type of knowledge	Research methods and their combination
1, for *Paper I*	Model of energy states of machine tools and feedback on the validation of the method to build KPIs based on those states.	Conceptual modeling in combination with empirical semi-structured interviews to five manufacturing companies.
2, for *Paper II*	Information about e-waste management's current state in Sweden, representative examples of economic, environmental and social issues about e-waste sorting and recycling, validation of the methodology to develop design prerequisites for the case study.	Literature study in combination with research project's outcomes and semi-structured interviews with a group of sector experts. Two study visits to Renova's Tagene recycling facility (Gothenburg, Sweden) and to El-Kretsen sorting facility (Arboga, Sweden).
2, for *Paper III*	Representative examples of social issues about e-waste sorting and possible future impacts on factory operators from the implementation of the *e-grader*.	Literature study, observations of *e-grader* demonstrator at work operated by humans and interviews to sector experts. A framework of KPIs was applied as a structured interview guide.
2, for *Paper IV*	Model of the sorting facility's behavior, estimation of the environmental and social impact from the use of the *e-grader*. Potential usefulness of the proposed support methodology.	Several methods were employed: discrete event simulation, life cycle assessment and stakeholder mapping. They used data collected from interviews and observations (see 3rd row of this table). A questionnaire was filled in by industrial representatives.

In addition to a discussion of the findings from the single research papers, Chapter 5 will also explore the implications arising from the research methodology being adopted. In order to address this last point, the research papers will be characterized in Chapter 5 through three dimensions: qualitative vs quantitative study, nature of the goal of the study, and theory development.

The nature of a research study's goal has been interpreted differently within research, according to the field of study. Yin (1994) has covered three kinds of studies distinguished in the social sciences: exploratory, descriptive and explanatory study. Blessing and Chakrabarti (2009), who focused on research methodology for design specifically, have also included, in addition to the previous three types, the prescriptive study (also known as normative research). To make their definition of prescriptive study applicable to other kinds of research beyond the research for design, the prescriptive study is defined as a study which aims to come up with a solution on how to address a specific problem. The prescriptive studies aim at estimating the impacts of actions and indeed prescribing recommendations to decision stakeholders. There is also another type of goal of study which is relevant for this thesis: the evaluative study. Powell (2006) defines evaluation research "as a type of study that uses standard social research methods for evaluative purposes, as a specific research methodology, and as an assessment process that employs special techniques unique to the evaluation of social programs".

The theory development dimension refers to the following kinds of logic reasoning: deductive, inductive and abductive reasoning, see Walton (2014) for an overview of them. Abductive reasoning makes researchers "move back and forth between induction and deduction—first converting observations into theories and then assessing those theories through action" (Morgan, 2007). From a general perspective, the representation of the research process in Figure 3, especially of the feedback loop on it, implicitly shows the abductive reasoning behind this research and the need to move between methods and case studies in order to re-think and consolidate the methods being proposed. The rationale of the use of abductive reasoning in this research stems from its pragmatic approach. In fact Feilzer (2010), sees pragmatism as a paradigm that supports the use of a continuous cycle of abductive reasoning driven primarily by the researcher's desire to produce socially useful knowledge, along with the use of a mix of different research methods.

3. Frame of reference and state of the art

This chapter aims to describe the research focus of this thesis by providing a frame of reference. Then, it showcases the state of the art of the research focus within the scientific literature.

3.1 Frame of reference

This section illustrates the theoretical foundation of this research. Figure 4 showcases the research focus as an intersection of these three fields: production systems, sustainability management and decision making.

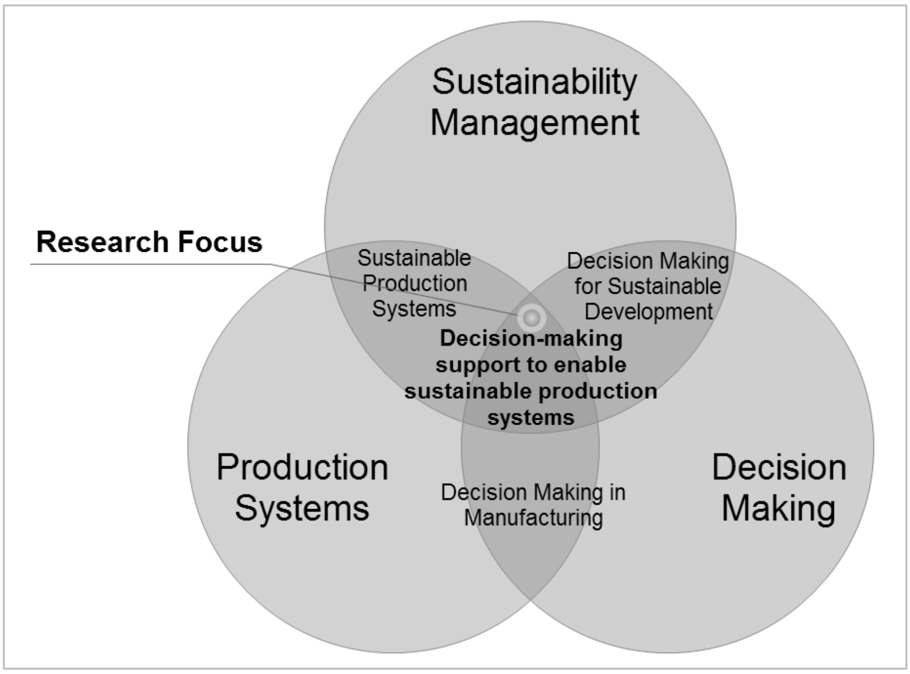

Figure 4: Research focus of this thesis.

The concepts drawn in Figure 4 are hereby specified.
First, Figure 5 represents the internal sub-systems within a production system that make transformation processes possible.

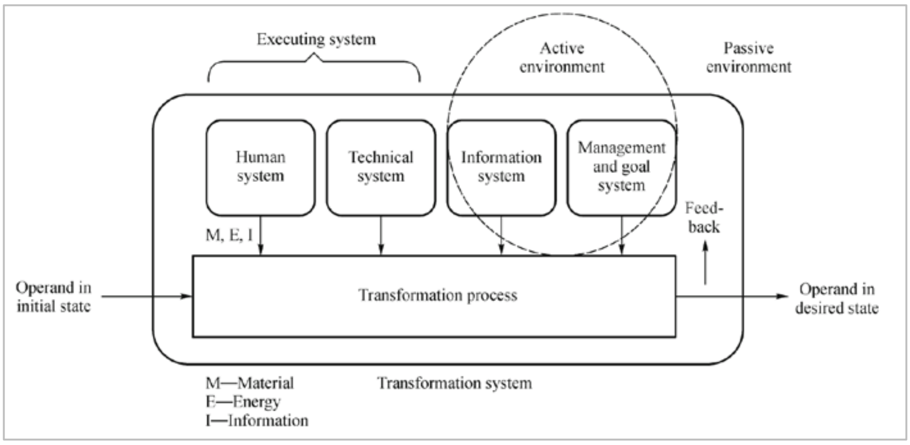

Figure 5: Production system as transformation process using different internal sub-systems. From Attri and Grover (2012).

Accordingly, in this thesis a production system is defined by facility or factory in which transformation processes convert inputs such as material, energy and information in to outputs, such as finished products, information and waste.
Moreover, once the life cycle of the product is ended, then recycling, remanufacturing and reverse logistics should be considered to secure sustainable business development in manufacturing (Gunasekaran and Spalanzani, 2012).

For this reason, in this thesis a production system is classified as a transformation system (as per previous definition) which can operate before or after the product use phase within the discrete manufacturing industry.

The title of this thesis suggests that this research offers a life-cycle perspective of production systems. Why so? As well as a product having a life cycle, a production system has its own life cycle too, and each life-cycle stage presents peculiar activities and decisions to be made. Attri and Grover (2015) offer a comprehensive review of the different models of life-cycle stages of a production system that have been proposed in the literature and have compiled the main activities involved in each stage. The two authors have shown how different researchers represent the life-cycle stages of a production system through different kind of models: some of them from a macro level focus on the pure differences between the engineering stage and the operation stage, such as the one by Preiss, Patterson et al. (2011). Other models, such as the one by Nakano, Noritake et al. (2008), are more detailed and focus on single activities like "plant design, evaluation of productivity and cost". Attri and Grover (2012) have characterized the different models under their review in to different dimensions and stressed their limitations.
Among the previously listed models, the one most suitably employed for this research is the one that would simplify the mapping of methods being proposed along the different stages of the production system which represents the case study.
A model that would visually represent the life-cycle stages of a production system is shown in Figure 6 and inspired by the model drawn by Wiktorsson (2000).

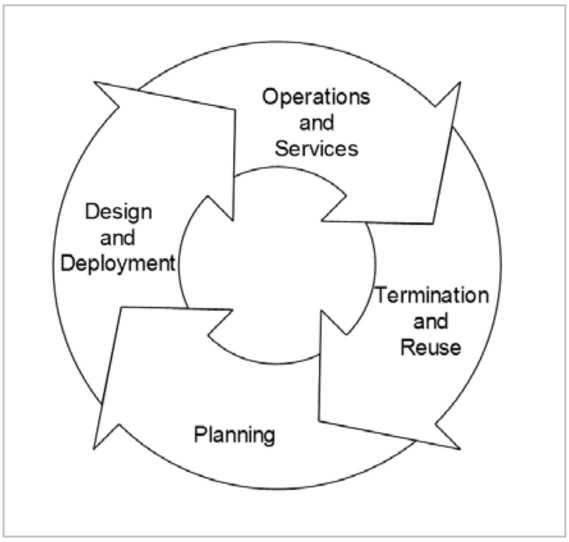

Figure 6: The life-cycle stage model for this research, inspired by Wiktorsson (2000).

The sequential stages that constitute it are: “planning, design and deployment, operations and services, and termination and re-use”. The latter leads to a new planning phase.
From Wiktorsson’s model some differences in terms of naming exist: the name of the life-cycle stages “realization” and “start-up” has become simply “deployment”. The stage “operation refinement” was turned in to “services” in order to include operation services for production systems, like maintenance, whose management impacts on sustainability performance (Ben-Daya, Ait-Kadi et al., 2009).
Another reason why Wiktorsson’s model was selected as baseline for this thesis upon the existing others is because the life cycle it presents does not end with a phase-out stage but with a “termination and re-use” phase instead. Such a choice commits to the focus on sustainability that this thesis has, as not only products but also production systems can be re-used (Bellgran and Säfsten, 2010).
Because of the scope of this thesis (see point 4 of section 1.6) the very first life stage of a production system, the planning stage, excludes choices related to product selection and product design. The planning stage will instead include considerations about what Shercliff and Lovatt (2001) label preliminary or conceptual design, “when little design or material detail has been fixed and all processes are open for consideration”. This stage requires, according to the two authors, “a broad-brush approach” to process selection, in terms of design requirements and system capabilities.

Global awareness on the theme of sustainable development was born in 1972 with the United Nations’ Conference on the Human Environment in Stockholm and ever since institutions and organizations have created manifold definitions of concepts related to sustainability. Hay, Duffy et al. (2014) carried out a literature investigation on sustainability-related concepts and created a model in order to reach a unified understanding of sustainability. In this way they wish for the effectiveness of human actions towards sustainability.
The need for economic and social well-being coupled with resource conservation has arisen across numerous industries, manufacturing included. This has led to the emergence of the

manufacturing paradigm "sustainable manufacturing" in the 90s. A description of manufacturing paradigms and the future trends of them is provided by Griffiths (2012).
Jayal, Badurdeen et al. (2010) recognized that there is no universally accepted definition for the term "sustainable manufacturing". A possible reason for this is because the concepts of sustainability and sustainable development are not universally defined.
In fact, most definitions of sustainability present the idea of sustainable development as a three dimensional concept where environmental, social and economic aspects have to be taken into account, as stated by Janeiro and Patel (2015). In this study, the two authors state that each of these dimensions is the result of considering a number of different criteria (or, as named in this thesis, KPIs) such as greenhouse gas emissions, labor conditions, economic growth, etc. Janeiro and Patel also state that these three dimensions of sustainability are not only multifaceted but also dependent upon each other. Moreover, the mutual consideration of these three dimensions would drive the consideration of the sub-systems depicted in Figure 5. For this reason, the whole concept of sustainability will be defined as economic, environmental and social sustainability in this thesis.

That said, among the definitions of sustainable manufacturing that Jayal, Badurdeen et al. (2010) reviewed, I chose the one presented by the U.S. Department of Commerce (2007). The U.S. Department of Commerce defines sustainable manufacturing as ‘‘the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound". For this thesis, a sustainable production system is a production system (as per previous definition) that realizes the creation of manufacturing products through the aforementioned process.
The reason for this choice is because the definition by the U.S. Department of Commerce appropriately stresses the existence of the three dimensions of sustainability.

A broad overview of the different levels of decision making in manufacturing have been explored by Reich-Weiser, Vijayaraghavan et al. (2008). Here, the authors illustrate how the metrics to support decision making for sustainable manufacturing may exist within several possible scales of analysis, from machine-tool scale to the supply-chain scales, and within different geographical scopes, from local to global. The way I attempt to support decision making for sustainable manufacturing has emerged already from the Introduction chapter, in particular from section 1.2, 1.4 and 1.6. In section 1.6 "Research scope and delimitations", point 1 indicates the scale of the unit of analysis and point 5 explicates through which approach I intend to support the decision making.

3.2 State of the art

The Introduction chapter and the Frame of reference's section narrowed the focus of this research, which is on methods for "decision making support to enable sustainable production systems". The goal of this section is to show the SOTA of such a research niche and to highlight

research gaps[9] that can be potentially addressed by this research. The gaps might be addressed both in this current research but also by future studies.
Since this thesis addresses a life-cycle perspective of production systems, the SOTA will differentiate the reviewed methodologies and methods in three main groups of life-cycle stages of production systems:

1. methods that support sustainable planning, design and deployment of production systems
2. methods that support sustainable operations and services in production systems
3. methods that support sustainable termination and re-use of production systems.

To define the SOTA, I performed a literature review by consulting the databases of Google scholar, Scopus and Web of science. The main key words used were: “sustainable”; “sustainability”, “design”, “requirement*”, “operations”, “manufacturing”, “production system*”, “decision making”, “indicator*”, “KPI”, “sustainability assessment*”. In the database’s search tool, I combined these words through several Boolean operators. I coupled my own investigation with recommendations of papers suitable to my needs after consulting with peers and supervisors.

1. Methods to support sustainable planning, design and deployment of production systems.

Barletta, Johansson et al. (2015b) (*Paper II*) reported that extensive studies, such as those by Herrmann, Bergmann et al. (2007), Heilala, Vatanen et al. (2008) and Pham and Thomas (2011) have been made on how to couple sustainability aspects and criteria with production system’s design in manufacturing. These studies adopted different methodological approaches. Herrmann, Bergmann et al. (2009) proposed an approach based on the definition of functional requirements and the identification of appropriate design parameters for sustainability-oriented production system’s design. Herrmann, Bergmann et al. (2007) and Heilala, Vatanen et al. (2008) used modeling and simulation tools to carry out optimization evaluations among sustainability criteria. In particular, Herrmann, Bergmann et al. (2007) provide decision support within the area of production system design optimization among economic and ecological criteria. Heilala, Vatanen et al. (2008) provide decision support within the area of production process system design (how, where and when the process is to be performed). The model proposed by the authors optimizes environmental and ergonomics criteria along with the level of automation of the plant, rather than its profitability.

Chapter 2 has shown that this research analyzed case studies based not only on traditional manufacturing facilities but also facilities for end of life processes in manufacturing, which is the case of e-waste sorting. With respect to that Barletta, Johansson et al. (2015b) (*Paper II*) concluded from the literature that previous studies did not match methods for plant design with the whole triple bottom line of sustainability (*Gap 1*). Moreover, Barletta, Larborn et al. (2016) (*Paper IV*) conducted a literature review on indicators and tools to analyze alternative reconfigurations of e-waste management systems with respect to the triple-bottom line of

[9] Research gaps are highlighted in the text through the format (*Gap#*). References to papers appended in this thesis are done through the format (*Paper#*).

sustainability. Here the authors showed that in the literature there is a lack of structured methodologies to support stakeholders in accessing sustainability impacts from e-waste management (*Gap 2*).

As illustrated in the Frame of reference's section, the deployment phase of production systems is to be intended as a phase concerning both the realization and start-up of the system. Therefore, it is licit to assume that if the planning and design stages account for sustainability criteria, the deployment phase will be affected accordingly. Nevertheless, the literature does provide research to support not only the design but also the deployment phase in production, see for instance (Bock and Linner, 2015, Pedersen, Nalpantidis et al., 2016) who specifically focused on support for robotics deployment.

2. Methods to support sustainable operations management in production systems.

This review focuses on KPIs as support method. The reason for this lies in the fact that performance indicators serve as a measure to decide whether a system is working as it is designed to do and help define progress toward a pre-set target, as told in May, Barletta et al. (2015) (*Paper I*). Therefore, KPIs represent a meaningful tool for decision support during the operations stage of production systems.

Based on the established Lowell Center Indicator Framework, Veleva and Ellenbecker (2001) have proposed twenty-two core indicators and a detailed guidance for their application to make companies measure their progress toward sustainable production systems. Gunasekaran and Spalanzani (2012) performed an extensive literature review on sustainable business development (SBD) in manufacturing and services: they concluded that there is a huge number of performance indicators scattered in the literature, but a clear framework for performance measures and metrics at strategic, tactical and operational levels including tangibles, intangibles, financial and non-financials aspect in SBD is lacking. Joung, Carrell et al. (2013) presented a comprehensive categorization of sustainability indicators in five dimensions of sustainability and explained how to use this indicator set to assess a company's manufacturing operations. As recognized by Pope, Annandale et al. (2004) there is a practical difficulty in integrating environmental, social and economic considerations in a way that realizes interlinks and minimises trade-offs. This difficulty applies to KPIs for sustainable production systems, accordingly (*Gap 3*).

However, there is one particular kind of performance measurable on a factory level which is able to merge both the economic and environmental sustainability dimensions: energy efficiency. From a gap analysis between literature SOTA and industry needs, Bunse, Vodicka et al. (2011) have called for an integration of energy efficiency performance in production management and Taisch, Sadr et al. (2013) have encouraged the introduction of energy efficiency as a key enabler for sustainability assessments. Using energy-related information and KPIs in factories enables better monitoring and control of energy consumption. Such a control enables enterprises to improve energy efficiency in production (May, Taisch et al., 2013) (*Paper A*). Bunse, Vodicka et al. (2011) showed the results of a gap analysis between state of the art and industry needs in the area of energy management in production. Here, the authors called for energy efficiency KPIs suitable for process and plant level and suitable for standardization (*Gap 4*), among other kinds of research gaps. The benefits from the use of such KPIs is the identification of weaknesses and areas for energy efficiency improvements related to the management of operations. *Gap 4* resulted still uncovered according to the literature review performed in (May, Barletta et al., 2015) (*Paper I*).

The European Factories of the Future Research Association has indicated social sustainability in manufacturing among the main opportunities of the 2014-2020 Roadmap. However, Fantini, Palasciano et al. (2014) reported that according to previous studies the social dimension of sustainability has not been sufficiently explored, unlike the economic and environmental dimensions. This finding was also stated by Thiel (2016), who illustrated several social domain implications, for instance, from Corporate Social Responsibility (CSR). Moreover, Thiel (2016) pointed out that the social side of sustainability is often depicted as socio-economic, because of a lack of CSR methods to measure complex social processes. From a decision-making point of view, such a lack of focus was pinpointed, on a more general level, by Zhang and Haapala (2015), who claimed that few efforts have investigated sustainable production decision making which addresses the three pillars of sustainability concurrently (*Gap 5*).

Securing a socially sustainable production system means also to evaluate work environment issues, that Searcy, Dixon et al.(2016) have defined as all aspects of the design and management of the work system that affect employees' interactions with the workplace. In Searcy, Dixon et al. (2016) the authors ran an extensive content analysis on 100 corporate social responsibility reports by focusing on work environment issues and the performance indicators employed to measure them. The authors concluded that companies emphasize high-regulated issues, such as safety-oriented indicators. However, psychosocial issues (e.g., work-related stress) of work environment, are generally underrepresented in the indicator disclosures (*Gap 6*). Moreover, Taghavi, Barletta et al. (2015) (*Paper III*) found that in order to achieve a socially sustainable manufacturing work system that can combat the demographic challenge, it should be able to meet the needs of both current and future employees and therefore it should be able to attract different societal groups as potential workers.

3. Methods to support termination and re-use of production systems.

To conclude the path over the several life-cycle stages of production systems, and in the hope of fostering sustainable manufacturing, it is assumed here that instead of dismissing the production system in its end of life (termination), it is possible to re-configure it and re-use it for future production needs (*assumption 4*). Therefore, in the model chosen to represent the life-cycle stages of a production system (see Figure 6) the termination and re-use phase is to be considered as a transition phase that precedes a new planning stage. Investigation into how to realize and enable reconfigurable manufacturing systems is not within the scope of this thesis. However, further references can be found at (Azab, ElMaraghy et al., 2013, Puik, Telgen et al.).

If analyzing the methods being reviewed in the SOTA from the perspective of production systems' life cycle, only Herrmann, Bergmann et al. (2009) drew a clear connection between the decisions made at a design stage and the decision made within the operation stage of production systems, and pinpointed the relevance of such a connection for sustainable manufacturing. The other studies being reviewed in this chapter seemed to have showed a lack of consideration towards the life-cycle perspective of production systems. In particular Herrmann, Bergmann et al. (2009) claimed that a challenge for the operations management is to incorporate appropriate requirements and design parameters that contribute to a more sustainable manufacturing (*Gap 7*).

An overview of sustainability assessment tools existing in the literature enriches and concludes the SOTA.

Sustainability assessment tools can be considered as structured methodologies that include several methods to support decision making. Therefore, they represent a higher and broader level of decision support if compared to the one being reviewed before. Ness, Urbel-Piirsalu et al. (2007) carried out a review and classification of sustainability assessment tools used in industrial sectors, which was further enriched by Taisch, Sadr et al. (2013). The latter divided the tools into four categories: sector-and-country-related assessments (e.g., input-output energy analysis), indicators/indices (e.g., human development index), product-related assessments (e.g., LCA) and project related assessments (e.g., full life-cycle cost accounting). According to the goal of the assessment, these tools can be used to evaluate both production system's design choices, such as layout planning, but also choices on an operation management level, such as energy management practices.
A problem involved in the use of sustainability assessment tools is the lack of guidelines and criteria on how to choose between these tools (Gasparatos and Scolobig, 2012). The authors stressed that sustainability assessment tools contain implicitly a certain sustainability perspective, assumptions on the measurements to be done, and value judgments with which analysts might not necessarily agree or be aware of. Naturally such an implication holds also for the methods previously reviewed.

Figure 7 visually summarizes the sets of methods for decision support for sustainability and locates them in the stage of the life cycle to which they are being applied.

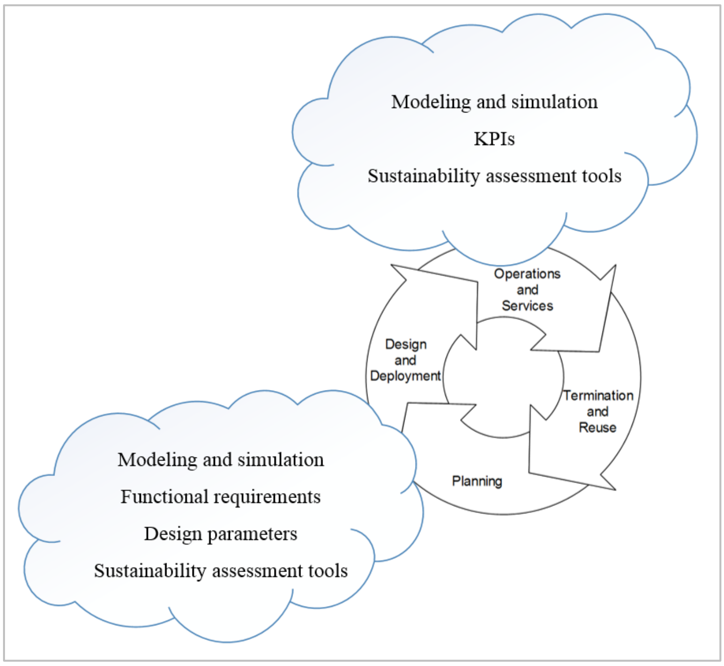

Figure 7: Methods and tools for decision support for sustainability next to the stage of the life cycle to which they are being applied.

The cloud at the bottom relates to the stages of planning, design and deployment, the cloud at the top relates to operations and services. Again, methods for driving a sustainable termination and re-use phase have not yet been found, and this phase has been considered as a transition preceding a new planning stage.

Chapter 3: Frame of reference and state of the art

4. Results

This chapters contains the answers to the two RQs of this thesis. Section 4.1 illustrates the answer to RQ1 and section 4.2 illustrates the answer to RQ2.

4.1 Methods in literature to support decision making for sustainable production systems

RQ1 is here restated:

RQ1: What are the currently available methods for decision-making support that help design, operate, and maintain sustainable production systems?

In the previous chapter, the SOTA showcased a literature review that indeed contributes to tackling RQ1. Such a literature review was made up of internal and external sources of data. The external sources of data come from some of the most recent and relevant scientific peer-reviewed studies that have tackled the problem of sustainable design and sustainable operations management of production systems. The internal sources data comes from the literature reviews that are part of the different papers appended in this thesis (*Paper I, Paper II, Paper III, Paper IV, Paper A*).
The following points summarize the conclusion from the SOTA and finalize the answer to RQ1:

- Methods that support decision making for sustainable production systems over their life cycle exist in the literature in different forms. Functional and design requirements of the production system that are specified over the planning stage can identify appropriate design parameters for sustainability. Modeling and simulation tools can support production system's design decisions, such as layout planning, but can also support decisions on an operations management level, like personnel resources' capacity. Specific KPIs can enable more sustainable operations in production systems by focusing on specific areas that need decision support, like energy efficiency, or representation in company reports, like psychological work-environment related issues of employees.
- Seven gaps relevant for this research have been identified from the SOTA. The research gaps can refer to areas that are either not extensively enough covered by research (*Gap 1, Gap 2, Gap 5, Gap 6, Gap 7*) or difficult challenges not yet addressed (*Gap 3, Gap 4*).

These research gaps reinforce and justify RQ2 on a higher level of detail, by tackling specific sustainability-related issues. This research addressed RQ2 through the development of two specific aspects:

- requirements to drive the design of sustainable production systems
- KPIs and methods to evaluate sustainability performances of production systems.

4.2 Comprehensive framework of the proposed methods

RQ2 is here restated:

RQ2: What typical requirements, methods, and KPIs enable the design of sustainable production systems and the assessment of their sustainability performances?

The comprehensive framework shown in Figure 8 visualizes the results of this research, which aimed to tackle RQ2 according to two dimensions: the first derives from the three dimensions of sustainability (economic, environmental and social) and the second stems from the life-cycle stages of production systems.

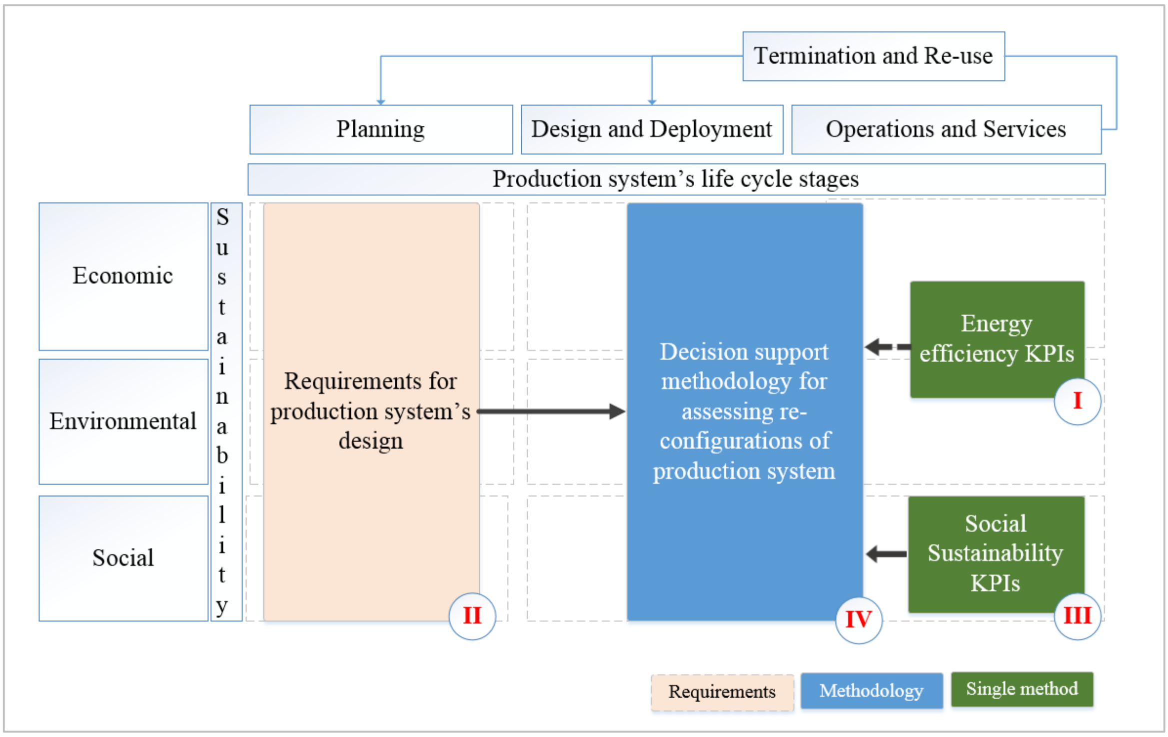

Figure 8: Comprehensive framework of the results. Numbers relate to the paper numbers and arrows connect papers that relate to each other.

The comprehensive framework is therefore matrix-shaped, and the rectangles within the matrix represent the single results of this research, each one associated with the related paper that generated its results. The area covered by each rectangle displays the extent to which sustainability is being covered and the life-cycle stage addressed. For instance, *Paper I* focuses on both economic and environmental sustainability performances and refers to the operations stage of production systems. The arrows in Figure 8 are to show that a result from a certain paper (output) provides an input into another paper. The nature of these input-output connections will become clear later in this chapter. In general, such connections reflect the connection between the requirements and the KPIs for sustainable production systems that were described in the research methodology section (see Figure 3). Full arrows connect *Paper II*,

Paper III and *Paper IV* as these papers all stem from the WEEE ID project, making it possible to use outputs from one paper as inputs for another one. *Paper I* showed a different case: the dotted arrow in Figure 8 reveals that even though the energy-efficiency KPIs of *Paper I* do not stem from the support methodology developed in *Paper IV*, they might still be incorporated into it.
Each of the next sections, from 4.2.1 to 4.2.4, describes each paper through a table that summarizes the main pieces of information for contextualizing the results offered in the paper. Then, an excerpt[10] of the paper gives the main results

4.2.1 Paper I

Table 3 provides the main pieces of information characterizing the research paper by May, Barletta et al. (2015), represented in this thesis as "*Paper I*" and titled: *Energy management in production: A novel method to develop key performance indicators for improving energy efficiency*.

Table 3: Characteristics of Paper I.

Characteristic	Information
Decision problem	Enabling the diagnosis and following improvement of energy efficiency of machine tools in manufacturing facilities.
Decision-making support	Novel methodology to develop energy-related KPIs (e-KPIs) that identify the major drivers of energy consumption (e.g., breakdowns, system losses).
Application	Machine tools in manufacturing facilities.
Life-cycle stage of the production system	Operations.
Informative background	The e-KPIs are KPIs which derive from cause-effect relationships between manufacturing states (i.e. causes of energy inefficiencies of the machines, measured in time), machine configurations and power consumptions.

The results from *Paper I* consist of a seven-step methodology to develop firm-tailored energy-related KPIs (e-KPIs), the formulation of six novel e-KPIs, guidelines for the implementation of the e-KPIs in advanced ICT systems in manufacturing environments, and finally, guidelines for their management within the company.
Since the focus of this research is on methods for decision making support, this section will provide only two of the main outcomes from *Paper I*: first, the structure whereby the main e-KPI is broken down into several e-KPIs for analysis purposes, and next a matrix visualizing how the values of the e-KPIs can offer information useful to improve energy efficiency in manufacturing.

[10] The results described from section 4.2.1 to section 4.2.4 represent the main findings from each paper. Please consult the appended papers in order to get a complete view of the results of this research.

The Lean Energy Indicator (eq. 1) has the purpose of showing how efficient the piece of equipment is in terms of energy consumption. The closer to 1 the Lean Energy Indicator is, the more the machine tool is consuming energy that adds value to the final manufactured product. Therefore, the closer to 1, the more the machine is consuming energy efficiently.

$$Lean\ Energy\ Indicator = \frac{Valuable\ Energy}{Overall\ Energy\ Consumption} \tag{1}$$

Eq. 2 below shows that the Lean Energy Indicator represents the ratio of energy consumed for producing saleable products to overall energy consumption of the machine over a certain time. The symbols used in the formulas for calculating indicators can be found Appendix A of *Paper I*.

$$Lean\ Energy\ Indicator = \frac{\sum_{i=1}^{n}(P_{processing\ i} \times Q_{good\ i} \times T_{processing\ i})}{Energy\ consumed\ in\ theoretical\ production\ time} \tag{2}$$

From a decision-making perspective, it is interesting for the production engineers and energy managers to be able to identify the major drivers of energy consumption within the facility, so that they can address them properly afterwards. The OEE indicator (Nakajima, 1988) is an example of how breaking down a KPI into different KPIs that look at specific performances of a production system (in this case, availability, performance and quality) helps find out the causes of inefficiency. Similarly, the Lean Energy Indicator has been designed in a way that allows an easy identification of the main causes of energy inefficiencies. In fact, the Lean Energy Indicator can be broken down in five e-KPIs, as shown in eq. 3.

$$Lean\ Energy\ Indicator = E_{opening} \times E_{usage} \times E_{avail} \times E_{sat} \times E_{quality} \tag{3}$$

The equations that define each of the e-KPIs in eq.3 can be found in Paper I. Not knowing the full equations of the e-KPIs will not affect the understanding of the informative value that such KPIs provide from a decision making perspective. What is relevant to know is that the value of each e-KPIs ranges from 0 to1 and identifies a specific performance within the manufacturing facility. In particular, the complement of $E_{quality}$ represents the percentage of energy, from the overall energy consumption that is wasted due to problems of quality (e.g., re-working of the product by the machine). The complement of E_{sat} represents the percentage of energy consumed because of unsaturation of the machine in the available time (e.g., due to minor stops and set-ups). The complement of E_{avail} represents the percentage of energy consumed because of breakdowns with the machine or energy spent over maintenance activities on it. The E_{usage} e-KPI assesses the impact on energy from causes at the level of the overall system and not strictly at the machine level. These causes are related to the management of the production system (blocking and starvation), or tool management, for instance. The $E_{opening}$ e-KPI assesses the impact on energy from post-holiday or post-shift start-ups of the machine.

As a result, the e-KPIs allow an easy identification of the areas for intervention and the responsible actors within the production system. In fact, the farthest the e- KPI value is from the ideal value of 1, the greater the need for intervention within the specific area will be. For example, a low value of E_{avail}: compared to other indicators $E_{opening}$; E_{usage}; E_{sat}; $E_{quality}$ which forms the Lean Energy Indicator suggests a need for intervention within the engineering of maintenance and/or in the maintenance function. Similarly, a low value of $E_{quality}$ suggests a strong impact of quality problems on energy inefficiencies. Once an action plan is drawn, the improvements consist of a reduction of energy consumption and related CO_2 emission. The energy consumption matrix illustrated in Figure 9 is to guide the development of an improvement plan.

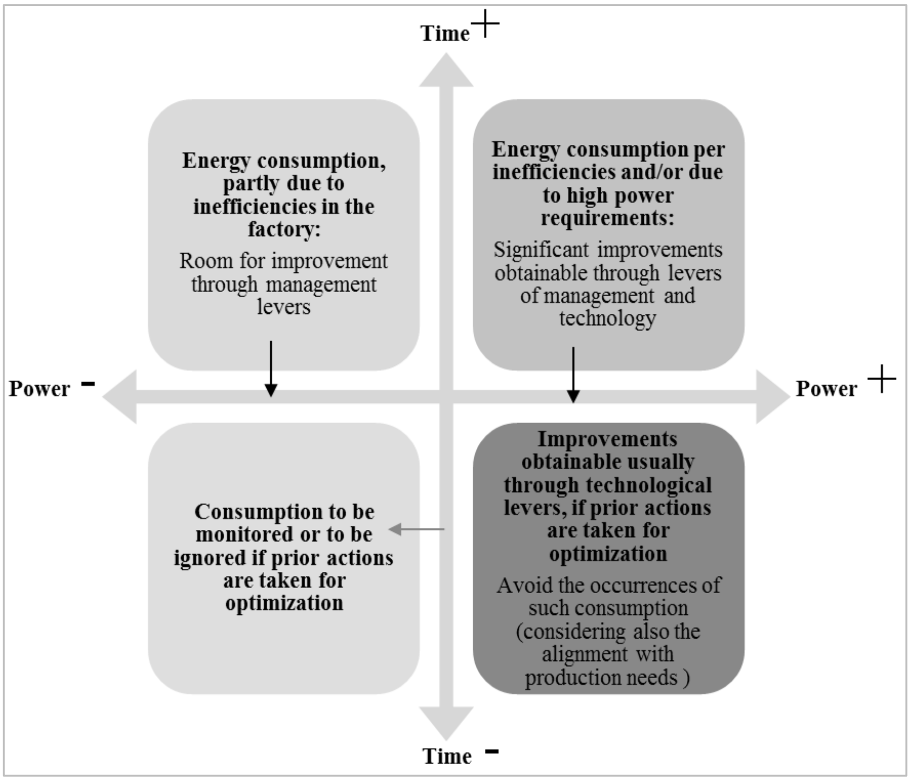

Figure 9: Energy consumption matrix for decision support. From May, Barletta et al. (2015).

The matrix includes two dimensions:

1. The horizontal dimension represents the magnitude of the individual energy consumption (e.g. power required for the ramp up phase of the machine).
2. The vertical dimension represents the time in which the single power requirement has been observed in the monitoring time T (e.g., the number of ramp ups times the single ramp up time).

In the end, *Paper I* advises on actions from an energy management perspective doable for each quadrant and suggests a prioritization of them.

4.2.2 Paper II

Table 4 provides the main pieces of information characterizing the research paper by Barletta, Johansson et al. (2015b), represented in this thesis as "*Paper II*" and titled: *Prerequisites for a high-level framework to design sustainable plants in the e-waste supply chain.*

Table 4: Characteristics of Paper II.

Characteristic	Information
Decision problem	Future implementation of an automatic piece of sorting equipment in e-waste treatment plants or within existing sorting plants run through manual labor.
Decision-making support	List of prerequisites to drive the design (or re-design) of an e-waste sorting plant in an economic, environmental and socially sustainable way.
Application	Electronic-waste treatment facility in Sweden.
Life-cycle stage of the production system	Planning.
Informative background	Within this work, a prerequisite means the specification of a strategic or operational decision, activity, piece of information, factor, or even research method pertaining plant design and operations management usable to design a fully sustainable plant for e-waste treatment.

The results from *Paper II* consist of the development of a list of theoretical prerequisites to design sustainable plants in the e-waste supply chain and instantiation of the prerequisites for the project case study, which stemmed from the WEEE ID project. The prerequisites refer to the economic, environmental and social side of sustainability. The results are displayed in Table 5.

Table 5: Results Paper II.

Theoretical Prerequisite	Prerequisite's definition for the case study of automated e-waste sorting	Complementary knowledge from primary data collection
Setting design goals with respect to Sustainability	***Economic sustainability goals*** ● Setting the return on investment or the payback time of the investment ● Improve the financial yield of sorting/recycling efficiency	To assess such goals: comparing design alternatives with respect to both short-term and long-term economic indicators, and with respect to both economy objectives and environmental impact simultaneously
	Environmental sustainability goals ●Separating each item containing acid-resistant material from those that do not contain acid-resistant material (reducing as best as possible sorting errors) ● Containing the environmental impact from plant's running (e.g. electricity consumption)	To assess such goals: evaluating the environmental pay-off of building and using the automated equipment compared to the manual, as-is sorting system
	Social sustainability goals ● Protecting operators from contamination from acid-resistant materials ● Retaining and motivating the operators; improving work satisfaction through ICT and data-driven operations	●As operators handle waste, they need to be carefully protected from dirt and toxics. Hence, retention and motivation are hot topics. ● Currently operators perform monotonous tasks: automation can shifts operators' tasks towards knowledge-and-data-driven activities
Setting design goals to comply the regulations	***Goals to comply WEEE Directive*** Supporting the current collection target (45% of electronics put on the market (POM)) and the future collection target set from 2019 (65% of electronics POM)	System's size and yield must support the achievement of WEEE collection targets (upstream) and WEEE recycling targets (downstream) established by the Directive
Identifying the stakeholders	***Company's management and engineering*** Company's top/middle management, production and environmental engineers, designers, logistics managers	Communication among these actors is crucial to make sure to include TBL goals within plant design
	Actors of electronic products' supply chain ● Final customers of electronics ● Producers, retailers and recyclers of electronics, recyclers of metals and plastics ● Municipalities, local communities	Artificial intelligence can enable the collection of statistics to add knowledge about process performances and products' life-cycle within a decision support system in WEEE supply chain (e.g., feedback to producers about use phase)
	Government and policy makers EU policy-makers and regulators, Swedish government	System design must support compliance schemes and anticipate regulation breakthroughs.
Setting relevant Key Performance Indicators (KPIs) to be monitored and assessed	***Economic KPIs*** ● Break-even point and payback time of the investment ● Sorting or recycling efficiency	An automated equipment guarantees a faster sorting if compared to the manual one, which leads to higher economical and operational KPIs and higher recycling rates downstream

	Operation management KPIs ● Lead time, cycle times ● Total throughput, throughputs of output fractions ●Number of reusable and recyclable components upon processed WEEE	Flexible, artificially intelligent sorting leads to increased productivity and, if integrated with sensor-technology and scanning, enables a smart update of sorting criteria to meet variable segregation needs or specifications
	Environmental KPIs ●CO_2 emissions from electricity consumption to run the equipment ●CO_2 emissions from transports ●Ecological and Human toxicity (Life Cycle Impact Assessment Indicators)	●Electricity consumption is one of the main source of environmental impact from plant running ●Broken lamps and some WEEE items can release toxics jeopardizing the environment and human health
	Social KPIs ●Rates of injury, lost days, absenteeism, personnel turnover ●Satisfaction from working environment	Automation can improve working conditions, safety, and satisfaction, provided that its introduction is supported by the proper training
Assessing the Information and Communication Technology (ICT) infrastructure	***ICT systems in production*** ●Sensors to feed the equipment and keep up speed ●PLC, control automated parts; HMI, ●Infrastructure for use of PLM data, methodologies and tools	Matching HMI with PLM is a way to facilitate the collection of WEEE data and statistics, as well as to facilitate the creation of collaborative platforms in WEEE supply chains
Assessing physical equipment and layout configuration	***Physical components, workers and layout*** Flexible, reconfigurable equipment allows to add/remove work stations or change the number of sorted fractions	A flexible equipment and layout meets the challenge of the huge variability of input streams in terms of amount and material contents of the WEEE items
Using of research methods and research tools for plant design	● Discrete Event Simulation (DES), Process flow simulation ● 3D Scanning of plant and of WEEE items	A combined use of such tools allows to assess sustainability of system's design and operations

Such a list of prerequisites gave input to the design of the system in which the *e-grader* was supposed to work and also advised on the kind of measurements that have to be monitored once the system is operationalized.

4.2.3 Paper III

Table 6 provides the main pieces of information characterizing the research paper by Taghavi, Barletta et al. (2015), represented in this thesis as "*Paper III*" and titled: *Social Implications of Introducing Innovative Technology into a Product-Service System: The Case of a Waste-Grading Machine in Electronic Waste Management.*

Table 6: Characteristics of Paper III.

Characteristic	Information
Decision problem	Future implementation of an automatic piece of sorting equipment within a sorting plant run through manual labor.
Decision-making support	Social sustainability KPIs framework for elaborating the social impact of the new technology for factory's operators.
Application	Electronic-waste treatment facility in Sweden
Life-cycle stage of the production system	Operations
Informative background	The Electronic Waste Management (EWM) system is seen as one form of Product Service System (PSS) that turns electronic waste from an environmental threat into a resource for society.

In order to provide management with advice on the social impacts from the new EWM system on operators, the authors used a previously established set of social sustainability key performance indicators included in several categories: labor code of conduct, personal development, work design, work-life balance, employee turnover, satisfaction management, and job security. Social implications were examined in the case where a specific innovative new technology was introduced to replace manual sorting of e-waste into re-use, refurbish and recycle fractions, which is the *e-grader*. The results from *Paper III* showed that the implementation of the e-grader can support proactive social sustainability in the factory, but some additional conditions need to be addressed by the customer organization to ensure that the potential risks identified in the interview are mitigated.

On one hand, the availability of the e-grader for the operators may support some proactive aspects of social sustainability, like competence development. Some additional conditions, that the sorting technology itself does not provide, need to be secured by the organization, in order to ensure a socially sustainable implementation:

- Education and training must be provided to employees using the equipment to prevent injuries and to make sure that the aggregated data tracked by the e-grader are utilized well
- Workers must be aware of the new responsibilities that are expected of them, such as analyzing the data and coming up with new ideas, in order to gain the advantage of more varied and meaningful work,

These two conditions have been recognized by the interviewees as keys to have employees willing to use the e-grader and an important contribution to a positive work environment. Nevertheless, tradeoffs between number of job opportunities and meaningful work content must be managed by companies.

4.2.4 Paper IV

Table 7 provides the main pieces of information characterizing the research paper by Barletta, Larborn et al. (2016) represented in this thesis with "*Paper IV*" and titled: *Towards an Assessment Methodology to Support Decision Making for Sustainable Electronic Waste Management Systems: Automatic Sorting Technology.*

Table 7: Characteristics of Paper IV.

Characteristic	Information
Decision problem	Future implementation of an automatic piece of sorting equipment within a sorting plant run through manual labor.
Decision-making support	Decision support methodology to assess whether the new technology will make a defined e-waste management system (EMS) more economic, environmental and socially sustainable than it is in its present state.
Application	Electronic-waste treatment facility in Sweden
Life-cycle stage of the production system	Design, but it is also applicable to the operations' stage.
Informative background	EMS are facilities and equipment within the whole e-waste supply chain which are made up of sorting centers, disassembly facilities and recycling facilities.

Paper IV is made up of a both a theoretical part and an empirical part. The first explores sustainability assessment methodologies for EMS and the second one applies a selection of such methodologies to the WEEE ID project case study. This section will show only the theoretical part, as findings from it can be applicable to other EMS and end-of-life processes in the discrete manufacturing sector. The empirical part is not presented here, as it shows the quantitative results from the economic and environmental assessment on the EMS case study compared to the as-is EMS. It is retrievable from the appended *Paper IV*.
The results of *Paper IV* can be summarized through the following points:

- A set of sustainability criteria and sustainability assessment tools suitable for applications to EMS that the authors have retrieved from separate studies. They are shown in Table 8.

Table 8: Indicators and tools to analyze alternative reconfigurations of EMS with respect to the triple-bottom line of sustainability. From Barletta, Larborn et al.(2016).

Sustainability Performance	Sustainability Indicators	Sustainability Assessment Tools
	Selection Performed by	
	Decision Makers	Decision Support Methodology's Users
Economic sustainability	Profit margin, revenues, Return of investment (ROI) Break-even point (BEP) Net present value (NPV) Payback time	Economic assessments of present and future e-waste streams [25], material flow analysis to forecast e-waste streams [26], break-even analyses, profitability analyses, analyses of operations-management performances through discrete event simulation (DES)
Environmental sustainability	Total energy consumption, Global warming potential Terrestrial ecotoxicity Freshwater ecotoxicity Metal depletion	Substance flow analysis (SFA), e.g., [27], life cycle assessment (LCA) [28] and environmental risk assessment (ERA), e.g., [15]
Social sustainability	Human ecotoxicity, Global reporting initiative (GRI) social sustainability indicators [29] KPIs of socially-sustainable operations [30]	Social LCA [31], assessment of implications on social sustainability from the introduction of a new technology into an EMS [30]

- A novel decision support methodology to assess sustainability of EMS, whose framework is illustrated in Figure 10. The framework contains the steps to be undertaken by decision-making stakeholders and users of the methodology in order to evaluate proposals of re-configurations of EMS according to sustainability criteria.

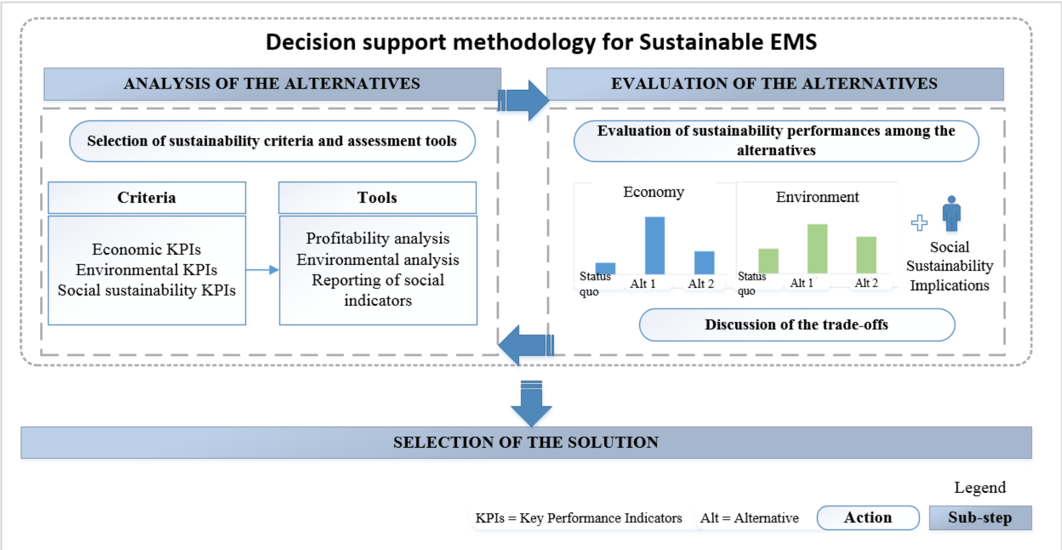

Figure 10: Framework of the decision support methodology. From Barletta, Larborn et al. (2016).

The decision support methodology relies on a selection of KPIs and tools previously reviewed in Table 8. In this regard, ROI and profit margin are the KPIs that have been applied for the economic assessment of the case study, whereas LCA and CO_2 emission calculations have been applied for the environmental assessment. The results of the economic assessment showed a more than double throughput rate for the to-be EMS with the e-grader, if compared to the as-is EMS. This drove the increase of the gross profit margin by 17%. The results of the environmental assessment showed that the energy consumption of the to-be EMS with the e-grader is 1333-times larger than the as-is EMS. Nevertheless, the absolute amount of energy and emissions caused by sorting activities is relatively small if compared to the energy spent by the technical building services of the facility (e.g., ventilation, overhead electricity). Such an environmental burden can still be offset quickly, if the e-waste can be reused rather than recycled thanks to the "diagnosis" from the *e-grader*. The social sustainability assessment presented in *Paper IV* referred to *Paper III* entirely. Further quantitative and qualitative impacts of the to-be EMS on the e-waste supply chain are presented in *Paper IV*.

- A stakeholder map (Figure 11) was drawn in order to capture the system boundaries of the three sustainability assessments from a product life-cycle perspective. It shows the influences occurring among the stakeholders of the electronics' life cycle following the introduction of the *e-grader* into the as-is EMS.

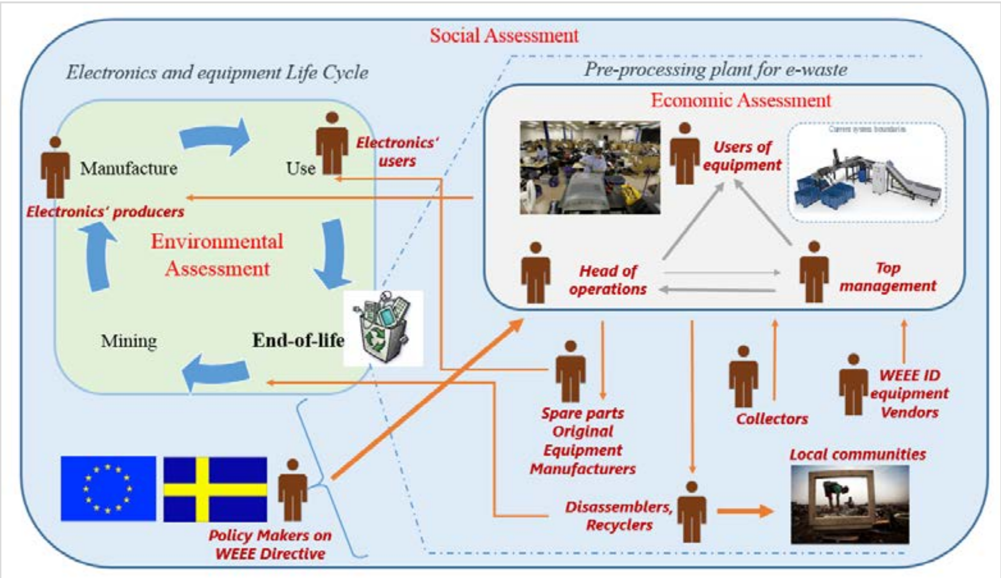

Figure 11: Stakeholder maps influences when introducing the e-grader and system boundaries of each assessment. From Barletta, Larborn et al. (2016).

Grey arrows represent influences acting within the e-waste facility, whereas orange arrows represent influences acting outside the e-waste facility, which may or may not affect its activities. The width of the arrows aims at qualitatively representing the strength of the influence from one actor towards another.

To conclude, section 4.2 presented a framework made up of requirements and methods to help managers and engineers develop and operate sustainable production systems. The application to these methods proved to provide meaningful information to support decision making within the areas of energy management and production systems' development. When impacts on economic, environmental and social performances in production systems are calculated (or envisioned) and properly displayed, decision makers are more likely to come up with choices that foster sustainable manufacturing.

5. Discussion

The discussion chapter is divided into five parts. The first one discusses the findings obtained from the research papers that have been illustrated in the previous chapter. The second discusses the quality of this research according to specific criteria. The third presents ethical considerations concerning this research. The fourth part illustrates the lessons learned from this thesis and the fifth part describes the future developments of this research work.

5.1 Discussion of the results

This section details:

- to what extent the results presented in the previous chapter contributed to answering RQ1 and RQ2
- how the results from the single research papers contributed to scientific knowledge and to stakeholders' decision making
- if and how well the results bridged the research gaps that were identified in the SOTA's section.
- how the research papers were categorized according to specific dimensions.

First, it is worthwhile to remember the problem that justified the need for this research: production managers and engineers must be provided with valid and trustworthy information that supports decision making related to sustainable production development and operations management. This can be done through proper frameworks, methods and KPIs. The importance of this is to allow decision stakeholders to check whether or not decisions and changes applied to production systems create efficient and environmentally-friendly facilities, which host positive working environments for employees. RQ1 and RQ2 were generated in order to explore such a problem from a research perspective.

RQ1 has been tackled by the literature study illustrated in Chapter 3. The main findings coming from this study have been summarized in section 4.1. From it, it is possible to conclude that the available research frameworks and methods that address this problem from a methodological perspective are indeed numerous and heterogeneous. This is compounded by the scope of this research, which tackles different life-cycle stages of production systems, where different decisions have to be supported. Moreover, several research gaps need to be addressed

How well was RQ1 approached? I attempted to deliver a SOTA which schematized the plethora of methods available, and highlighted their value and limitations. Nevertheless, such a SOTA was not the result of one or more publications focused on RQ1, but put together from different sources, both from the appended research papers and other secondary literature. For this reason, the quality of the results for RQ1 may have been negatively affected by the absence of a peer-review process on the SOTA, which ultimately constituted a limitation of this research.
Nevertheless, carrying out such a literature review resulted in the identification of seven research gaps, which were partially addressed in this research and can be explored by future research as well.

This research provided new knowledge in some specific areas of focus among those being asked by RQ2. The following paragraphs list the contributions produced by *Paper I, Paper II, Paper III* and *Paper IV* and point out research gaps that were addressed by the papers.

Paper I provided the following contributions for the decision stakeholders:

- Six e-KPIs that support identification of energy efficiency improvement areas in production systems
- A practical guide for companies to identify the e-KPIs which are most valuable for them to monitor
- A method that employs the use of an action plan for achieving energy saving targets.

Paper I provided the following contributions to knowledge:

- A seven-step methodology to develop firm-tailored e-KPIs
- A tool to possibly fulfill *Gap 4* recounted in *Paper I*, which advocated appropriate energy efficiency performance indicators to compare energy-use profiles of machines and processes.

Paper II provided the following contributions for the decision stakeholders:

- Informative support for the future implementation of a novel automatic piece of sorting equipment (*e-grader*), in a sorting facility in Sweden. In the WEEE-ID case study, the results from *Paper II* were used to identify sustainability goals that the stakeholders wanted to reach and the requirements needed to achieve them.
- Inputs for conducting the sustainability assessment of the to-be sorting system. In particular, *Paper II* suggested DES to assess facility design alternatives and suggested KPIs suitable to compare the alternatives and measure sustainability goals. KPIs were investigated in detail in *Paper III* and *Paper IV*, whereas DES was implemented in *Paper IV*.

Paper II provided two main contributions to knowledge:

- Support for a fully sustainable e-waste treatment system design through requirement specifications. This represented an advancement in the area of e-waste management as few attempts of this kind of decision making support had been proposed in the literature (see *Gap 1*).
- Exemplification of the benefits and limitations of introducing automation and artificial intelligence into processes that are traditionally performed by humans.

Paper III provided the following contribution for the decision stakeholders:

- Recommendations on the work design of operators, to be supplied to human-resource specialists and operations managers who manage plants where the *e-grader* or similar equipment can be implemented.

Paper III provided the following contribution to knowledge:

- A promising first step towards the development of methodical approaches for examining social impacts of product service systems, which have been found lacking in the literature

Paper IV provided the following contribution for the decision stakeholders:

- Useful information for decision making and identification of the requirements to further assess the broader impacts on the social landscape in which EMS operate. To exemplify, a finding from the stakeholder map in *Paper IV* expresses how policy makers can incentivize the adoption of the *e-grader* within sorting and recycling centers through several means, for instance monetary incentives from tax reductions.

Paper IV provided two main contributions to knowledge:

- A decision support methodology providing KPIs and assessment methodologies which encompass the whole triple-bottom line of sustainability. The authors demonstrated that such a holistic approach has not been pursued by previous studies within e-waste management, which generally focus on only one or two aspects of the triple-bottom line of sustainability (this gap is tightly related to *Gap 2*)
- A possible suitability of the decision support methodology for future applications in production systems handling other waste streams, besides electronics.

From the above description, it is possible to notice that some of the research gaps from the SOTA have not been addressed, fully or partially.
The gap that this research did not manage to explore is *Gap 3*. It refers to the practical difficulty of integrating environmental, social and economic considerations so that interlinks are considered and the need for trade-offs minimized. In fact, *Paper IV* analyzed the environmental, social and economic impacts as if they were three different silos, without considering how they might hinder or reinforce each other. The same goes for the requirements for sustainable production system design offered by *Paper II*. Such a partition stems from a reductionism approach with which the triple bottom line of sustainability is often addressed in research, against which *Gap 3* advocated a holistic approach instead. Naturally, the work done in *Paper IV* can be intended as a precursor to a future study where *Gap 3* is explored purposefully.

The gaps that have been partially covered by this research are *Gap 6* and *Gap 7*.

With respect to *Gap 6*, *Paper III* evaluated the social impacts from the implementation of the *e-grader*, not only through safety-oriented indicators, but also through qualitative indicators addressing some of the human needs that play a role in the work environment, such as work-life balance. Psychosocial issues like mental demands and stress levels (currently underrepresented in indicator disclosures (see *Gap 6*)), were not tackled fully. In order to deliver an assessment of them which is scientifically accurate, further knowledge from other disciplines is required as well, for instance in the areas of organizational behavior, psychology and cognitive automation.
Gap 7 refers to the need for the operations management to incorporate requirements and design parameters in order to effectively foster sustainable manufacturing. Links between the requirements drawn in the planning stage (*Paper II*) and the KPIs used at the operations stage

(*Paper III* and P*aper IV*) exist on a practical level (dictated also by the WEEE ID project's needs) but not on a methodological level. This comes from the research framework's design, which has been built inductively and through a bottom-up approach, by putting together different experiences gained within the WEEE ID project. An up-front, top-down vision would have allowed a deeper specification of the design requirements of the facility and an understanding of how they would have affected sustainable operations management in the facility.

It is possible to conclude that RQ2 has been addressed by the studies included in the comprehensive framework shown in Figure 8. In fact, this framework is constituted by novel methods and methodologies that provided information that supports decision making for sustainability. However, RQ2 was not fully tackled by such a framework. This is due to two main reasons:

- The presence of research gaps not fully addressed
- Life-cycle stages for which it was not possible to explore through focused studies, such as the design and deployment stage and the termination and re-use stage.

It follows that these two reasons drive future works on RQ2.

Now that a clear picture of the research papers has been provided, a synthesis of them can now be drawn as a sum up through Table 9

Table 9: Synthesis and research approach for the core studies of this thesis.

Paper	**RQ**	**Focus**	**Research approach**		
			Goal	**Reasoning**	**Data and methods**
I, II, III, IV,A and secondary literature	RQ1	Review of methods for decision-making support to enable sustainable production systems	Exploratory	Inductive	Qualitative
I	RQ2	Methodology to develop e-KPIs	Evaluative	Abductive	Mixed
II	RQ2	Prerequisites to design sustainable plants	Evaluative	Inductive	Qualitative
III	RQ2	Social sustainability KPIs for factory operators	Prescriptive	Inductive	Qualitative
VI	RQ2	Assessment methodology to support decision making for sustainable production systems	Prescriptive	Abductive	Mixed

Table 2, dealing with the research methodology, may be used to recall the methods used in each paper.

5.2 Quality, strengths and weaknesses of this research

Criteria are needed in order to conduct a quality assessment. Quality research criteria differ according to the nature of the knowledge explored within the research. In particular Guba (1981) referred to the concept of "rigor" for the case of the rationalistic (which he also labelled “quantitative”) paradigm and "trustworthiness" as the parallel term for “qualitative rigor”. For Guba, each paradigm requires paradigm-specific criteria.
Within the rationalistic paradigm, the criteria Guba proposed to reach the goal of rigor are internal validity, external validity, reliability, and objectivity. The criteria Lincoln and Guba (1985) illustrated in order to ensure trustworthiness in the case of qualitative paradigm are credibility, transferability, dependability and confirmability.
They parallel according to the scheme in Table 10:

Table 10: Parallels between the scientific and naturalistic terms appropriate to the four aspects of trustworthiness. From Guba (1981).

Scientific term	Naturalistic term
Internal validity	Credibility
External validity, generalizability	Transferability
Reliability	Dependability
Objectivity	Confirmability

Since this research is made up of qualitative studies and mixed methods studies that used mostly qualitative methods, I will self-evaluate the trustworthiness of this research first, and then proceed to an evaluation of its rigor.

Credibility refers to the credibility of the data and the interpretation of results. To secure credible results, two of the main strategies advised by Lincoln and Guba (1985) were adopted to secure credibility: prolonged engagement and member checking. For instance, in *Study 2* I took part in all the steps of the WEEE ID project (which lasted for two years) and asked interviewees to check how the results put in the research papers were presented before proceeding with the submission of the papers.

The criterion of transferability refers to the transferability of results. In other words, the findings have applicability in other contexts. For this kind of research, grounded in the case study methodology, the focus is on getting in-depth insights about a specific case, rather than being concerned with the “breath” of transferrable results. Nevertheless, it has to be possible for future researchers to judge whether the proposed framework of methods are applicable or not to other cases. The way to make this judgment possible is providing what Geertz (1973) calls “thick description”, which is a rich account of the details of a culture, which in this case is to be intended as a specific case study. Therefore, the transferability of results were handled by ensuring the provision of a detailed description of the case studies in question within the research papers. These descriptions contained details such as the goals of the research project, the system boundaries of the case study, the role that the interviewees have in the company and in the research project, if any. From a transferability perspective, a special attention was given to the decision support methodology proposed in *Paper IV*. The questionnaire mentioned in section 2.2 was designed to validate the first setting of the decision support methodology and understand the possibility of transferring this method to other industrial realities in the e-waste management. The feedback received was unanimously positive and encouraged further developments and applications of the decision support methodology.

On a general level, it can be said that the proposed framework of methods is fully or partially applicable to companies in the discrete manufacturing supply chain as long as:

- The availability of necessary data is provided (see *assumption 2*). For instance, in the case of using e-KPIs from *Paper I* it must be possible to know energy consumption rates of machine tools, thanks to estimations or monitoring systems connected to SCADA (Supervisory Control and Data Acquisition) systems.
- The availability of analysis tools is provided, such as LCA software solutions, DES software solutions.

As long as these two conditions hold, it is arguable that the methods being proposed in this research can potentially be applicable to both big and small-medium enterprises, and that the geographical locations of them does not seem to play a role. However, future research will reveal whether this hypothesis is confirmable or not.

Dependability refers to the stability of the data and how changes occurring within the context of the study can affect the conduction of the research. Dependability of data was not considered to be an issue for this research, as the case studies benefited from a fairly stable context for all over the research. Even in this case, giving a "thick description" of the existing case allowed the consideration of any possible dependability of the study, provided that this description was kept updated. Keeping track of update meetings among project partners and project status reports allowed an awareness of any possible source of dependability.

Confirmability refers to the neutrality whereby the researcher approaches the study with the aim of not making personal values and theoretical inclinations shape the findings of the research. An aspect that may have hindered the confirmability of this research is that in some cases I was the same person who designed interviews, performed them and reported the results. The possibility of bias is far more likely in such a setting, if compared to the case of an interview designed by one person and performed by another. Even when recognizing that complete objectivity is impossible in business research (Bryman and Bell, 2011), this approach presents risks of introducing biases to the study all the way through the research process, from when questions are posed to when the results are presented. It is also arguable that despite this research not being meant as action research, an approach like the one described resembles action research in many ways. This calls for a possible future re-definition of the distance between my role as researcher and the context of the study.

The information provided so far discussed the qualitative side of this research, which is the most predominant when compared to its quantitative side. Hence, the aspects previously discussed cover most of the methodological approach adopted for this research. What makes

this research quantitative as in cases of mixed method studies is the presence of quantitative indicators and discrete event simulations such as decision making support. Within the whole scheme of this research, the use of these two tools affect one specific criterion of rigor, which is reliability.
Reliability is concerned "with issues of consistency of measures" (Bryman and Bell, 2011). In this context, reliability can be affected by how the DES experiments are designed. In *Paper IV* the number and the simulated time of the experiments have been set high enough to have significant and non-random results. Means and standard deviations of the output variables (e.g., throughput of the system) have been reported. These measures have then been discussed with experts of simulation of production systems to see if they are credible, according to the input variables and the characteristics of the systems.

The rest of the section illustrates the main points of strength and weakness of this research.

The main strength of this research relates to the fact that it informs stakeholders of the impact that decisions done on a production-system level have on sustainability performance, and it does so through either existing methods organized in a structured framework (see *Paper II, III and IV*), or with novel methods (*Paper I*). As discussed previously, room for the applicability of these methods to other production realities exist and will be explored in the future.
Naturally, the simple act of informing decision stakeholders about sustainability impacts might not lead to an effective improvement of sustainability performance of the company. This concern gets even more critical when understanding that sustainability implies a long-term commitment from several groups of actors. However, having more informed decisions available qualifies it as first step to achieve more sustainable production systems.

The weaknesses of this research are summed-up in the following points, which can be considered its limitations:

- This research lacks methods for scenario planning and risk analysis on an economic, environmental and social level. They need to be included in the proposed framework of methods in order to support more reliable and solid decision making. However, in some cases, findings from this research cast light on possible future risks from a sustainability standpoint, which can be an object of further studies.
- Because of the combination of "case study research methodology" and "pragmatism", this research did not attempt to explore alternatives methods beyond the ones proposed in order to comprehensively address the case study in object. So, it can be argued that more effective, quick and robust methods to address the same kinds of problems are in existence. However, it will be left to future case studies to cast light on further specific points of weakness of the proposed methods and inspire alternative methodological approaches.
- The following limitation is connected to the use of mixed methods research. Feilzer (2010) pointed out that "there is a chance, of course, that a mixed methods design leads to heterogeneous results that need to be interpreted carefully". She posed an interesting

question in that regard, by wondering whether “such results undermine one or more of the methods used” or “they simply represent different dimensions of the interrogated phenomenon”. This concern relates to the issue of drawing conclusions that can englobe the findings from quantitative and qualitative analysis in a homogeneous and understandable way. A structured way to address sustainability holistically (as advocated in *Gap 3*, which was not addressed in this research at this stage) represents as a solution to this issue.

5.3 Research ethics

The aim of this research did not present any possible concern from an ethical perspective. However, risks of misconduct exist, both from the researchers’ side and the company stakeholders’ side.

From my side, I openly communicated to the industrial project partners the intention of publishing the results of the research projects that I was contributing to. Starting from this premise, data collections and data disclosures were done in a context of common agreement and care for sensitive information.

In general, the researchers have the duty to adopt validation techniques and ensure the non-fabrication of input data, such as member checking (as for my case) with experts or further company representatives and triangulation of the results with other studies that are similar in aim and context (which I lacked availability to because of the very specific nature of the research project).

From the company stakeholders’ side, the trustworthiness of the research findings might be hindered by possible misconducts by the decision stakeholders, from the way they treat data and present results to their shareholders actions.

For instance, a lack of responsibility by the company representatives to provide good-quality data hinders the validity and trustworthiness of this research.

In this context, falsifying the results (e.g., selectively reporting them) can lead to unhealthy decisions from a sustainability point of view, such as greatly promoting economic growth at a significant cost for the environment. To prevent this scenario from happening, several solutions can be put in place, such as:

- A close collaboration between the users of the methods (that can also be external to the company) and the decision stakeholders, up to the disclosure of the results
- Participation of the company at sustainability audits and environmental and social product declarations.

5.4 Lessons learned

In the following list I reported my own reflections stemming from the experience I gained so far.

- Sustainability is not to be meant as a permanent condition or a property of a production system. Sustainability has to be understood instead as a direction to keep striving towards. For this reason, assessments on sustainability performances of production systems have to be carried out periodically, where methods and measurements should be questioned and shared among the users of the methods and the decision stakeholders.

- The number and the diversity of sustainability-related definitions within the literature do not help companies and society comprehend what it means to be sustainable within their own reality. This leads to risks of seeing just one side of complex problems, as those related to sustainability in manufacturing often are. A focus on environmental sustainability only, or even forms of worst green washing, can be generated from this near-sighted view.

- Applied research's world can be affected from such a near-sighted view of sustainability too. In particular, some research may overemphasize the extent to which sustainability is being addressed (e.g., just one pillar, rather than the whole triple bottom line), or present sustainability as a strategic goal that does not get translated into focused actions and tools once the research gets performed.

- Even though the topics of leadership and management in sustainability projects were not in the scope of this research, they are determinant for the success of any methodological approach that aims to enable sustainable development in industry. In particular, if the company leadership is committed to sustainability, then it is likely to have dedicated resources and employees equally committed to sustainability.

5.5 Future developments

Two main aspects, already pointed out by previous research, have been confirmed and require future research and development:

1. Decisions in early life-cycle stages affect system performances in the later stages of the life cycle. Links between design requirements and KPIs for operation managements have been drawn within the several pieces of this research, but methodological approaches that realize these links in a way that supports decision making still need to be explored.

2. Realizing truly sustainable systems (where of course, production systems are included) requires the understanding and modeling of the interdependences between the

economic, environmental and social pillar of sustainability. Holism and system thinking need to prevail against the reductionism approach with which this and other research has been carried out. However, studying the three pillars of sustainability separately has given me a deep knowledge of them that can be used as an input for future holistic approaches

6. Conclusions

The manufacturing industry impacts national GDPs, the wellbeing of global societies and the health of planet Earth. It is of a paramount importance therefore that decision stakeholders of this industry are aware of the impact that the design and operations of production systems have on sustainability performances. This awareness constitutes the first step for a wise decision making that takes sustainability into full account. Against this landscape, the purpose of this research was to give decision stakeholders within the discrete manufacturing supply chain methods and measurements that support sustainable production systems all the way through their life cycle.

6.1 Summary

This thesis gives as outcomes:

1. A literature's state of the art methods that enable sustainable production systems at each of the stages of their life cycle. These methods constituted the answer to RQ1. The approaches available are indeed numerous and heterogeneous and operate at different scales. Seven research gaps related to the goal and scope of this research have been identified and among them there are still research gaps not being addressed.
   RQ1 has been addressed to a partial extent. If this literature review lacks a peer-review process as a whole, it nevertheless benefits from being an amalgamation of several pieces of state of the art research gathered from the peer-reviewed papers appended in this thesis.

2. A framework made up of requirements and methods to help managers and engineers develop and operate sustainable production systems. This framework constituted the answer to RQ2. The framework put together the results from the appended peer-review papers. The methods employed to assess sustainability were: novel energy KPIs, a set of social sustainability KPIs, life cycle assessment, and discrete event simulation. KPIs as decision support, on their own or within broader methodologies, covered a primary role among the methods being proposed. The main outcome of this research proved to support decision making within specific stages of production systems' life cycle: planning, design and deployment, and operations and services. Within the operations stage of *Study 1*, the use of the e-KPIs clearly enabled improvements of energy-related performances (such as specific energy consumptions) thanks to their ability to diagnose the major hotspots causing energy inefficiency. If coupled with DES, these energy KPIs can support evaluation of energy management initiatives. In *Study 2,* focusing on all three stages, approaching the designing of a sustainable e-waste facility through prerequisites drove the choice of methods and KPIs used to assess the sustainability performances of such a facility. The application of DES and LCA highlighted a win-win between economic and environmental sustainability from the use of the *e-grader,* whereas the application of social sustainability KPIs envisioned opportunities but also

threads for operators working in the e-waste sorting. To conclude, this framework qualifies as an answer to RQ2, at least partially. In fact, the case studies did not explore the whole life cycle stages of production systems. The termination and re-use phase has not been addressed, and deeper studies have to be done in the future for the design and deployment stage of the system. This research provided a bigger number of inputs to the operations phase.

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Appendix

Data collection forms

Excerpt of the excel sheet that outline of the structured interview for collecting input data to the DES model in Paper IV.

	Value	Unit
number of shifts	1	
number of lines	1	
length line (conveyor belt)	4,5	m
operators for loading and unloading items to/from the lines	1	

Description of the semi-structured interview for Study 1 – Paper I

The design of the interview hereby presented is a verbatim excerpt from *Paper I.*

The interview is divided into four parts, each of which contains a set of open-ended questions:

- The first part – Business context – aims at ascertaining the existence of an effective alignment between the information obtained from the selected company and the information necessary. Through a series of questions, a check is performed on the compatibility of the company's profile with the profile of companies for which the method can potentially be applied. Moreover, by virtue of this introductory check, the quality and accuracy of the information obtained from the interview is ensured.
- Second part – Industrial Scenario – proposes a series of questions to investigate the state of the art regarding energy-related performance indicators in production and to acquire information beyond those available in the literature.
- The third part – Design Method – aims at evaluating the design of the method considered in terms of scope, comprehensiveness of the elements analyzed, consistency and continuity between the logical steps and stages of the method.
- The fourth part – Implementation of the Method – concerns the possible structure and drivers for actual use of the e-KPI method. This last part focused on the strengths and weaknesses (both technological and managerial) and expected benefits of the implementation of the proposed method.

Description of the semi-structured interview for Study 2. In particular, Paper II mainly, and Paper III and Paper IV to some extent.

The interview was divided in four main sections, each one with a specific focus.

- The first part - General-context- aims at exploring how the e-waste recycling supply chain operates in Sweden. A special focus was given in identifying the core activities within the value chain, their main impact on the environment and the role of humans and operators within them.

- The second part – e-waste collection - aims at exploring e-waste collection phase specifically. Questions were about what are the e-waste items suitable to be collected and the main problems occurring in the collection stage.

- The third part – e-waste sorting - aims at exploring e-waste sorting phase specifically, which was the focus of the WEEE ID project. Questions touched different aspects of this phase: the business model adopted by the company, the pricing policy applied to the sorted e-waste items, the main costs involved in the process, the different sorting criteria applied to e-waste items and the rationale behind them. Moreover, questions enquired about the use of specific KPIs for operations management and what target values are expected from them.

- The fourth part - statistics collection - aims at figuring out what are the product-related data collected through statistics by the company, how they are collected and recorded, how the company employs the knowledge extrapolated from statistic and the impact that prediction models have on to the e-waste supply chain.

Key performance indicators of socially sustainable operations used in Paper III as interview guide.

Table 11: Key performance indicators of socially sustainable operations, from Taghavi, Barletta et al. (2015).

Key performance indicators
Labour code of conduct: • Occupational health and safety • No of absenteeism/ fatalities • No of incidents/ high risks related to occupation • Fair pay
Personal development, Talent management and career development
Work design • Challenging & stimulating job • Participation • Empowerment
Work-life balance
Employee Turnover and Satisfaction management
Job Security

Text of the questionnaire forwarded via email. The data collected from this questionnaire supported Study 2, in particular, Paper IV.
1

The concept of the decision support tool has specific characteristics, which have been reported in the five questions below. Express the extent of the value that the decision support tool would bring to your company.

The evaluation scale is:

1	2	3	4	5
No value	Limited value	Average value	Valuable	Very valuable

You can directly cross or underline the cell you selected and get back to us by replying to this email.

Questionnaire:

1. Would your company benefit from a virtual model of your complete facility showing resources' utilization, capacity, energy consumption, and throughput?

1	2	3	4	5

2. Would your company benefit from a model where you can compare economical return of investments of various systems for waste management?

1	2	3	4	5

3. Would your company benefit from a model where you can compare and understand environmental incentives for waste management?

1	2	3	4	5

4. Would your company benefit from having a better understanding of actors and their relationships in your supply chain of waste management?

1	2	3	4	5

5. All in all, would your company benefit from a tool embedding all the functionalities listed above to support the decision making process?

1	2	3	4	5