THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Resource-Efficient Manufacturing Through Enhanced Data Utilization

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An illustration of relationships between sustainable manufacturing, resource efficiency in manufacturing, and resource efficiency assessment.

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ABSTRACT

In the global transition towards sustainability, manufacturing companies are responsible for taking actions towards better resource efficiency. While many manufacturing companies have managed to find macro-level resource-efficient solutions, measuring resource efficiency at micro levels remains a challenge. Essential resource flows—material, energy, and waste—are often studied in isolated studies, and existing assessment methods are not always applicable to factory operations. Though many studies have worked on the role of industrial digitalization in improving resource efficiency and environmental impact reduction by addressing data-related issues, there is still a need for more concrete understanding regarding the development and application of assessment methods for resource efficiency.

As a part of this joint journey, this research focuses on understanding the challenges among manufacturing companies when working on resource efficiency and the opportunities for solving the challenges in a data-informed manner. A systematic literature review and two case studies, conducted using design research methodology, identified challenges in factory data readiness, reflecting that data from factories were not yet ready enough for resource efficiency assessments. Implementation factors, including enablers and barriers, were also identified for the effective resource efficiency assessment methods.

Based on these findings, a conceptual integration model was developed to connect resource efficiency assessments with production information systems. The model also includes a method library and a data readiness check to support practical applications. The findings highlight the importance of factory data readiness in embedding resource efficiency assessments into factory operations. Instead of creating new assessment methods or collecting a huge amount of data, enhancing the implementation of existing assessment methods is key to improving resource efficiency in manufacturing. Additionally, integrating resource efficiency assessments with production information systems ensures alignment with digital technologies from industrial digitalization.

This thesis contributes to a more consistent understanding of resource efficiency methods in the research area. The integration model and attached practical tools help manufacturing companies make data-informed decisions in resource efficiency assessments in both short and long terms. The thesis offers a foundation for resource efficiency improvement in manufacturing and potential through continuous work in the future.

Keywords: manufacturing, resource efficiency, assessment, production information systems, factory data

Hope your road is a long one.

May there be many summer mornings when,

with what pleasure, what joy,

you enter harbors you're seeing for the first time;

Ithaka

C. P. Cavafy

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First, I want to thank my supervisor, Prof. Mélanie Despeisse. If I were to envision a future career, you would be a role model. You have always encouraged my enthusiasm for research and reminded me of how fascinating it is. More than that, you have guided me to walk through the process of learning how to initiate, conduct, and communicate the work like a researcher.

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Finally, I want to dedicate this thesis to my family. To my mother Xiaojun and father Weishun, thank you for your unconditional love and belief in me, even when I am thousands of miles away from home. To Dr. Dan Li, thank you for always standing by my side through the laughter and tears. Though you already know that being a PhD student is not always easy, I hope you do not feel being a PhD student's partner could be even tougher (only joking). Thank you, and I hope this thesis brought you some enjoyment.

Qi Fang

Gothenburg, January 2025

LIST OF APPENDED PAPERS

Paper 1: Review of Resource Efficiency Assessments in Manufacturing: An Integration Model for Production Information Systems

Qi Fang, Mélanie Despeisse, Björn Johansson (2025)

Submitted to a scientific journal.

Qi Fang developed and performed tasks including study initiation, methodology, literature search, data analysis, investigation, writing, review, and visualization. Mélanie Despeisse and Björn Johansson guided study planning and supported the reviewing.

Paper 2: Exploring Factory Data for Resource Efficiency Assessment - A Case Study in a Truck Manufacturing Company

Qi Fang, Mélanie Despeisse, Ebru Turanoglu Bekar, Lena Moestam, Helena Söderberg, Dennis Andersson, Björn Johansson (2023)

Presented at EcoDesign 2023 International Symposium.

Qi Fang developed and performed tasks including methodology, data collection, data analysis, investigation, writing, review, and visualization. Mélanie Despeisse and Björn Johansson planned the study. Ebru Turanoglu Bekar, Lena Moestam, Helena Söderberg, and Dennis Andersson supported the data collection and analysis.

LIST OF ADDITIONAL PAPERS

Paper I: Environmental impact assessment of boatbuilding process with ocean plastic

Qi Fang, Mélanie Despeisse, Xiaoxia Chen (2020)

Presented at the 27th CIRP Life Cycle Engineering Conference (LCE2020). Published in Procedia CIRP, Volume 90, 2020, Pages 274-279, ISSN 2212-8271.

Paper II: Developing Data Models for Smart Environmental Performance Management in Production

Mélanie Despeisse, **Qi Fang**, Ebru Turanoglu Bekar, Nils Ólafur Egilsson, Karolina Kazmierczak, Lena Moestam, Helena Söderberg, Dennis Andersson, Jenny Hörnlund & Björn Molin (2023)

Presented at APMS 2023. Published in IFIP Advances in Information and Communication Technology, vol 692. Springer, Cham.

Paper III: Challenges and opportunities to advance manufacturing research for sustainable battery life cycles.

Björn Johansson, Mélanie Despeisse, Jon Bokrantz, Greta Braun, Huizhong Cao, Arpita Chari, **Qi Fang**, Clarissa A González Chávez, Anders Skoogh, Henrik Söderlund, Hao Wang, Kristina Wärmefjord, Lars Nyborg, Jinhua Sun, Roland Örtengren, Kelsea Schumacher, Laura Espinal, Katherine Morris, Jason Nunley, Yusuke Kishita, Yasushi Umeda, Federica Acerbi, Marta Pinzone, Hanna Persson, Sophie Charpentier, Kristina Edström, Daniel Brandell, Maheshwaran Gopalakrishnan, Hossein Rahnama, Lena Abrahamsson, Anna Öhrwall Rönnbäck, Johan Stahre (2024)

Published at Front. Manuf. Technol., 20 August 2024, Sec. Sustainable Life Cycle Engineering and Manufacturing Volume 4-2024.

Paper IV: Implementation of ISO 23247 for digital twins of production systems: Towards AI-based, Sustainable, and XR-based human-centric manufacturing

Huizhong Cao, Henrik Söderlund, **Qi Fang**, Siyuan Chen, Lejla Erdal, Ammar Gubartalla, Paulo Victor Lopes, Guodong Shao, Per Lonnehed, Henri Putto, Abbe Ahmed, Sven Ekered, Björn Johansson (2025)

Submitted to a scientific journal.

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LIST OF ABBREVIATIONS

SDG	Sustainable Development Goal
EU	European Union
DT	Digital Twin
IOT	Internet Of Things
RQ	Research Question
TBL	Triple-Bottom Line
CE	Circular Economy
ERP	Enterprise Resource Planning
MES	Manufacturing Execution System
SCADA	Supervisory Control And Data Acquisition
HMI	Human Machine Interface
PLCS	Programmable Logic Controllers
ISA	International Society Of Automation
SMES	Small And Medium Sized Enterprises
DRM	Design Research Methodology
RC	Research Clarification
DS-I	Descriptive Study I
PS	Prescriptive Study
DS-II	Descriptive Study II
IDEF0	Icam Definition For Function Modeling
AI	Artificial Intelligence

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1

INTRODUCTION

The chapter provides a description of the background, the problem statement, research aim and objectives, research questions, as well as scope and delimitation. The chapter ends with an outline of the thesis.

1.1 Background

Recently, the manufacturing industry is undergoing a significant shift towards responsible consumption and production, aligning with Sustainable Development Goal (SDG) 12. This goal emphasizes improving resource efficiency in reducing environmental impact while improving economic and social sustainability. The United Nations 2030 Agenda also highlights the manufacturing sector in achieving SDG 12 by prioritizing actions that enhance resource efficiency. According to the Sustainable Development Goals Report 2023 (United Nations Department of Economic and Social Affairs, 2023), the material footprint per capita in high-income countries remains approximately ten times higher than in low-income countries. This contrast indicates the urgent need for high-income regions, such as Europe, to lead as role models. To achieve the first climate-neutral continent by 2050 and reduce at least 55% net greenhouse gas emissions by 2030 compared to 1990 levels, the European Union (EU) has introduced the EU Taxonomy for Sustainable Activities, a comprehensive classification system designed to define and standardize what constitutes sustainable economic activity (The European parliament and the council of the European Union, 2020). The new EU taxonomy urges manufacturing companies to measure and report their resource efficiency performance under guidelines. Therefore, for manufacturing companies in Europe, the growing focus on sustainable development presents a dual opportunity: to enhance their sustainability performance and to uphold exceptional quality and productivity. This balancing is not only a strategic advantage but also a social responsibility in the face of global climate challenges.

In response to the expectations of government and society, manufacturing companies keep seeking solutions to resource efficiency, and a lot of them can report on resource efficiency at macro levels, such as across the supply chain and enterprise level. But to lead the transition towards resource-efficient manufacturing, being able to measure resource efficiency at a micro level (e.g., factory, line, process, etc.) and identify improvements is seen as a key capability (Duflou et al., 2012; Ghisellini et al., 2016; Kristensen and Mosgaard, 2020). To manage resource efficiency at the factory level, material, energy, and waste are identified as critical resource flows (Ball et al., 2009). Though the need for a generic understanding of these key resource flows in and out of the manufacturing facilities and how they can potentially interact with other resource flows was highlighted (Ball et al., 2009), the resource flows were often explored separately with keywords in studies such as "material efficiency" (Schmidt and Nakajima, 2013; Zhang et al., 2018), "energy saving" (Abdelaziz et al., 2011), and "waste flow mapping" (Kurdve et al., 2015).

However, despite the clear importance of resource efficiency at the factory level being recognized for decades, many manufacturing companies still struggle to adopt practices for resource efficiency and find applicable methods to measure resource efficiency (Kim et al., 2024). For industrial users, it was challenging to identify a single tool that met all their requirements for supporting the assessment in a manufacturing setting (Chen et al., 2014; Pande and Adil, 2022). Several different review studies concluded that assessment methods for sustainability in manufacturing have limited usability, including criteria such as generic applicability, time and resources required for assessment, and a holistic view of sustainability (Ahmad et al., 2022; Chen et al., 2013; Moldavska and Welo, 2015).

The industrial revolution provides opportunities for manufacturing companies. Implementation of digital technologies such as digital twin (DT) and the Internet of Things (IoT) can contribute positively to environmental sustainability by increasing resources and information efficiency in manufacturing (Chen et al., 2020; Maddikunta et al., 2022). But reviews of empirical studies also suggested that industrial digitalization should support resource efficiency more systematically by addressing issues with data such as availability, transparency, and access (Acerbi et al., 2021; Despeisse et al., 2022). Many existing studies demonstrating the potential impact of industrial digitalization also found a lack of solid validation of actual impact (Piscicelli, 2023).

To support manufacturing companies in the transition from "reporting resource efficiency at a macro level as the purpose" to "improving resource efficiency at a factory level as the priority," more concrete knowledge related to the development and application of assessment methods for resource efficiency is needed. Considering the gaps presented, this thesis focuses on understanding the challenges in manufacturing companies when working on resource efficiency at the factory level and the opportunities for solving these challenges in a data-informed manner.

1.2 Vision and aim

The vision of this research is to sustain a livable climate where the manufacturing industry can achieve net zero emissions by operating resource-efficiently.

With this vision, this thesis aims to equip manufacturing companies with knowledge and tools for being resource-efficient by making data-informed decisions and maximizing the value of factory data and assessment methods for resource efficiency.

1.3 Research questions

Two research questions (RQs) have been formulated to support the creation of the aimed solution:

RQ1. What are the challenges for resource-efficient manufacturing?

The first RQ focuses on the current situation of resource efficiency in manufacturing regarding material, energy, and waste flows. Challenges must be understood if a solution is to be provided. The challenges are explored by identifying enablers and barriers in resource-efficient manufacturing, considering two perspectives: the development and application of assessment methods for resource efficiency.

RQ2. How can manufacturing companies make data-informed decisions that lead to resource efficiency?

To become resource-efficient, manufacturing companies need both knowledge and practical tools. Based on the challenges identified in RQ1, RQ2 focuses on knowledge and tool development to tackle those challenges in conducting data-informed resource efficiency assessments. This thesis prioritized assessment method selection for resource efficiency and data preparation because they involve decision making in the early stage of resource efficiency assessments.

1.4 Scope and delimitation

This thesis aims to support resource-efficient manufacturing by improving the efficiency of critical resource flows at the factory level, including material, energy, and waste flow, in the light of decision-making supported by factory data. Figure 1 maps the scope of this thesis and sets some delimitations.

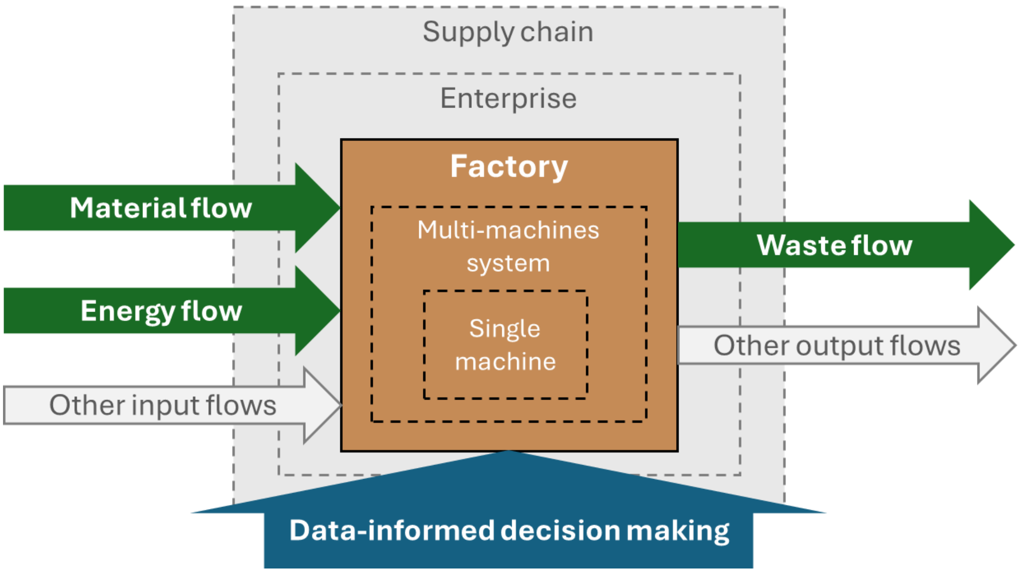

Figure 1. Scope and delimitations of the thesis.

In the development of resource-efficient manufacturing, it is important to consider different resource flows. Resource flows in manufacturing companies have great diversity, ranging from tangible material consumption to intangible people capability. This thesis initially sets material, energy, and waste flows as three critical resource flows that have a direct impact on the manufacturing system's economic and environmental performance (Ball et al., 2009). Other resource flows, such as human labor, may also be included in the analysis of assessment methods for resource efficiency but will not be further investigated in this thesis.

In terms of the boundary of manufacturing systems, this thesis discusses resource efficiency below factory level, including single or multi-machine systems. Data-informed decisions in this research are supposed to be made under the direct support of factory data, highlighting the improvement-oriented work from production operations. The whole enterprise or supply chain is included in the system boundary because decisions related to resource efficiency at those higher levels are more organizational and distant from operation.

1.5 Outline of the thesis

Following this first chapter introducing the importance of this research, this thesis is structured into six chapters, as outlined in Table 1.

Table 1. Overview of thesis structure.

Chapter	Content
2 Frame of reference	Introductions of the theories and concepts required to position this research.
3 Research methodology	A description of the entire research process, including the view from science, research design, execution, and synthesis of the findings.
4 Results	An overview of the two appended papers that are essential to addressing the research questions. Additional findings from ongoing studies are also included because they aid in the accomplishment of the goal of this research.
5 Discussion	Responding to the research questions and explaining the findings. This chapter also outlines the research's contribution, considers its methodological reflection, and makes suggestions for future research.
6 Conclusion	A summary of the key findings and their conclusions.

2

FRAME OF REFERENCE

This chapter presents the theoretical foundation that this research relies on. Connections to existing literature are established to position this research in a broad academic discourse.

The frame of reference of this thesis consists of several key elements. An impact model of these elements is presented in Figure 2. The element of sustainable manufacturing is connected to the vision of this research as an overarching goal. Resource efficiency in manufacturing, as a key strategy for achieving sustainable manufacturing as well as a lens for sustainability performance measurement, has a positive impact on sustainable manufacturing. Production information systems are supporting elements. Good quality of factory data serves as a foundation for advanced production information systems, therefore helping make decisions related to resource efficiency in manufacturing.

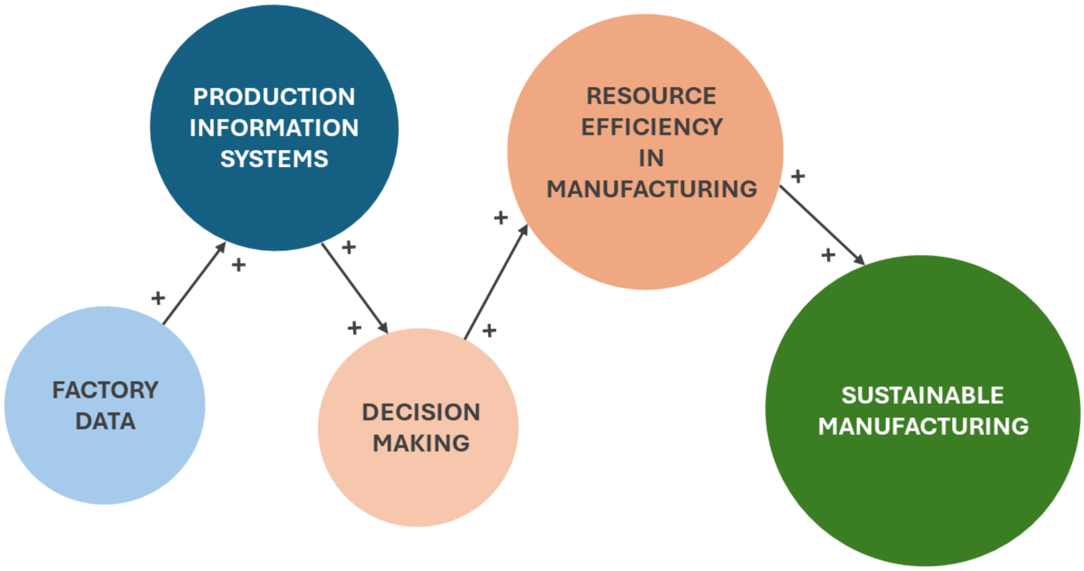

Figure 2. An impact model of the frame of reference in which this research is positioned.

2.1 Sustainable manufacturing

The topic of sustainability is and will remain critical for both the present and coming generations. As a cornerstone of civilization, manufacturing plays a key role in creating a sustainable future (Garetti and Taisch, 2012). More and more attention from researchers and industrial practitioners is paid to the concept of sustainable manufacturing, though the interpretations and understanding of it have become inconsistent nowadays. Some research tried to connect sustainable manufacturing to technologies, such as Industry 4.0, addressing opportunities offered by the industrial revolution (Machado et al., 2020; Sartal et al., 2020). Other studies prioritized framework development, interpreting it into main contributors to sustainable manufacturing (Rosen and Kishawy, 2012). Establishing a sustainability culture was highlighted by Rosen and Kishawy among the eight key contributors they identified. Their framework also included environmental controls, monitoring, and remediation to maintain long-term competitiveness (Rosen and Kishawy, 2012).

In practice, sustainable manufacturing is often related to analysis and improvement of processes at micro-level in manufacturing (Duflou et al., 2012). In the meantime, industry relates facility management, production scheduling, and supply chain design to sustainable manufacturing a lot at the macro-level (Haapala et al., 2013). However, many manufacturers benefited from improving production efficiency for maximized profit but still struggled in integrating the social and environmental factors for sustainable manufacturing (Qureshi et al., 2015). In face of the challenge, some manufacturers were able to perform environmental monitoring at the macro-level and show the figures for improvement. But the improvement at process levels lacks details (Despeisse et al., 2012b).

2.1.1 Performance measurement of sustainable manufacturing

Indicators are needed in measuring the sustainability performance of manufacturing systems at different levels. However, a lot of indicators are in solitude, therefore making it more difficult for manufacturers to decide which one to use in specific cases.

Material used, energy consumed, and air emissions were the most often used and developed indicators from the Triple-Bottom Line (TBL) perspective for sustainable manufacturing (Ahmad et al., 2019). Solid waste was the least mature indicator regarding environmental sustainability. Only cost-based variables were used for economic evaluation, and social sustainability was often evaluated by using indicators related to workers, local community, and society. Another fact from this review was that a third of reviewed indicators were only used once according to the literature. Moreover, indicators for product-level sustainability performance were found to be more developed than other manufacturing layers (Ahmad et al., 2019). Besides the TBL, sustainability indicators can also be categorized in a study from five dimensions: environmental stewardship, economic growth, social well-being, technological advancement, and performance management (Joung et al., 2013).

2.1.2 Resource efficiency in manufacturing

Human civilization relies on natural resources such as minerals, water, energy, land, and so on. Humankind will encounter its growth limitations if no control is put over the consumption of resources. For everyone on this planet, resource efficiency is about keeping improving quality of life while using resources more wisely (Weterings et al., 2013).

For manufacturing companies, recourse efficiency can refer to enhancing intangible capabilities of employees' learning outcomes when discussing enterprise performance (Roger G., Kimberly A., et al., 2002). But more often, resource efficiency focuses on tangible resource flows that were recognized as enablers that bring benefits from all sustainability perspectives in industrial decarbonization (Kim et al., 2024). Resource efficiency is also defined as a primary strategy for sustainable manufacturing, focusing on managing resources holistically rather than at a single point in manufacturing, independent from waste minimization, mistrial efficiency, and eco-efficiency (Abdul Rashid et al., 2008). Resource efficiency also needs good transparency in the manufacturing value chain, as upstream and downstream processes are interacting a lot with each other in the current industry setting (Blume, 2020).

There have been different opinions about the relationship between concepts, such as circular economy (CE) and circularity, with resource efficiency. The European Union (EU) highlights resource efficiency as the key to resource independence, while the circular economy is a part of the resource efficiency strategy (Baldassarre, 2025). However, researchers also claimed that resource efficiency is a topical area of the circular economy (Holzer et al., 2021). This thesis discusses resource efficiency-related concepts and how this inconsistency can impact the development of assessment methods for resource efficiency and industrial practice in an extended literature review.

2.2 Decision making in manufacturing

The fast-changing technologies and external environment position the manufacturing industry in challenges of quick responding. To make decisions in the manufacturing environment, decision-makers need to evaluate different alternatives and choose one based on a set of conflicting criteria (Rao, 2007). Typical manufacturing decisions include material selection for a given product characteristic, selection of machining parameters, design of the factory layout, failure analysis for equipment, and so on. Given the complexity of manufacturing scenarios, the decision-making process often needs to consider multiple criteria (Venkata Rao and Patel, 2010).

In data-intensive manufacturing, the role of data in decision-making has been highlighted in research. Researchers found that including data in the decision-making process in manufacturing demonstrated positive impacts on overall performance (Brynjolfsson and McElheran, 2016). Improvement at SMEs was more observable because decision makers in small organizations are closer to physical processes, where data are generated and collected (Brynjolfsson and McElheran, 2016). Another essential enabler in data-driven decision making is the adaptation of digital technologies that support data collection, monitoring, analysis, and modeling (Helu et al., 2016).

Despite the importance of data in manufacturing, decisions should not be completely dependent on or driven by data. Instead, data-informed decision-making was proposed in the education research area to avoid the risk of ignoring moral dimensions when making decisions totally driven by data (Shen and Cooley, 2008). In sustainable manufacturing, data-informed decision making refers to a holistic view of all sustainability dimensions, not making decisions solely driven by one of these bottom lines.

2.3 Production information system

None of the activities in production management, such as analysis, design, development, implementation, and operation of production systems, can exist without information, which needs to be identified and managed at all production system levels (Boggs, 1988). In manufacturing factories, the production information systems can be a collection of software applications that are intended to automate the collection, storing, and displaying of the data. Production information systems provide data to equipment and applications and consolidate data for people involved in the production to view and utilize (Shizuo Itoh, 2002). The role of information systems in manufacturing companies can be studied at different scales: just-in-time production, technology development, manufacturing strategies, quality management, human resource management, and supply chain management (Matsui, 2001; Shizuo Itoh, 2002).

The model in Figure 3 illustrates activities involved in different manufacturing hierarchies (International Society of Automation, 2010). This standardized hierarchical model defines data flows and information exchanges as well as integrations between manufacturing operations and control systems. Depending on the type of manufacturing system, production information systems can partially or completely cover the levels shown in the figure but should always start with data gathering from the physical production process. Examples of representative technologies or software at each level are also given by this model: enterprise resource planning (ERP) for business and logistics management; manufacturing execution system (MES) for operation planning; supervisory control and data acquisition (SCADA) and human machine interface (HMI) for monitoring and supervision; programmable logic controllers (PLCs) to sense and control processes; and machines and sensors that facilitate physical production.

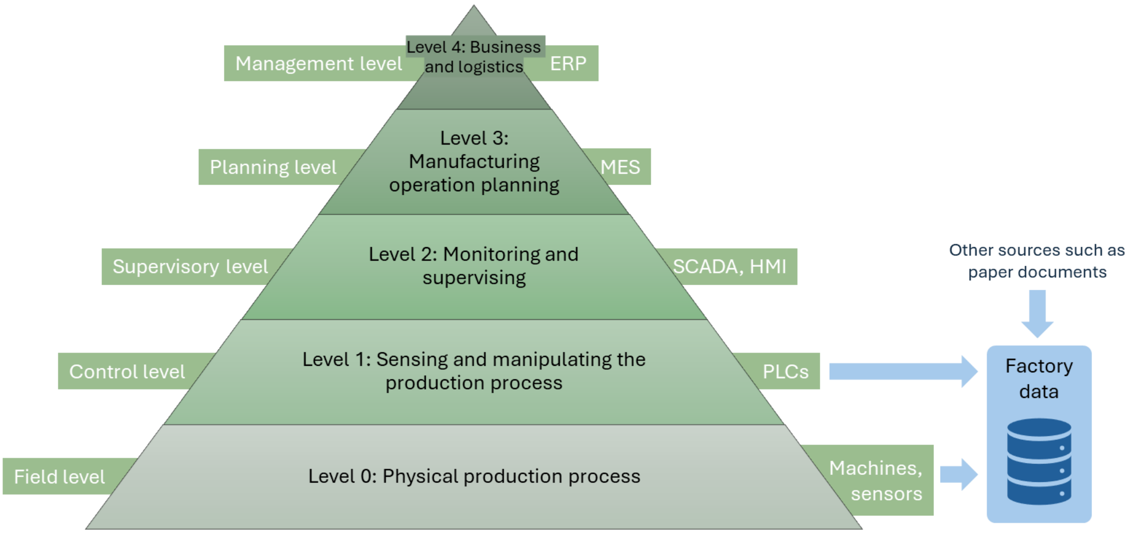

Figure 3. A hierarchical model of production information systems based on ISA-95, including factory data supply (Gangurde, 2016; International Society of Automation, 2010).

From physical production processes to top-level business management, production information systems play an important role regarding data collection and conversion between data and information in the manufacturing pyramid.

In this pyramid, factory data refers to data that can be collected from production operations through various means, including paper documents, sensors, and automated production devices (Gangurde, 2016). Factory data collection from field levels is the foundation of information processing and compiling for business management, as shown in the hierarchical model of production information systems in Figure 3.

A significant increase in the amount of factory data was observed together with the advent of Industry 4.0 and IoT in industrial digitalization. To leverage this factory data for competitive advantages, manufacturing companies have to enhance the utilization of factory data (Gröger et al., 2016). For small and medium-sized enterprises (SMEs), the value of factory data also started to get attention. In addition, requirements on data can vary in different manufacturing strategy contexts. For example, compared to mass production, data from manufacturing one-of-a-kind products put special requirements on production information systems for more accurate and timely data-information conversion (Dean et al., 2009).

3

RESEARCH METHODOLOGY

This chapter describes the methodology used in this thesis. This chapter starts with the adopted view of science and research methods. Studies conducted are described and presented at the end of the chapter.

3.1 Worldview

People view and interpret the world around them through the lens formed from their own cultural upbringing and experiences. The goal when I started my education in mechanical engineering was to keep being flexible and agile in this changing world. Following that, I worked as a production engineer for several years in the pharmaceutical and automotive industries, where I was exposed to a variety of problem-solving scenarios that influenced my philosophical worldview on pragmatism (Saliya, 2023). However, the shared values, beliefs, and methodologies within the surrounding research community also have an impact on researchers' worldviews (Kuhn, 1970). When I first began to conduct research activities, the research community, which values sustainability very much, introduced me to positivism, a paradigm that holds that research objectives exist independently of the outside world (Guba and Lincoln, 2005). Using a positivistic viewpoint in the context of sustainable manufacturing research places an emphasis on objectively measuring performance and improvement.

Pragmatism and positivism coexist and enhance one another in light of the aim and research questions generated in this thesis (Saliya, 2023). The pragmatic side leads this research to be positioned in design science, focusing on creating systems and tools to address practical problems of resource efficiency assessments in manufacturing through inductive approaches (Niiniluoto, 1993). In addition, the positivistic viewpoint directs the development of scientific knowledge to more precisely describe resource efficiency in manufacturing. In this thesis, positivism also examines the objectivity, reliability, validity, and generalizability of practical tools and scientific knowledge.

3.2 Research design

Design Research Methodology (DRM) is widely used and accepted in applied science. Following DRM helps create a good standing point for researchers in communicating their research. The other strength of DRM is flexibility regarding research processes and methods. DRM allows the use of different research methods based on specific needs on various research topics (Blessing and Chakrabarti, 2009). Four stages of DRM and corresponding studies designed for this research are shown in Figure 4.

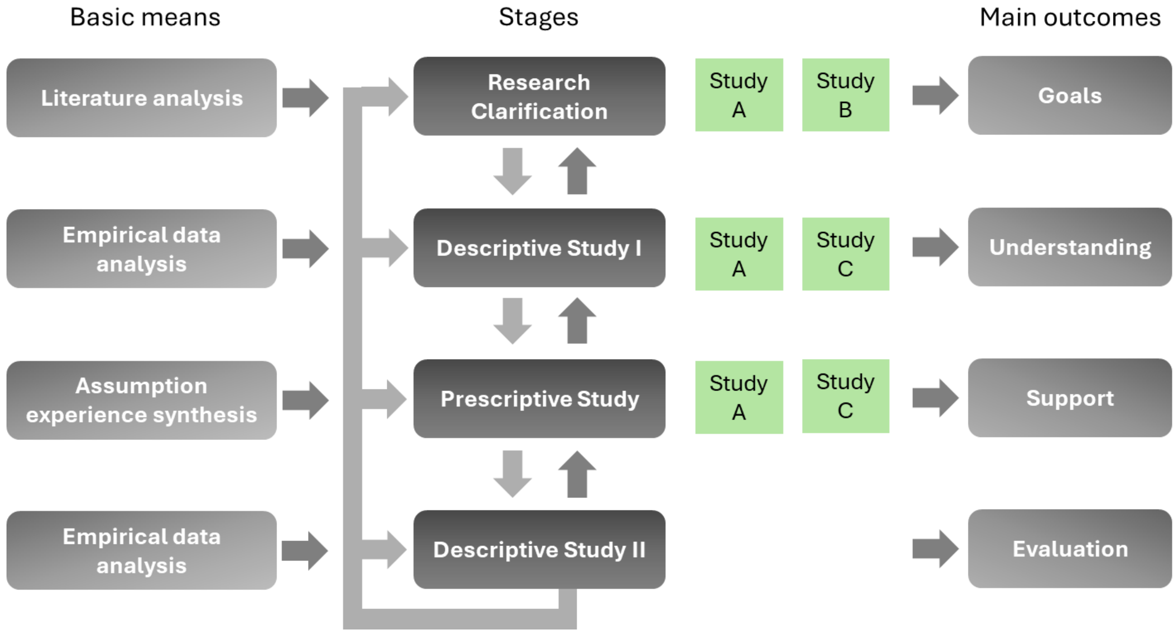

Figure 4. The stages of DRM and corresponding studies conducted in this research (Blessing and Chakrabarti, 2009).

In the research clarification (RC) stage, a literature analysis is often used to initially screen the current and desired situation of a research area and therefore formulate a clear vision, aim, and research focuses. In this research, literature on the broad topic of sustainable manufacturing was read to find the topic of interest: resource efficiency in manufacturing. A systematic literature review (*Study A*) was conducted to further understand the current situation of resource-efficient manufacturing. Vision, aim, and research questions of the thesis were formed afterwards. Together with this review study, an empirical case study (*Study B*) was conducted to help shape the research goals from an industrial practitioner's perspective.

The second stage, descriptive study I (DS-I), aims to further complement the understanding of the existing situation of the selected focuses. The systematic literature review (*Study A*) further investigated the current situation of resource-efficient manufacturing from the perspective of challenges in implementation. A multi-case study (*Study C*) conducted with three industrial manufacturers focused on the reflections from industrial practitioners at this stage, which was complementary to the summary of the current situation done by the literature review.

The later stage, prescriptive study (PS), aims to strengthen the understanding of future visions pictured in research clarification and deliver proposed support that will be needed to reach the desired situation. Once again, the systematic literature review (*Study A*) contributed by proposing an integration model with practical tools that support practitioners to tackle the challenges in the current situation of resource-efficient manufacturing found in DS-I. The multi-case study (*Study C*) with different manufacturing sites aimed to further develop the proposed model and tools. A detailed description of the three studies as well as data collection methods can be found in Section 3.3. The research design is also visualized in a timeline in Figure 5.

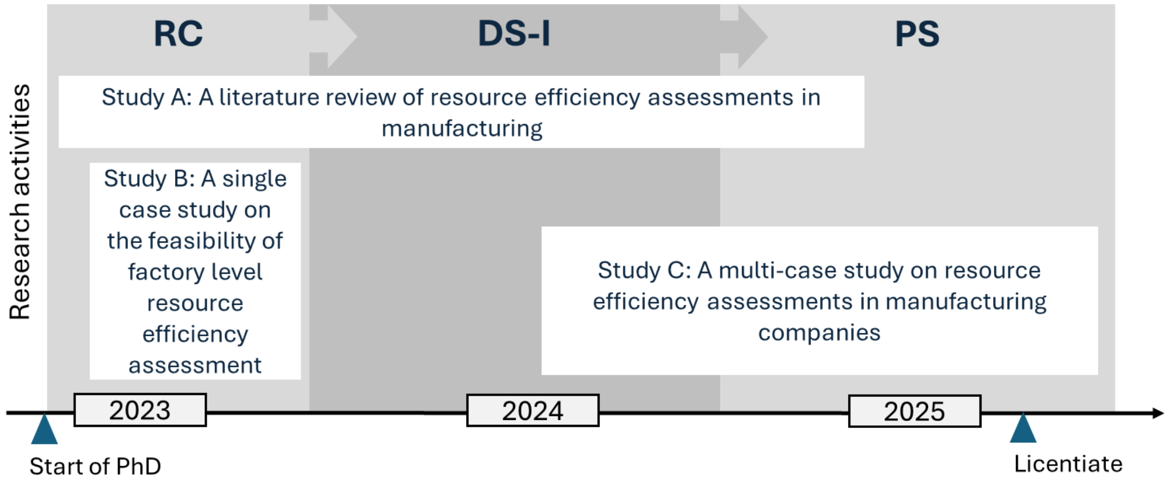

Figure 5. Visualization of the research process in a timeline.

In this thesis, studies were designed to be multi-purpose, covering several stages in one study. For instance, the literature review (*Study A*) combined a full investigation into the current situation of resource-efficient manufacturing as well as initial development of a practical model. As shown in the DRM framework, possible iterations are anticipated between stages. But this parallel design helped avoid unnecessary revisits to past studies, which can be hard in the context of collaborative empirical studies with industry.

According to the categorization of Blessing and Chakrabarti, this research falls into the type 2 DRM: "comprehensive study of the existing situation" (Blessing and Chakrabarti, 2009). As shown in Figure 6, this thesis delivered a comprehensive study of the challenges in resource-efficient manufacturing based on literature review and empirical studies. The support, as expected from the prescriptive study, was the initial model and tools.

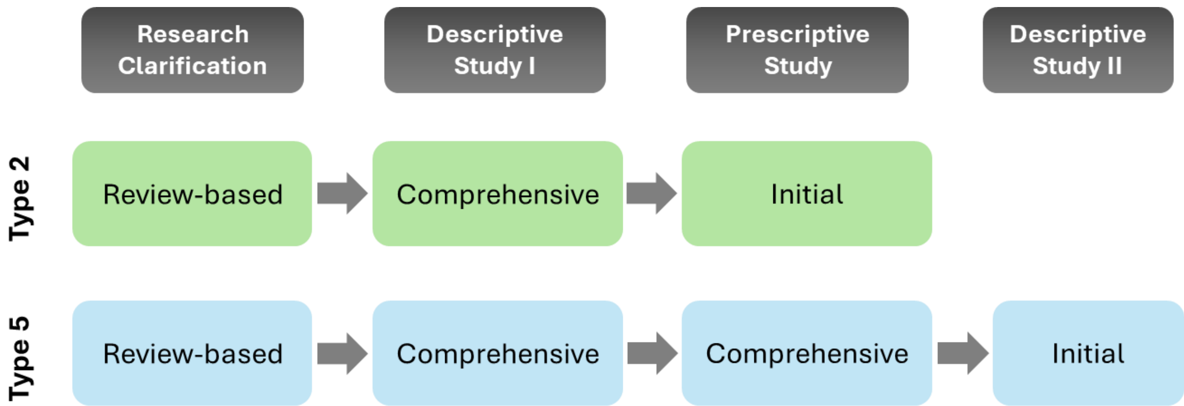

Figure 6. Selected type of DRM in this thesis and its continuation in future research (Blessing and Chakrabarti, 2009).

The plan for future research aims to deliver mature support based on the current initiated model and tools. The research will also reach the last stage of DRM, descriptive study II (DS-II), which has the task of evaluating the actual impact of the developed model and tools.

3.3 Data collection and data analysis

To build this research on existing knowledge as well as to answer research questions in a contemporary industrial setting, a literature review study and case studies were planned and carried out in this research. Figure 7 presents the studies conducted in this research.

	Study A	Study B	Study C
Type of study	Systematic literature review	Single case study	Multi-case study
Case selection		A truck manufacturing site in automitive industry	Three manufacturing sites with different machining processes
Data collection	Literature review	Observation; Workshop	
Data analysis	Coding of 49 papers by using nine label groups; Analyzing 38 assessment methods for resource efficiency	Manufacturing process mapping; Qualitative analysis of data availability; Feasibility analysis of resource efficiency assessments	Manufacturing process mapping; Data readiness check for selected assessment methods for resource efficiency; Benchmarking between cases; Special analysis for manufatcuring SME
Documentation	Paper 1	Paper 2	Licentiate thesis and future publication

Figure 7. Summaries of studies conducted in this research.

3.3.1 Study A: A review of resource efficiency assessments in manufacturing

The literature study started with an introduction of the research field of sustainable manufacturing. By collecting and synthesizing relevant publications, this study clarified resource efficiency in manufacturing as the focused research area and identified the research gap in resource efficiency assessments. This review study followed a guideline developed by Hannah Snyder (Snyder, 2019) for developing, conducting, and evaluating literature review studies, aiming to understand, generalize, and resolve the challenges in resource-efficient manufacturing.

In the literature review process, publications found in the initial search went through the exclusion criteria based on their subject area and research objectives. The inclusion of publication was based on three attributes of effective assessment methods for resource efficiency: applicability, scope, and impacts. Papers that were kept after two rounds of selection were used as core papers for backwards snowballing. The same exclusion and inclusion criteria were applied after snowballing. The final sample was coded into a method library with selected assessment methods for resource efficiency. The analysis of assessment methods for resource efficiency identifies implementation factors (including enabling and hindering factors) in the implementation of resource efficiency assessments. These implementation factors were used as guides in the development of an integration model.

3.3.2 Study B: A single case study

Study B was conducted with a truck manufacturing site that has been working collaboratively on the topic of resource efficiency in manufacturing. The frame beam workshop was selected for a feasibility study of implementing factory-level resource efficiency assessments, supporting understanding the challenges from the lens of practitioners.

This case study followed a factory-level prototype methodology (Despeisse et al., 2012a) in three steps, including manufacturing understanding, qualitative mapping, and quantitative mapping. Gemba walks and workshops with company participants with varying responsibilities contributed to the improved understanding of the processes and operational intricacies. The study adopted IDEF0 and spaghetti diagrams to map the selected manufacturing area qualitatively, together with a classification of data availability. These visualizations further provided researchers and industrial participants with a more holistic understanding of the existing resource flows. In the quantitative mapping, material flow analysis, resource efficiency flowchart, and energy portfolio were selected as two assessment methods for resource efficiency to be tested in the framebeam manufacturing area. These quantitative methods provided a foundation in this study to further discuss the feasibility of measuring resource efficiency performance in the case study company.

3.3.3 Study C: A multi-case study

Study C is a multi-case study that involved three manufacturing sites, focusing on their machining processes. These participants play different roles within a value chain, including original equipment manufacturers and component suppliers. The size of participating manufacturing companies varies from SMEs to large multinational manufacturers. Data collection at those manufacturing sites was facilitated by Gemba walks and workshops, as similar as in Study B, following the three steps in the factory-level prototype methodology: manufacturing system understanding, qualitative mapping, and quantitative mapping.

In addition, this multi-case study considered an adequate level of diversity in participating manufacturing sites for exploring the expectations from industry regarding the integration model proposed in the literature review study (*Study A*). At the same time, the similarity of starting with machining processes in all three manufacturing sites allows potential benchmarking in later analysis.

3.4 Measures to enhance research quality

To make the research trustworthy, measures were taken to enhance the quality of research from two perspectives: research design and study execution.

The overall research design followed the well-developed methodology of DRM as the core of the research design. Though the stages in DRM seem logically obvious, it is a helpful tool to structure a rigorous research project systematically. The systematic literature review also followed guidelines developed by Snyder to compile and organize existing knowledge on resource efficiency in manufacturing (Snyder, 2019). On top of the systematic literature review in the review-based stage RC, an additional empirical study was designed to cross-check the clarified research focus for research validity. To ensure the comprehensiveness of stage DS-I, the multi-case study chose participants from the same manufacturing sector to ensure good consistency in case selection for future generalizability. The coverage over different types of organizations also aimed to improve the usability of research in practice. A general principle for selecting industrial partners was reaching out to them from collaborative research projects. The engagement level is a crucial enabler for adding value to knowledge and practice (Yin, 2009).

Measures were also taken during the execution of research activities. Researchers had regular conversations with industrial companies to keep their engagement prolonged. Material used in studies and talks was documented for good transparency and traceability. To evaluate and validate conducted case studies, results from case studies were presented to participating industrial practitioners for them to confirm the results (Säfsten and Gustavsson, 2020).

Furthermore, some reflections on the selection of methodology and research ethics are presented later in the Discussion (see Section 5.5 Methodological reflections).

4

RESULTS

In this chapter, the main findings from the appended papers are presented. The first section is a description of how appended papers relate to RQs, and a summary of each paper is provided. The findings are further discussed in the discussion chapter.

4.1 Relationship between RQs, studies, papers, and contributions

This thesis is scoped to focus on understanding challenges for resource-efficient manufacturing (RQ1) and how manufacturing companies make data-informed decisions that lead to resource efficiency in factories (RQ2). Table 2 summarizes the main findings from documented results and their contribution to the RQs.

RQ1. What are the challenges for resource-efficient manufacturing?

RQ2. How can manufacturing companies make data-informed decisions that lead to resource efficiency?

Table 2. Summary of the main contributions from the papers and documentation.

Documentation	Main contribution to RQ1	Main contribution to RQ2
Study A Paper 1	**Major contribution** Focused on understanding the current situation of material, energy, and waste efficiency in manufacturing. Explored challenges reflected from literature and summarized implementation factors to answer RQ1. Identified research direction: there is a lack of the capability to make data-informed decisions in application for resource-efficient manufacturing. The research direction forms RQ2 for this study.	**Major contribution** Proposed an initial model, integrating with the production information systems, for manufacturing companies to make data-informed decisions in resource efficiency assessments, based on the answers to RQ1.
Study B Paper 2	**Major contribution** Identified research direction: academia and industry need better understanding of resource efficiency in manufacturing. The research direction motivates RQ1 for this study. Findings presented by this paper contribute to answering RQ1.	Minor contribution Findings from the empirical study presented in this paper are considered as user requests in the development of the proposed model.
Study C Part of this licentiate thesis	Minor contribution Findings from empirical studies reflect on the challenges and implementation factors found in Paper 1.	**Major contribution** Continued the development of the proposed model collaboratively with manufacturing companies. Outcomes are mainly for method selection and data preparation for the early stage of conducting resource efficiency assessment.

4.2 Summary of Paper 1 – the systematic literature review

Title: Review of Resource Efficiency Assessments in Manufacturing: An Integration Model for Production Information Systems

Short description:

Using a systematic literature review, the paper answers the question, *"How can production information systems support resource efficiency assessments in manufacturing companies?"* guided by three objectives:

1) Identifying effective assessment methods for resource efficiency in manufacturing.
2) Identifying enabling and hindering factors in the implementation of resource efficiency assessment.
3) Creating an integration model for the production information system.

For the literature review, the search string below was applied to the title, abstract, or keywords:

("resource efficien")*
AND
(material OR energy* OR waste*)*
AND
(indicator OR method* OR tool* OR approach* OR measure)*
AND
(manufact)*
AND
(sustainab OR green* OR environment*)*

This resulted in 388 papers from Scopus in the initial search.

As shown in Figure 8, scope and four label groups were applied in exclusion and inclusion. 33 papers were kept and used as core papers for snowballing. After applying the same exclusion and inclusion criteria, 16 papers were kept in the final sample. In total, 49 papers were coded. Finally, a method library of 38 assessment methods for resource efficiency was created (available in Appendix - The Method Library).

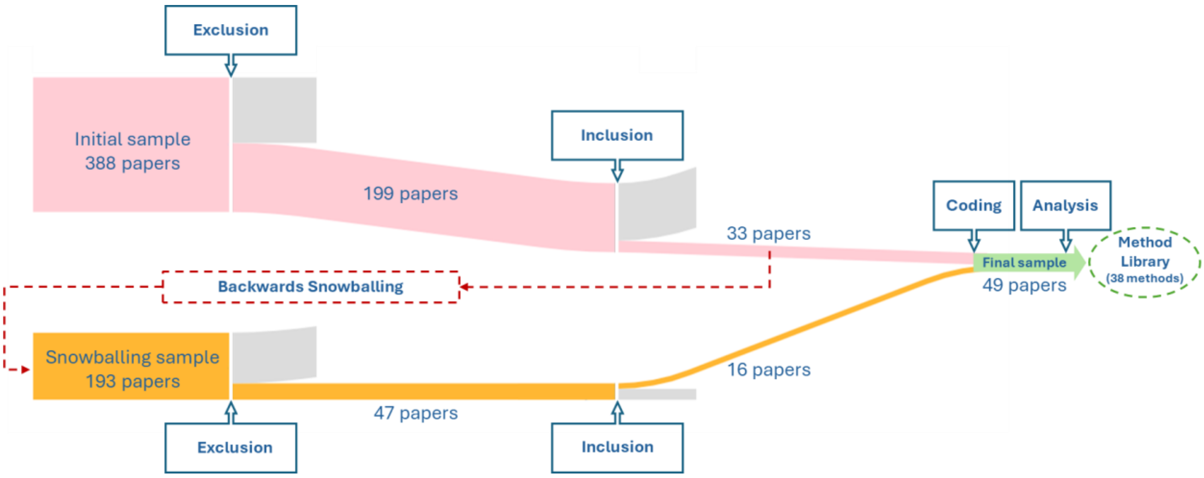

Figure 8. The process of systematic review with the exclusion criteria and the labels groups used for inclusion, coding, and analysis.

The exclusion was done based on the subject area and research objectives in found publications. Only publications focusing on developing resource efficiency assessment methods for the manufacturing industry were kept. Studies related to building, construction, or technical problem-solving (e.g., material processing, tooling path optimization) were excluded. Effective assessment methods for resource efficiency were identified using the following inclusion criteria. Label groups 1-4 shown in Table 3 were used as the inclusion criteria based on three attributes of effective assessment methods for resource efficiency: applicability, scope, and impacts. On top of label groups 1-4, five additional label groups were developed for coding and in-depth analysis. Each paper was coded individually by nine label groups in total.

Table 3. Label groups developed for inclusion, coding and analysis.

Label group	Abbreviation	Definition
1-Type of study (applicability)		
Methods development	MED	New assessment methods development
Indicator development	IND	New indicators development
Single case study	SCS	/
Multi-case study	MCS	/
2-Applied level (scope)		
Machine	MAC	Single machine or single process
Cell	CELL	Line or multi-machine system
Factory	FAC	The facility includes cells or lines
3-Sustainability dimension (impact)		
Environmental	ENV	/
Economic	ECO	/
Social	SOC	/
4-Improvement area (impact)		
Operation management	OP	Improvement in operations, such as changing machining parameters
Manufacturing strategy	STRA	Strategic improvement, such as supplier management
Technology change	TECH	Adoption of new technical solutions
5-Research field		
Production management	PM	Generic production and manufacturing systems management
Machining and tooling	MT	Machining and tooling process
6-Base approach		
Life cycle assessment	LCA	Assessment of environmental impact throughout a system's life cycle
Simulation or modelling	SIM	Simulated production in different means
Lean management	LEAN	Lean management
Material flow analysis	MFA	/
Value stream mapping	VSM	/
Emergy	EME	/
Exergy	EXE	/
Industrial metabolism	IND	/
7-Focused resource flow		
Material	MAT	Material flow in manufacturing systems, such raw material consumption
Energy	ENE	Energy flow in manufacturing systems, such electricity consumption
Water	WAT	Water flow in manufacturing systems

Waste	WAS	Waste flow in manufacturing systems, such as solid waste and wastewater
Service	SER	Intangible wealth in manufacturing systems, such as office expenses, labor protection fees
8-Connection with production information systems		
Enterprise resource planning or Manufacturing resource planning	ERP	IT system or software to collect, store, manage and interpret data from business activities and resources
Manufacturing execution system	MES	IT system or software to collect, store, manage and interpret data from business activities and resources
Bill of material	BOM	List of raw materials, parts, and components used in manufacturing
SCADA	SCADA	Supervisory Control and Data Acquisition
Manually	MAN	Data are collected from manufacturing systems manually, such from operators
Secondary data	SD	Data collection through public/non-public database, such as life cycle database
Unspecified data collection	UDC	/
9-Connection with standard		
Global standard	GS	Globally recognized standards
Regional standard	RS	Standards used in specific regions, such EU standard
Others standard	OS	Other hierarchy of standards
Unspecified standard	US	/

The identification of effective assessment methods for resource efficiency was the first objective directly aided by the coded final sample. Analysis was performed on single label groups and across different groups.

Main results:

Analysis of assessment methods for resource efficiency

This review used case studies to evaluate the applicability of assessment methods for resource efficiency. Out of the 245 publications that made it to the inclusion stage for the applicability check, 189 (76%) had no case studies for the newly developed methods in the manufacturing setting; 55 (22%) had single case studies, and only 4 (2%) had multiple case studies, as shown in Figure 9.

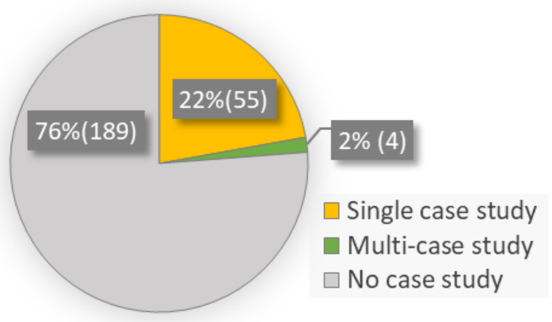

Figure 9. The percentage of publications include single case study, multi-case study, or no case study.

All three applied levels—machine, cell, and factory—have been covered by the method library, with 19, 17, and 21 methods, respectively, as seen in Figure 10. Compared to machine level and factory level, production cell level offered fewer alternatives for procedures created for a specific scope.

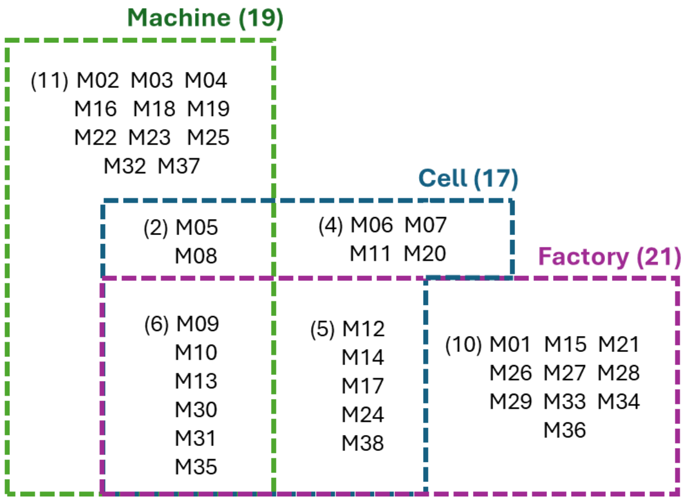

Figure 10. Coverage of the method library at the applied level.

A low level of maturity in integrating data demands from resource efficiency assessments and routine data management in manufacturing businesses was shown by the heat map of links between the method library and production information systems in Figure 11. Additionally, 23 library methods lacked a data source specification.

Connection with Production IS		Applied level			Base approach								
		MAC	CELL	FAC	LCX	SIM	LEAN	MFA	VSM	EME	EXE	IND
ERP	1	1	1	0	1	1	0	0	0	0	0	0
MES	2	1	1	1	1	2	0	0	0	0	0	0
BOM	1	1	1	0	0	0	0	0	0	1	0	0
SCADA	1	1	0	0	0	1	0	0	0	0	0	0
MAN	11	5	8	7	2	3	0	2	2	3	1	0
SD	7	3	3	4	2	3	0	1	1	1	1	0
UDC	34	17	15	20	5	16	1	8	4	3	2	1
Connection%		11%	12%	5%	17%	20%	0%	0%	0%	0%	0%	0%

Figure 11. The connection to production information systems of the method library against their applied level and base approach.

Connections to standards were considered in the coding system to assess how the development of these assessment methods for resource efficiency interacted with regional, global, and other forms of standardization. Only a small number of the library's methods have strong ties to standards, as seen in Figure 12, which displays the current situation.

Connection with standards		Applied level			Base approach							
		MAC	CELL	FAC	LCA	SIM	LEAN	MFA	VSM	EME	EXE	IND
GS	8	2	3	7	3	2	0	5	2	0	0	0
RS	1	0	0	1	0	0	0	1	0	0	0	0
OS	3	1	1	1	0	2	0	0	0	0	0	1
US	26	15	13	13	4	15	1	3	3	3	2	0
Standardization%		21%	24%	38%	33%	25%	0%	63%	25%	0%	0%	100%

Figure 12. The connection to standards of the method library against their applied level and base approach.

Implementation factors (enabling factors and hindering factors)

The systematic review of the 38 assessment methods for resource efficiency identified several enabling and hindering factors, which are compiled in Figure 13.

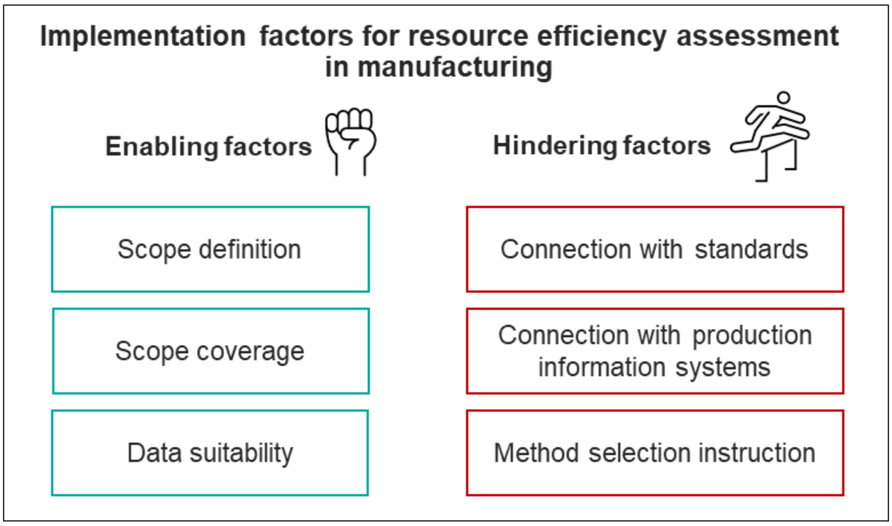

Figure 13. An overview of the enabling and hindering factors for the implementation of resource efficiency assessment in manufacturing.

The main enabling factors included:

- Scope definition: Well-defined scope and impact of methods for application to align with the environmental goals.
- Scope coverage: Broad coverage of resource flows, potentially through diverse base approaches.
- Data suitability: Production data suitability for resource efficiency assessments (manufacturers have data needed in resource efficiency assessments).

And the main hindering factors identified included:

- Connection with standards: Inadequate instruction in method selection and execution (for example, clear strategic alignment with companies' environmental goals and targets).
- Connection with production information systems: Insufficient connection to standards to support compatibility between assessments (when combining methods to increase the coverage of different environmental aspects and other sustainability dimensions), transferability of the results (especially for inter-organization sustainability assessment), and regulatory compliance.
- Method selection instructions: Insufficient connection to production information systems (thereby creating barriers for companies to implement the advanced methods due to the lack of time and human resources for data collection and management).

Discussion:

Terminology usage in resource efficiency assessment methods

The inconsistent use of terminologies in assessment methods for resource efficiency found in this review method was a challenge in the literature search. The first search was found to be lacking a few important papers from the research areas of sustainable manufacturing and resource efficiency. Additional snowballing was created for complementarity to cover the desired research topic as thoroughly as possible. The variety of terms used in assessment methods for resource efficiency makes it difficult for manufacturing organizations to find and choose the best approaches. Both academic research and industry collaboration can benefit from improved language alignment around resource efficiency in manufacturing.

Effectiveness of resource efficiency assessment method implementation

- Integrating production information systems for resource efficiency assessment

Regarding data management, the simulation and modelling-based resource efficiency assessment method in the method library are more closely connected to production information systems. One argument is that industrial digitalization, where the importance of data is widely recognized, is more directly linked to manufacturing system simulation and modelling. The integration of resource efficiency assessment methods with production information systems for data collection, which were derived from traditional production management approaches like material flow analysis and value stream mapping, still has great potential (Thiede et al., 2016).

- Connecting standards for resource efficiency assessment

Even though manufacturing resource efficiency standards and regulations are being debated a lot these days, there is still no well-established connection between regulation research and practical assessment methods for resource efficiency. Future research should consider improved standardization of assessment methods for resource efficiency for both compliance and successful application.

The learning effort needed for industrial implementation of assessment methods for resource efficiency can be greatly decreased by integrating standardized processes or education. By offering precise instructions, the standardized methods make it simpler for manufacturing personnel to adopt them, guaranteeing that resource efficiency thinking is included into daily production rather than being a one-time occurrence. Additionally, industrial users are more likely to adopt assessment methods that incorporate processes and indicators that are in line with current standards or regulations for compliance purposes.

The integration model

New procedures for industrial users, primarily for indicator selection, have been developed in the research area of sustainable manufacturing. For instance, a procedure for choosing key performance indicators at the manufacturing process level was published in 2018 because manufacturers needed to better understand and choose from the many available indicators (Kibira et al., 2018). In 2019, another study specifically reviewed circular economy indicators from the literature and further designed a tool to help industrial users find appropriate indicators based on their own cases and indicators' characteristics (Saidani et al., 2019). These new procedures were approved as value-adding by increasing the effectiveness of implementing assessment methods for resource efficiency. This paper developed an integration model with some additional features to increase the efficiency of implementing assessment methods for resource efficiency in manufacturing companies (Figure 14).

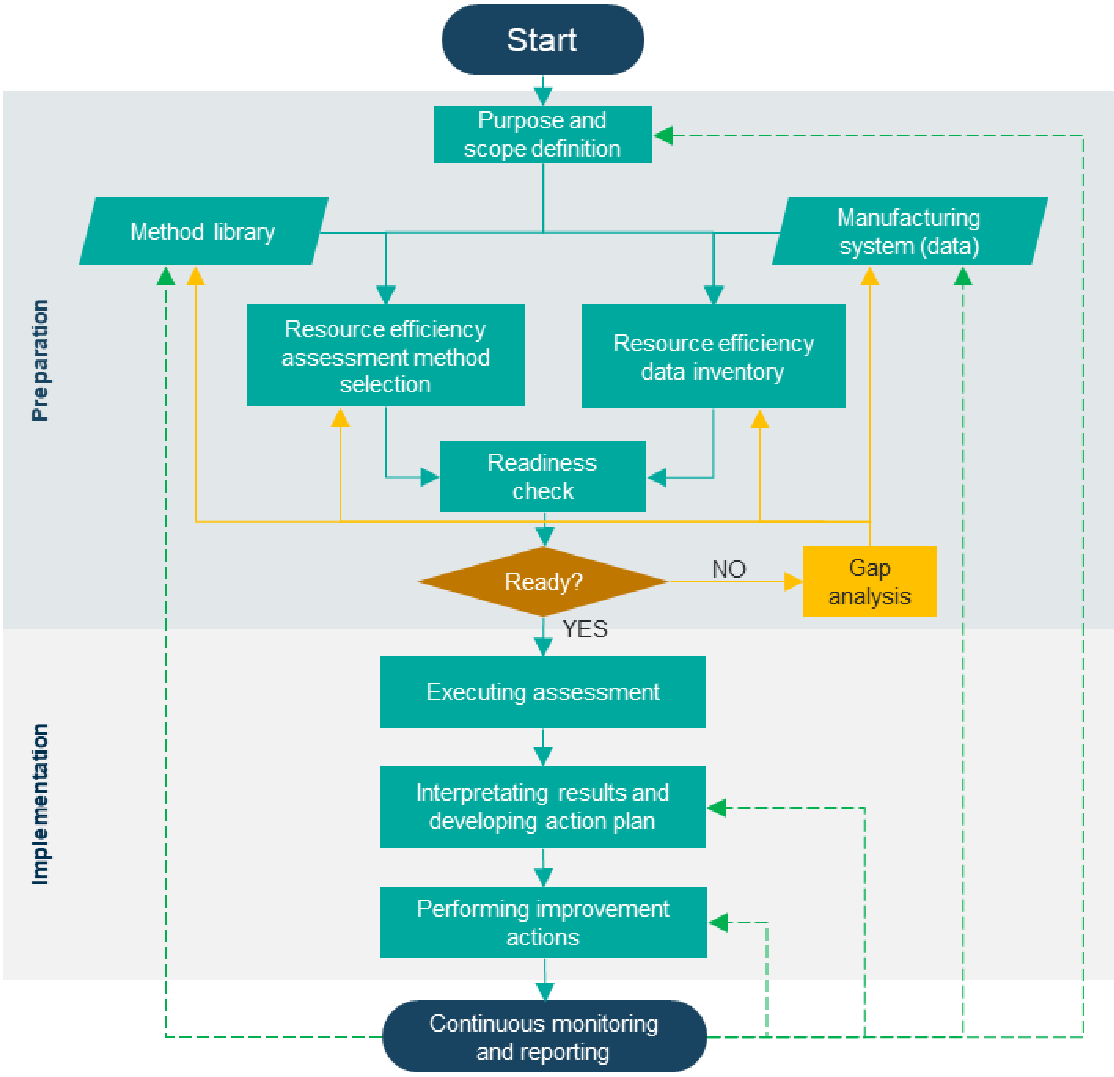

Figure 14. The integration model for implementing assessment methods for resource efficiency.

The proposed integration model offers manufacturing companies two entry points during the preparation phase: selecting assessment methods for resource efficiency based on their strategic sustainability goals (top-down) or based on the data available in their factories (bottom-up). The model helps manufacturing companies better prepare for resource efficiency assessments execution by aligning assessment methods with available data. To connect resource efficiency assessment and factory data, the resource efficiency data inventory is established according to specific data needs. Ideally, companies should manage this inventory within their regular production information systems, such as Manufacturing Execution Systems (MES).

A data readiness check compares the resource efficiency data inventory with data required by assessment methods. If data gaps exist, immediate actions include reviewing the inventory or reselecting methods, while long-term actions involve installing additional measurement, using secondary data, or enhancing data management systems. If data fulfills the requirements, the model proceeds to implementation, covering execution, result interpretation, action plans, and improvement activities.

4.3 Summary of Paper 2 – the single case study

Title: Exploring Factory Data for Resource Efficiency Assessment - A Case Study at a Truck Manufacturing Company

Short description:

Between 2022 and 2023, a case study was conducted with a truck manufacturer in Sweden to identify data requirements for conducting resource efficiency assessments in the truck frame beam manufacturing area. This study aims to bridge the gap between academia and industry in terms of method development and practical applications.

The focus of this case study is the feasibility of implementing resource efficiency assessment in a manufacturing organization in terms of the data required. By addressing this research focus, the study hopes to detect any hidden challenges that may emerge during the adoption of basic assessment methods for resource efficiency in the selected manufacturing area. The study also aims to offer preliminary guidelines for future scale-up implications. The feasibility study followed three steps shown in Figure 15.

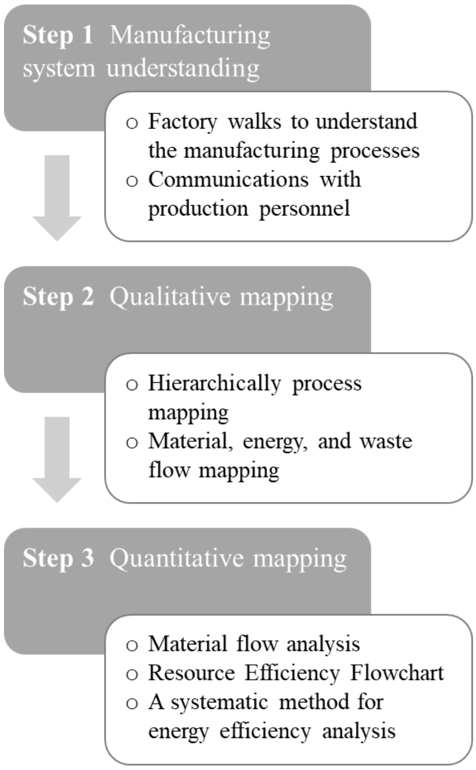

Figure 15. Three steps followed in the single case study.

In the qualitative mapping, two process mapping tools were used to help make the selection of feasible assessment methods for resource efficiency and get a deeper knowledge of the factory data that was available. To illustrate the hierarchies of manufacturing processes, the IDEF0 framework and its functional units modeling approach were selected for this study (Presley and Liles, 1998). As shown in Table 4, related data for each input and output flow was categorized into three groups on top of a simple decomposition view (Robinson and Bhatia, 1995). The spaghetti chart, which incorporates pertinent production plan information, was also used in this feasibility study to illustrate the material, energy, water, chemicals, and waste flows (hence resource flows).

Table 4. Classification approach of data in input and output.

Category of data		Definition of data category
Category A	Collected	Data in this category are already collected for assessments in the operation
Category B	Available but not collected	Data are available from equipment or other sources but require extra efforts to be collected for assessments
Category C	Not available	Data are not available in the current production system; Category C requires further investigation or proper estimation in assessments

Main results:

Qualitative mapping

Three separate layers are illustrated in a hierarchical process mapping of the case study truck manufacturing company (as shown in Figure 16): the factory, the production area, and the beam manufacturing processes. Activities, constraints, and mechanisms are shown inside each functional unit to emphasize their primary purposes. The input and output arrows in the graphics are color-coded to match the data categories listed in Table 4.

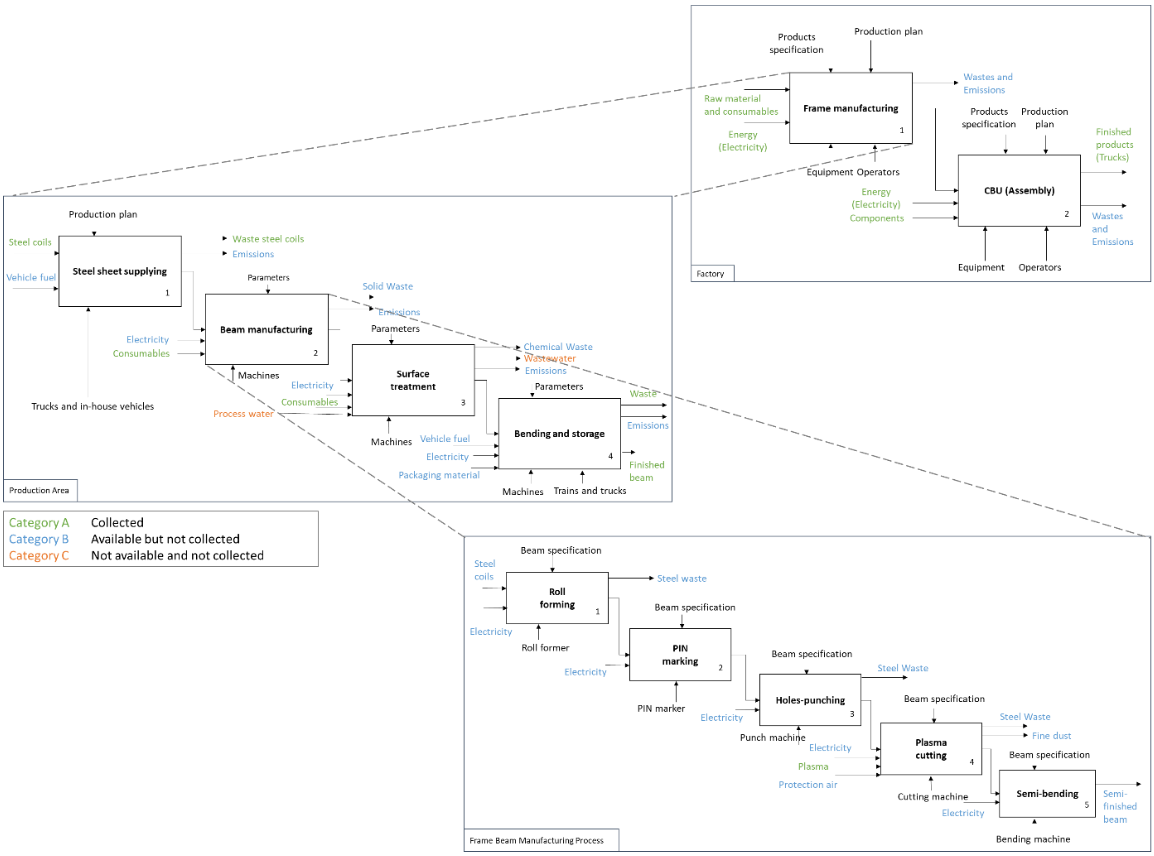

Figure 16. Process mapping of factory, production area, and beam manufacturing processes.

A spaghetti diagram mapping the resource flows in the frame beam manufacturing area is shown in Figure 17. The flow of metal material, as the major material of the main product, is driving the production flow. At several stages, additional materials are also shown to enter the process, and waste can be generated. Based on the real layout of production facilities, the mapping also includes the ventilation and energy supply systems.

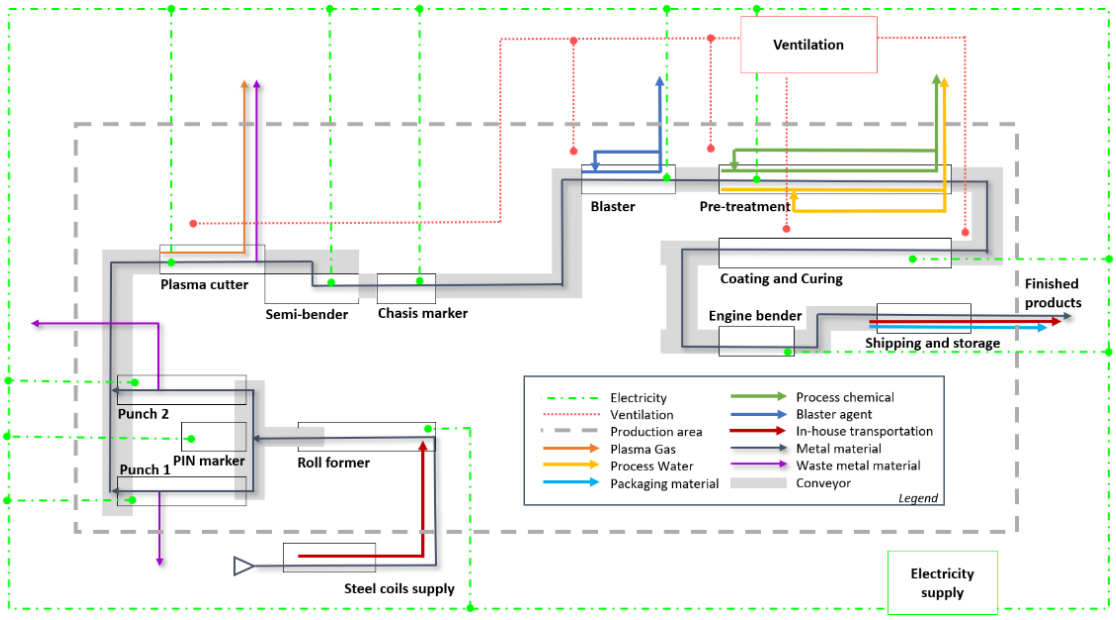

Figure 17. Resources flow mapping of the frame beam manufacturing area.

Quantitative mapping

At the factory level, data in category A (collected) has the biggest share, as shown in Figure 18. This demonstrated that the implementation of basic resource efficiency assessment at the factory level has been made possible by the better availability of data.

The proportion of data in categories B (available but not collected) and C (not available) rises as the research moves deeper into the manufacturing site's more intricate levels. This makes it more challenging to conduct resource efficiency assessments at these levels.

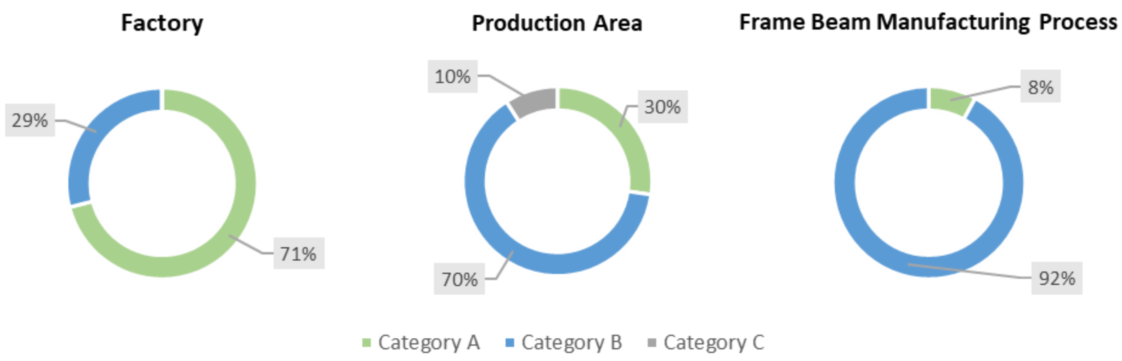

Figure 18. Distribution of three data categories at factory, production area, and process levels.

Discussion:

Challenges in data completeness and reliability

A conceptual data quality framework developed by Levitin and Redman in 1995 suggests that there are five dimensions that are crucial in data quality analysis: contents, scope, level of detail, composition, and consistency (Levitin et al., 1994). Furthermore, data scarcity and reliability issues are two limitations in system modelling and assessment in the context of production data management (data scarcity refers to the limited availability of data, while reliability issues encompass the accuracy and trustworthiness of the data itself) (Despeisse and Bekar, 2020).

- Data scarcity hinders full-scale resource efficiency assessments

Improved data collection is needed, especially at the production area and manufacturing process levels, as indicated by the trend in Figure 18. To guarantee the effectiveness of resource efficiency assessments, it is imperative to match the initial phase of data collection with the requirements of the assessment methods for resource efficiency. Data that are most important to the assessment being carried out might be prioritized by manufacturing companies.

- Data reliability hinders resource efficiency assessments

A thorough examination of the resource flow data that was gathered is necessary to identify gaps in data reliability. There can be various issues with data reliability; for example, in this case study, the electricity consumption data were found to be inconsistent due to the unsynchronized timestamps on machines.

- Unstandardized data collection templates hinder resource efficiency assessments

The standardization of data collection has been constrained in this feasibility study by the manual collection of data on operating activities and material flows. Comparing and combining data from various resource flows or time periods becomes challenging. Improving the effectiveness of quantitative analysis requires addressing the standardization of data templates (Ćwikła, 2014). Standardized data templates can improve data quality, expedite data management procedures, and enable more thorough and trustworthy quantitative analysis.

4.4 Results from the multi-case study

Short description:

A multi-case study has been in progress with three manufacturing companies since early 2024, focusing on collaborative development of the initial integration model for resource efficiency assessment. The study follows the three steps (shown in Figure 15), starting with manufacturing understanding, then qualitative mapping, to quantitative mapping. The qualitative mapping continues to use the IDEF0 functional units modeling approach (Presley and Liles, 1998) and the data classification approach (shown in Table 4). While performing these steps, requirements and expectations are collected to convert the initial integration model into a user-friendly tool. The prioritized part of the model is the data readiness check tool (shown in Figure 14), which helps evaluate whether the factory data can fulfill the data required by assessment methods for resource efficiency.

Main results:

Qualitative mapping of the machining processes in two manufacturing sites

To understand the complexity of the machining area in manufacturing site A, the data availability and the qualitative mapping were drawn for three levels: production area, machining processes, and machining machines (only the first two layers are shown in Figure 19). At the machining area level, raw material, chemicals, and consumables consumption were available and could be allocated to the cylinder blocks production. Energy consumption was available, but the data was aggregated for the whole building where the machining line shares with other production areas. It is not known yet how much energy consumption should be allocated to the machining line. The mapping can zoom in to individual machines. The machining process consists of four sub-processes: preset, machining, assembly, washing, and drying. Only a few resource flows have corresponding consumption monitored for the machining process. However, when breaking down to single machines, it was currently infeasible to have resource consumption data.

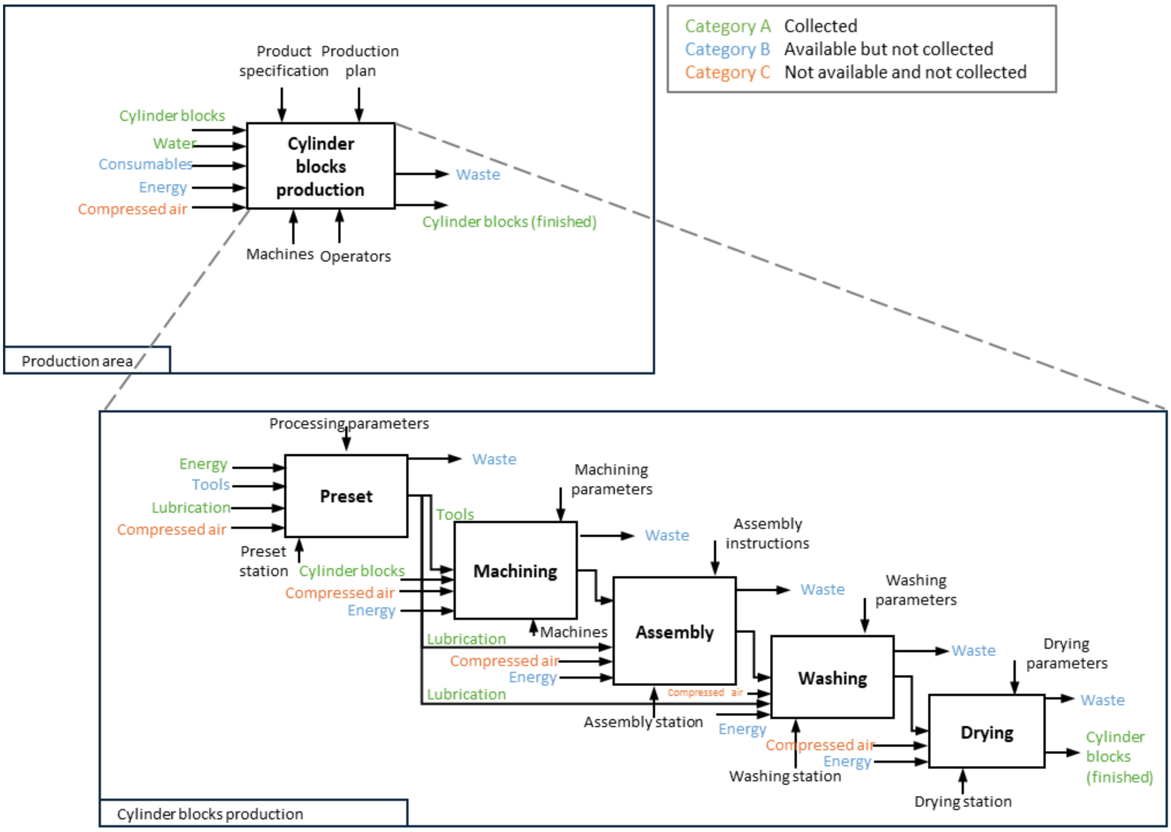

Figure 19. Process mapping of machining area and machining processes.

A qualitative mapping of the machining area at manufacturing site B was also performed after the mapping of site A. The machining area was selected for two reasons: the machining area was the factory's focus area for resource efficiency, and mapping similar manufacturing processes can help future benchmarking between sites in this multi-case study.

Demonstration - Data readiness check for resource efficiency assessments

The multi-case study developed a demonstration of a data readiness check based on the method library and the integration model proposed in the literature review (*Paper 1*). This demonstration tested the two entry points designed in the integration model. Additionally, it explored the feasibility of embedding a data readiness check into qualitative mapping. The demonstration used blurred information and data from previous case studies.

The top-down approach chose energy consumption as the strategic focus. Energy portfolio (method no. 31) from the assessment method library for resource efficiency was selected (Thiede et al., 2012). The bottom-up approach selected qualitative process flow maps (method no. 26), representing the method library in this simplified demonstration (Smith and Ball, 2012).

The demonstrated manufacturing area, a production line with four stations, was visualized in Figure 20. Resource flows going into and out of each station were specified based on the understanding about the manufacturing area, including data availability, data handling, and data sampling rate. Data requirements were indicated by a circle (method no. 26) and a triangle (method no. 31). Data availability was indicated by the color coding: available resource flow data were marked in green, and those unavailable data were marked in red.

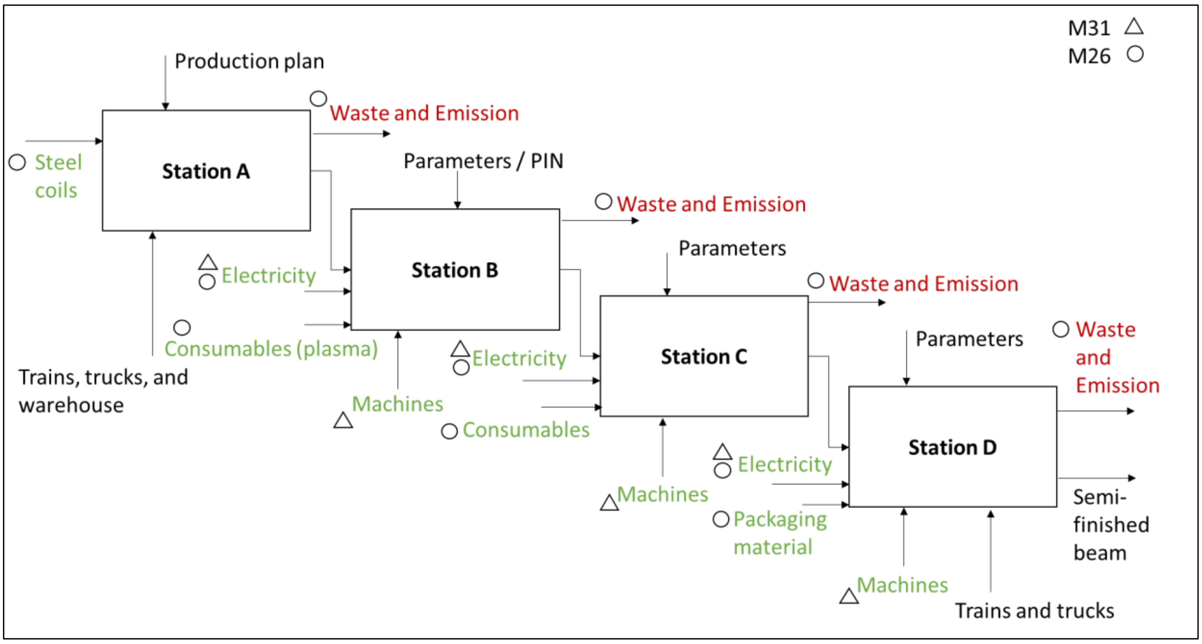

Figure 20. Data readiness checks visualized within a process mapping.

The demonstrated readiness check only considers data availability preliminarily. Data readiness for two methods was shown in Figure 21. Because energy consumption data had good availability, the top-down approach was evaluated as feasible for the manufacturing area. In the bottom-up approach, data readiness still needs to be improved because data of waste flow was not available for potential methods.

Resource Efficiency Assessment Methods	Data Readiness (0-100)	Traffic Lights
M26: Qualitative process flow maps	70	
M31: Energy portfolio	100	

Figure 21. Data readiness dashboard of the demonstration.

In this simplified demonstration, the resource efficiency assessment moved on with the energy portfolio method. The gaps in data readiness for implementing the other alternate were analyzed to initiate additional data collection.

Discussion:

Next step: scale-up data readiness check from demonstration to multi-cases

The demonstration was a simplified use case. Methods selected in both approaches were too basic to show the complexity in real-world cases. The multi-case study will be a platform for future work. Considering the data availability at different levels in selected manufacturing sites based on the process mappings, further resource efficiency assessments will focus on the machining area level for all three sites. Both top-down and bottom-up approaches will be tested within these manufacturing areas, identifying feasible assessment methods for resource efficiency with the current available data from the method library as well as taking companies' strategic goals into account.

The systematic categorization of assessment methods for resource efficiency in the literature review study provides a foundation for scaling up the data readiness check as well as further resource efficiency assessments. However, for industrial users to perform the check and assessment autonomously, the study process needs a user-friendly interface and clear step-by-step instructions.

5

DISCUSSION

This chapter elaborates on and answers the research questions. The contributions of this research are highlighted. Furthermore, reflections on methodology used in this thesis and future research direction are discussed.

5.1 Answer to RQ1 - What are the challenges for resource-efficient manufacturing?

Summing up the outcomes from studies conducted, challenges for effective resource efficiency assessments in manufacturing can be discussed from three elements: *Foundation* – foundational knowledge in the research area; *Drive* – applicability of assessment methods for resource efficiency; and "*Lubricant*" – data readiness in manufacturing factories. Figure 22 is an illustration of the challenges and how they may interact with each other.

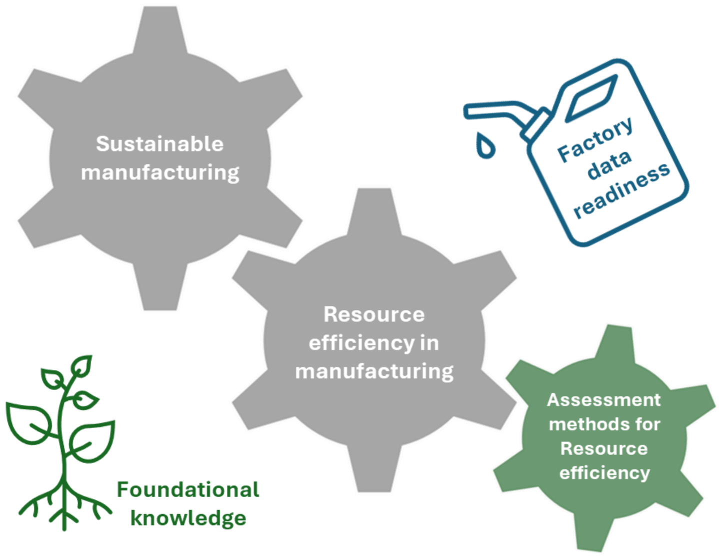

Figure 22. Challenges for resource-efficient manufacturing in foundational knowledge, assessment methods, and factory data readiness.

5.1.1 Foundational knowledge in the research area of resource-efficient manufacturing

Like any other area of research, resource efficiency in manufacturing is built on foundational knowledge, which helps understand relevant concepts and identify gaps in existing research. Terminology usages are typically important from this research perspective.

Resource efficiency is not always chosen as a key word in studies related to resource-efficient manufacturing. Researchers may use resource efficiency in general even though they only focus on a specific resource flow in manufacturing, such as energy consumption (Larek et al., 2011). While other researchers working on energy consumption may use other keywords like energy management systems instead of discussing resource efficiency as an umbrella terminology (Lee et al., 2024; Vikhorev et al., 2013). Researchers also use the term resource-efficient manufacturing but only focus on reducing production costs and maximizing profits for manufacturers (Gould and Colwill, 2015).

Terminologies around production information systems need to be further standardized as well. Researchers use manufacturing information systems to facilitate energy consumption (Vikhorev et al., 2013). When researchers were trying to identify an information source for resource flow model parameterization, they also used the term manufacturing IT systems (Leiden et al., 2021).

In this thesis, the usage of different terms around resource efficiency hindered the searching for existing literature. A few important papers were found missing from the research domain of sustainable manufacturing and resource efficiency from the initial search. Additional snowballing was conducted to cover the research domain as comprehensively as possible. In the implementation of assessment methods for resource efficiency, manufacturing companies find it challenging to identify and select suitable methods due to the diversity of keywords used in method development. Both academia and industry can benefit from improved terminology alignment around resource efficiency in manufacturing.

5.1.2 Applicability of assessment methods for resource efficiency

Finding assessment methods for resource efficiency that work effectively for factories remains a challenge for manufacturing companies. Several implementation factors were identified from the review of assessment methods for resource efficiency (shown in Figure 13). Combining the findings from case studies, the applicability of assessment methods for resource efficiency is impacted from several different aspects: instructions for implementation, performance measurement and indicator usage, and connections to standards and production information systems.

Industrial users prefer using assessment methods for resource efficiency with a clearly defined scope and focused resource flow as the starting point. Those assessment methods with clear scope and target resource flows often have more detailed instruction on data requirements. Manufacturing companies can quickly evaluate whether a specific method is feasible with the data they currently have. Additionally, many assessment methods start with the assessment itself without describing the circumstances under which this method should be suitable, for instance, possible contributions to strategic goals. Step-by-step instructions are not always available for potential users in industry.

The effectiveness of industrial applications is also affected by the indicator used in assessment methods for resource efficiency. Basic indicators like absolute resource consumption are straightforward and widely used, but they are not capable of communicating from the standpoint of sustainability performance. Indicators converted from direct resource consumption can vary a lot. Carbon emissions from material, energy, and waste flows are used to report resource efficiency from an environmental sustainability perspective in studies but not in a standardized way (Billy et al., 2022; Zheng et al., 2022), which hinders benchmarking across the industry. Moreover, assessment methods for resource efficiency also need to comply with legislation in the face of the increasing expectations from government and society. Assessment methods for resource efficiency aligned with legislation in measuring and reporting environmental sustainability performance are welcomed by practitioners.

For a single assessment method, the connection to standards affects mostly reporting under the legislation, as discussed as one of the enablers. But when combining methods to increase the coverage of different environmental aspects and other sustainability dimensions, alignment with the same standards across methods will support compatibility and transferability of the results. On top of the connection to standards, connections to production information systems support manufacturing companies in implementing resource efficiency assessments by saving time and human resources in data collection.

5.1.3 Factory data readiness

To prepare for optimization of resource efficiency, manufacturing companies should have factory data ready as inputs for resource efficiency assessments. In this thesis, the readiness of factory data is interpreted from three characteristics: data availability, data reliability, and data inventory standardization.

Results from both case studies indicated a pattern that data required in resource efficiency assessments had limited availability at the production area and process level compared to the factory level. Having access to data about resource flow that goes in and out of the whole factory may make it possible to produce some resource efficiency indicators, such as resource consumption per product. However, in-depth assessment requires better data availability at lower levels in the factory for higher resolution in performance analysis, bottleneck detection, and improvement. Moreover, factory data availability does not necessarily need to cover everything. Depending on the selected (or likely to be selected) assessment methods for resource efficiency, prioritization can be made in data collection.

Given the complexity regarding equipment and operation in manufacturing factories, maintaining the reliability of factory data is crucial to resource efficiency assessments' integrity. Issues regarding data reliability were found when examining data collected for resource efficiency assessments in the conducted case studies. For instance, timestamps on equipment could lose synchronization, particularly for equipment that has been in service for many years. In some cases, manually collected data needs to be further calibrated as well. Data recorded from logbooks can be inconsistent due to human errors.

These data reliability issues are relatively easy to fix once identified by applying immediate actions or Kaizen projects in the long term. In the feasibility study conducted in this thesis, manufacturers set up regular calibrations for their equipment and measurement gears. Training on improving record integrity for operators and double-confirming rules was also applied on the site. But finding the root cause of unreliability in factory data and preventing unreliable data from generation is more important than firefighting.

A standardized data inventory helps the implementation of any kind of assessment in industry, despite the means of data handling. Case studies conducted in this thesis showed that many manufacturing companies have not considered resource efficiency assessments when building up on-site data inventory. In both cases, collected data of resource flows varied in forms and sampling rates, making later data processing for quantitative analysis challenging (Ćwikła, 2014). Additionally, standardized templates for collecting data of different resource flows can improve data reliability in manual handling. Besides internal assessment, standardized data inventory for resource efficiency assessment purposes can also facilitate easy benchmarking with external organizations.

Nevertheless, these challenges in foundational knowledge, method applicability, and data readiness are relevant to each other. For instance, industrial practices of preparing factory data readiness and enhancing the applicability of assessment methods for resource efficiency will contribute to foundational knowledge development, encouraging collaborative knowledge creation. While connecting assessment methods for resource efficiency to production information systems, manufacturing companies can build up data inventory for long-term use.

5.2 Answer to RQ2 - How can manufacturing companies make data-informed decisions that lead to resource efficiency?

To tackle the challenges identified from the three elements shown in Figure 22, manufacturing companies are in the driver´s seat for resource efficiency regarding the factory data readiness. This thesis discusses reforming the way of conducting resource efficiency assessments by proposing an integration model (Figure 14) that offers manufacturing companies two entry points in both strategic (top-down) or opportunistic (bottom-up) scenarios.

Also, to highlight "data-informed decision making" in the answer to RQ2, this thesis identified two critical decision-making points: decisions on assessment methods selection and resource efficiency assessment execution. To utilize factory data while making these decisions, actions such as connecting to production information systems, building up resource efficiency data inventory, and evaluating factory data readiness for resource efficiency assessments should be taken by manufacturing companies.

Figure 23 illustrates the two different entry points under strategic and opportunistic scenarios as well as when the two critical decisions are made. The text that follows describes how data-informed decision-making is enabled with actions to involve factory data.

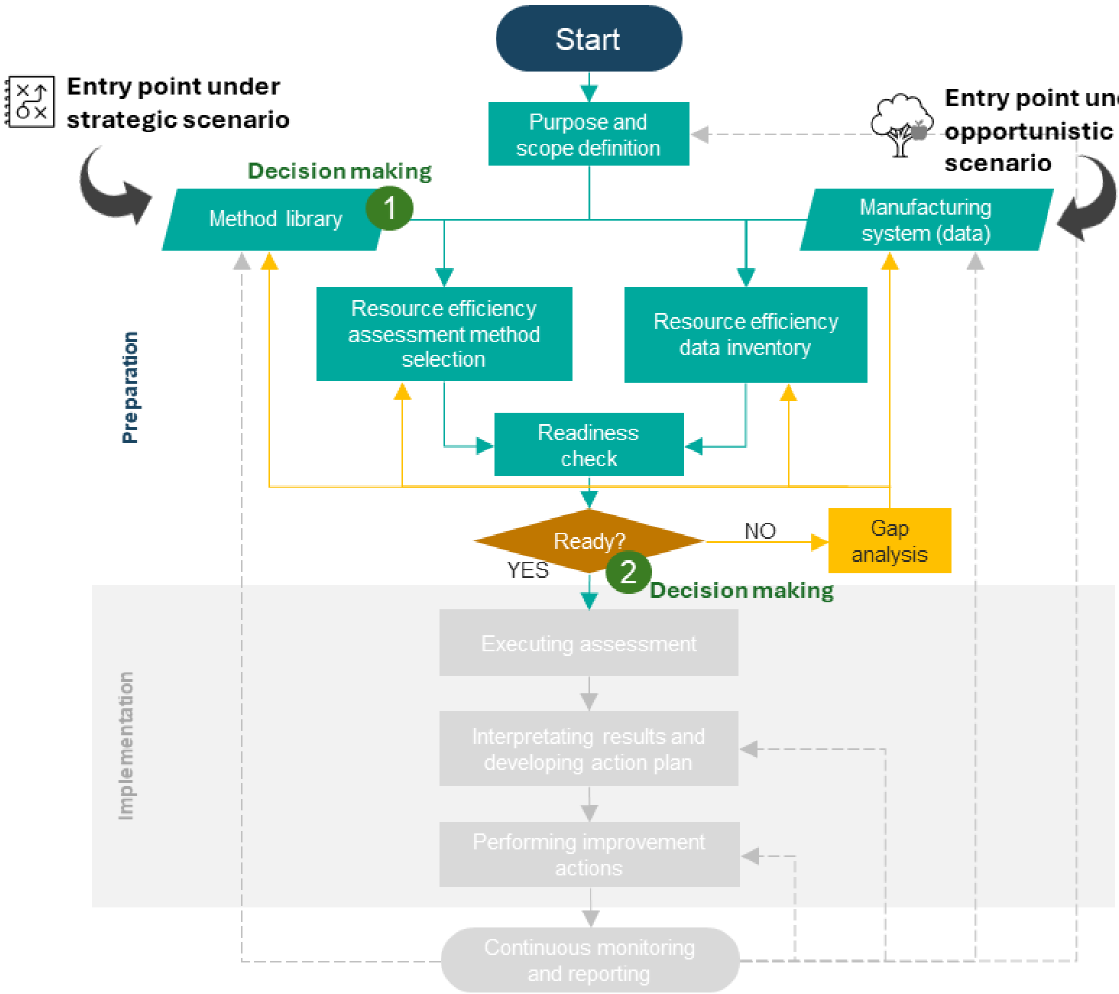

Figure 23. Decision-making points in resource efficiency assessments under strategic and opportunistic scenarios.

5.2.1 Connecting to production information systems and building up resource efficiency data inventory

Assessment methods for resource efficiency reviewed in this research often rely on extensive efforts on data collection and processing. These assessment activities can be beneficial for quarterly or annual reporting purposes. However, conducting another round of assessments for continuous monitoring can be time-consuming. It is also more challenging to reuse the results for planning and improvement activities than just for one-time reporting. Connecting resource efficiency assessments to production information systems can ease the sourcing of factory data and therefore help tackle data-related issues.

The connections are built during the preparation phase, where manufacturing companies maximize the use of their factory data and create the data inventory. As shown in Figure 23, the resource efficiency data inventory can be established with or without selected assessment methods for resource efficiency, depending on the chosen entry point. In the strategic scenario, manufacturing companies will bring data requirements from selected assessment methods for resource efficiency to their production information systems and collect corresponding data. In the opportunistic scenario, currently available factory data related to resource consumption will be extracted from production information systems and examined with reference to data requirements of different assessment methods in the library. The assessment will proceed only with feasible methods. In both scenarios, production information systems in manufacturing companies will be the main data sources for resource efficiency data inventory and in the later execution of assessment or future iterations.

5.2.2 Perform data readiness check for resource efficiency assessments

In both scenarios illustrated in Figure 23, a data readiness check is performed to determine whether the assessment process can move on to execution or not (additional actions are needed).

In the strategic scenario, manufacturing companies kick off resource efficiency assessments with selected methods focusing on specific resource flows. According to the data requirements, data are collected from production information systems and stored in resource efficiency data inventory. The resource efficiency data inventory is examined regarding data readiness to check if collected data can fulfill the requirements. The readiness of data indicates the feasibility of selected assessment methods for resource efficiency.

In the opportunistic scenario, resource efficiency data inventory has inputs from the assessment method library for resource efficiency and existing production information systems. In this case, data readiness check aims to identify feasible assessment methods with data available from manufacturing factories in the current situation.

The demonstration presented as a part of the results from the ongoing multi-case study (described in Section 4.4) proved the feasibility of data readiness checks in both strategic and opportunistic scenarios. For industrial implementation, the readiness check tool needs to be extended to all 38 assessment methods for resource efficiency and to methods that could potentially be added to the library.

5.3 Contributions to knowledge

In the research area of resource-efficient manufacturing, improving the maturity of knowledge requires a better understanding of the definition of resource efficiency and what the challenges are in the manufacturing setting.

This thesis reviewed research areas related to resource efficiency in manufacturing, focusing on material, energy, and waste efficiencies. Furthermore, assessment methods for resource efficiency were systematically categorized, and a method library was created. Analysis based on this categorization contributes to a more consistent understanding of assessment methods. Future research on this topic now has a solid foundation to initiate discussions on, such as following the systematic categorization in developing new assessment methods for resource efficiency.

This thesis also identified the gap between the development of assessment methods for resource efficiency development in academia and applications of these methods in industry. By investigating the implementation factors in effective resource efficiency assessments, this thesis provides insights into enablers and barriers from theory to practice. With findings presented in this thesis, awareness has been brought to the obstacles that must be considered when conducting resource efficiency assessment studies. For instance, the development of assessment methods for resource efficiency should include explicit data requirements and be able to connect to relevant standards. These implementation factors will also equip manufacturing companies with awareness regarding data readiness, instructions, and legislation. Knowledge-wise, the method library created from the systematic literature review helps industrial users to better understand the variety in assessment methods for resource efficiency. Overcoming the lack of one-solution fits all, this thesis empowers manufacturing companies to select the one best suited for their factory data and the purpose of performing resource efficiency assessments.

5.4 Contribution to practice

This thesis has developed a preliminary integration model for manufacturing companies to effectively implement resource efficiency assessments. The first two tools introduced in this new model are:

- Connecting the implementation of resource efficiency assessments with production information systems, and
- Performing data readiness checks.

In general, the integration model in this research guides manufacturing companies through the implementation of assessment methods for resource efficiency and points out critical decision points in the preparation stage, including selecting methods and evaluating data readiness for execution. Manufacturing companies can connect their ongoing resource efficiency assessments to production information systems at certain points for data collection and build up resource efficiency data inventory later depending on the entry point they chose. The two entry points lead manufacturing companies to different scenarios (strategic and opportunistic), where they perform data readiness checks before executing resource efficiency assessments.

In the short term, the practical model allows manufacturing companies to take a chance of using currently available data to perform resource efficiency assessments. The method library with standardized categorization can facilitate a fast identification of potential assessment methods for resource efficiency by using the given factory data. Though the opportunistic approach can be criticized for lacking long-term planning in resource efficiency improvement, it still adds value by achieving low-hanging fruits, especially for SMEs and industrial practitioners early on in their transformation journey. Every time with updated data or method library, manufacturing companies may retain the opportunistic approach and build up an initial data inventory for future attempts of adopting a strategic approach.

The long-term contribution is mainly driven by the strategic approach. The current method library and its potential to include more effective assessment methods for resource efficiency enable flexible method selection for diverse strategic goals. Iterations triggered by evaluating data readiness will eventually complete the resource efficiency data inventory in manufacturing companies. A matured resource efficiency data inventory does not aim to include as much data as possible but only maintains necessary data for desired resource efficiency assessments.

5.5 Methodological reflections

This section is a continuation of the discussion on research methodology for research design and execution in Section 3.4, including methodological reflections on methodology selection, data collection methods, scientific quality, and research ethical considerations.

5.5.1 Methodology and data collection methods selection

Given the aim and objectives of this research, collaborations with industry are important to develop practical solutions for achieving resource efficiency. Methodologies for participatory research, such as action research, were also in consideration for the research in this thesis.

Action research, defined as a participatory, democratic approach to bringing theory and practice together by solving problems practically (Brydon-Miller et al., 2003), seems to be a good fit in this research for the purpose of developing solutions to realizing resource-efficient manufacturing. In person, the commitments often made by action researchers to engage practitioners and to deliver helpful tools are fascinating. While bridging between theory and practice, action research also focuses heavily on changes and reflections (Avison et al., 1999). An important criterion of assessing action research quality is to evaluate the changes made by practitioners in their organizations. In this thesis, changes in resource efficiency assessments-related activities take time.

Although action research was not used in overall research design, its collaborative approach still inspired the facilitation of research activities under the DRM framework. The case studies conducted with industrial partners used on-site visits and workshops to meet and engage people. The close collaboration made it possible to understand the expectations from practitioners and gather data as well as information needed by the knowledge creation in a limited time. The collaborative approach also directs future research to focus on implementation and making changes in real-world manufacturing.

5.5.2 Scientific quality of the research

Good research is expected to be fact-based and unbiased. Though the starting point for doing research on the topic of data utilization in resource-efficient manufacturing is personal interests and concerns, the research has been keeping the objectivity. The DS stage in the DRM makes sure that the existing condition of the aimed research area is carefully evaluated. Research objectives and questions are assessed and modified based on an expanded understanding of the current situation of resource efficiency assessments in manufacturing companies. Research activities are all documented, and results are openly shared with participants for traceability and transparency.

The quality of the descriptive results can be assessed by internal and external validity (Brogan, 2013; Kirk and Miller, 1986; Yin, 2009). While answering RQ1, three elements that support resource efficiency in manufacturing were identified, and then challenges identified from different studies were grouped correspondingly for further discussion. Observation and analysis done in case studies and literature reviews were direct inputs for discussing challenges, showing a good internal validity. Externally, the descriptive findings on in-depth challenges were recognized by participating industrial partners, which provide good platforms for future validation of the developed model and tools. Moreover, applications of these initial prescriptive outcomes (answers to RQ2) are not limited to currently studied manufacturing companies. New partners from different industry sectors (such as building and construction) can also find this thesis inspirational and adopt the findings in other contexts.

5.5.3 Ethical considerations

To conduct research that is not only appreciated by the scientific community but also adds value to society, researchers are expected to relate to and uphold certain standards and norms in the professional activities (Säfsten and Gustavsson, 2020). This thesis discusses ethics based on the research ethics guidelines provided in Good Research Practice (Swedish Research Council, 2017).

This research first considered confidentiality in communications with industrial partners, including data to be published, personal information, and confidential information. For example, for papers that are written based on case studies, industrial participants must approve them before submissions. Key data or information will be blurred in publications if necessary. This research also tried to maintain good openness and transparency when sharing data, results, ideas, and tools with industrial participants. Research can be difficult to understand. It is important to make information accessible and open to questions from participants. Improving the skill of communicating complex challenges with people from different hierarchies is also a learning objective in this thesis.

5.6 Future work

The future research will continue working on the completeness and maturity of the proposed integration model for effective implementation of assessment methods for resource efficiency in manufacturing companies. Besides the features that help manufacturing companies connect resource efficiency assessments to production information systems and perform data readiness checks in the preparation phase, the research will move forward to the implementation phase with collaborated industrial partners. The maturity of the proposed model will be enhanced from multiple dimensions. The library of effective assessment methods for resource efficiency will be updated regularly to include new methods. The systematic categorization of methods in the library will also be optimized to better connect to standards, legislation, and production information systems. So far as presented in this thesis, the development and demonstration of tools have been mainly driven by researchers. To achieve autonomous decision-making in selecting assessment methods for resource efficiency and data readiness checks, future research needs to lower the effort level for manufacturing companies to get started, considering effective knowledge transfer and upskilling. A more user-friendly interface will be developed and validated together with industrial practitioners.

Another direction for future research is to identify joint interests with the research area of digital technologies in the manufacturing sector. Artificial intelligence (AI), which has huge capacity in terms of data analytics, has not been considering resource efficiency in manufacturing as a clear objective (Waltersmann et al., 2021). Through assisting production planning and optimization, AI solutions showed their potential impact on energy efficiency, but the link in between was not clearly stated. In future research, AI could be employed directly in the establishment of resource efficiency data inventory for manufacturing companies, tackling data-related issues such as availability, reliability, and standardization. Other technologies, such as product digital passports and digital twins, can also help tackle data-related issues in effective resource efficiency assessments at manufacturing companies. Interdisciplinary collaborations will add extra value to this research journey towards resource-efficient manufacturing.

6

CONCLUSION

In this final chapter the results of the research are discussed and concluded.

The aim of this thesis is to provide a solution for manufacturing companies to achieve resource efficiency and make data-informed decisions by effectively utilizing factory data and assessment methods for resource efficiency. The solution was formed in two steps through answering two research questions.

Answers to the first research question presented three elements that support resource-efficient manufacturing: 1) foundational knowledge in the research area, including consistent terminology and performance indicator usage; 2) applicability of assessment methods for resource efficiency, including instructions for implementation, performance indicator usage, and connections to standards and production information systems; and 3) readiness of factory data in manufacturing companies, covering data availability, data reliability, and data inventory standardization. The three interconnected elements need to work together to achieve resource-efficient manufacturing.

Answers to the second research question identified two decision-making points, including the decision on selecting assessment methods for resource efficiency and resource efficiency assessment execution. To make data-informed decisions, this thesis suggests manufacturing companies take two actions: connecting production information systems to build up resource efficiency data inventory and performing data readiness checks in resource efficiency assessments. This thesis also proposed two scenarios where manufacturing companies can make decisions in a data-informed manner: strategic and opportunistic. Detailed instructions on handling both scenarios were also provided.

This research contributes to knowledge through the systematic categorization of assessment methods for resource efficiency and analysis of challenges as well as impact factors in effective resource efficiency assessments. Actions and tools suggested are value-adding to industrial practice, especially when bringing more practitioners on board. Future research will focus on completing and maturing the tools together with validation in the real world.

Given the large number of methods available and the increasing availability of industrial data, creating new assessment methods for resource efficiency or simply collecting more data is no longer an effective way to improve resource efficiency in manufacturing. Both academia and industry need a better understanding of assessment methods for resource efficiency and factory data and, therefore, be able to connect resource efficiency assessments with production information systems for agile data sourcing and ensuring just adequate data readiness.

REFERENCES

Abdelaziz, E.A., Saidur, R., Mekhilef, S., 2011. A review on energy saving strategies in industrial sector. Renewable and Sustainable Energy Reviews 15, 150–168. https://doi.org/10.1016/j.rser.2010.09.003

Abdul Rashid, S.H., Evans, S., Longhurst, P., 2008. A comparison of four sustainable manufacturing strategies. International Journal of Sustainable Engineering 1, 214–229. https://doi.org/10.1080/19397030802513836

Acerbi, F., Sassanelli, C., Terzi, S., Taisch, M., 2021. A Systematic Literature Review on Data and Information Required for Circular Manufacturing Strategies Adoption. Sustainability 13, 2047. https://doi.org/10.3390/su13042047

Ahmad, S., Wong, K.Y., Butt, S.I., 2022. Status of sustainable manufacturing practices: literature review and trends of triple bottom-line-based sustainability assessment methodologies. Environ Sci Pollut Res 30, 43068–43095. https://doi.org/10.1007/s11356-022-22172-z

Ahmad, S., Wong, K.Y., Rajoo, S., 2019. Sustainability indicators for manufacturing sectors: A literature survey and maturity analysis from the triple-bottom line perspective. JMTM 30, 312–334. https://doi.org/10.1108/JMTM-03-2018-0091

Avison, D.E., Lau, F., Myers, M.D., Nielsen, P.A., 1999. Action research. Communications of the ACM. https://doi.org/10.1145/291469.291479

Baldassarre, B., 2025. Circular economy for resource security in the European Union (EU): Case study, research framework, and future directions. Ecological Economics 227, 108345. https://doi.org/10.1016/j.ecolecon.2024.108345

Ball, P.D., Evans, S., Levers, A., Ellison, D., 2009. Zero carbon manufacturing facility — towards integrating material, energy, and waste process flows. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 223, 1085–1096. https://doi.org/10.1243/09544054JEM1357

Billy, R.G., Monnier, L., Nybakke, E., Isaksen, M., Müller, D.B., 2022. Systemic Approaches for Emission Reduction in Industrial Plants Based on Physical Accounting: Example for an Aluminum Smelter. Environ. Sci. Technol. 56, 1973–1982. https://doi.org/10.1021/acs.est.1c05681

Blessing, L.T.M., Chakrabarti, A., 2009. DRM, a Design Research Methodology. Springer London, London. https://doi.org/10.1007/978-1-84882-587-1

Blume, S.A., 2020. Resource Efficiency in Manufacturing Value Chains, Sustainable Production, Life Cycle Engineering and Management. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-51894-3

Boggs, R.A., 1988. Implications of Formal Production Information Systems for Production Management. Int Jrnl of Op & Prod Mnagemnt 8, 22–33. https://doi.org/10.1108/eb054832

Brogan, M., 2013. Research Methods: Information, Systems and Contexts. Australian Academic & Research Libraries 44, 259–261. https://doi.org/10.1080/00048623.2013.860663

Brydon-Miller, M., Greenwood, D., Maguire, P., 2003. Why Action Research? Action Research 1, 9–28. https://doi.org/10.1177/14767503030011002

Brynjolfsson, E., McElheran, K., 2016. Data in Action: Data-Driven Decision Making in U.S. Manufacturing. SSRN Journal. https://doi.org/10.2139/ssrn.2722502

Chen, D., Schudeleit, T., Posselt, G., Thiede, S., 2013. A State-of-the-art Review and Evaluation of Tools for Factory Sustainability Assessment. Procedia CIRP 9, 85–90. https://doi.org/10.1016/j.procir.2013.06.173

Chen, D., Thiede, S., Schudeleit, T., Herrmann, C., 2014. A holistic and rapid sustainability assessment tool for manufacturing SMEs. CIRP Annals 63, 437–440. https://doi.org/10.1016/j.cirp.2014.03.113

Chen, X., Despeisse, M., Johansson, B., 2020. Environmental Sustainability of Digitalization in Manufacturing: A Review. Sustainability 12, 10298. https://doi.org/10.3390/su122410298

Ćwikła, G., 2014. Methods of Manufacturing Data Acquisition for Production Management - A Review. Advanced Materials Research 837, 618–623. https://doi.org/10.4028/www.scientific.net/AMR.837.618

Dean, P.R., Tu, Y.L., Xue, D., 2009. An information system for one-of-a-kind production. International Journal of Production Research 47, 1071–1087. https://doi.org/10.1080/00207540701543593

Despeisse, M., Ball, P.D., Evans, S., Levers, A., 2012a. Industrial ecology at factory level – a conceptual model. Journal of Cleaner Production 31, 30–39. https://doi.org/10.1016/j.jclepro.2012.02.027

Despeisse, M., Bekar, E.T., 2020. Challenges in Data Life Cycle Management for Sustainable Cyber-Physical Production Systems, in: Lalic, B., Majstorovic, V., Marjanovic, U., von Cieminski, G., Romero, D. (Eds.), Advances in Production Management Systems. Towards Smart and Digital Manufacturing. Springer International Publishing, Cham, pp. 57–65.

Despeisse, M., Chari, A., González Chávez, C.A., Monteiro, H., Machado, C.G., Johansson, B., 2022. A systematic review of empirical studies on green manufacturing: eight propositions and a research framework for digitalized sustainable manufacturing. Production & Manufacturing Research 10, 727–759. https://doi.org/10.1080/21693277.2022.2127428

Despeisse, M., Mbaye, F., Ball, P.D., Levers, A., 2012b. The emergence of sustainable manufacturing practices. Production Planning & Control 23, 354–376. https://doi.org/10.1080/09537287.2011.555425

Duflou, J.R., Sutherland, J.W., Dornfeld, D., Herrmann, C., Jeswiet, J., Kara, S., Hauschild, M., Kellens, K., 2012. Towards energy and resource efficient manufacturing: A processes and systems approach. CIRP Annals 61, 587–609. https://doi.org/10.1016/j.cirp.2012.05.002

Gangurde, S.R., 2016. Benchmark the best factory data collection system (FDC) using AHP-GRA method. Benchmarking: An International Journal 23, 359–370. https://doi.org/10.1108/BIJ-03-2014-0023

Garetti, M., Taisch, M., 2012. Sustainable manufacturing: trends and research challenges. Production Planning & Control 23, 83–104. https://doi.org/10.1080/09537287.2011.591619

Ghisellini, P., Cialani, C., Ulgiati, S., 2016. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production 114, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Gould, O., Colwill, J., 2015. A framework for material flow assessment in manufacturing systems. Journal of Industrial and Production Engineering 32, 55–66. https://doi.org/10.1080/21681015.2014.1000403

Gröger, C., Kassner, L., Hoos, E., Königsberger, J., Kiefer, C., Silcher, S., Mitschang, B., 2016. The Data-driven Factory - Leveraging Big Industrial Data for Agile, Learning and Human-centric Manufacturing:, in: Proceedings of the 18th International Conference on Enterprise Information Systems. Presented at the 18th International Conference on Enterprise Information Systems, SCITEPRESS - Science and and Technology Publications, Rome, Italy, pp. 40–52. https://doi.org/10.5220/0005831500400052

Guba, E.G., Lincoln, Y.S., 2005. Paradigmatic Controversies, Contradictions, and Emerging Confluences.

Haapala, K.R., Zhao, F., Camelio, J., Sutherland, J.W., Skerlos, S.J., Dornfeld, D.A., Jawahir, I.S., Clarens, A.F., Rickli, J.L., 2013. A Review of Engineering Research in Sustainable Manufacturing. Journal of Manufacturing Science and Engineering 135, 041013. https://doi.org/10.1115/1.4024040

Helu, M., Libes, D., Lubell, J., Lyons, K., Morris, K.C., 2016. Enabling Smart Manufacturing Technologies for Decision-Making Support, in: Volume 1B: 36th Computers and Information in Engineering Conference. Presented at the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, American Society of Mechanical Engineers, Charlotte, North Carolina, USA, p. V01BT02A035. https://doi.org/10.1115/DETC2016-59721

Holzer, D., Rauter, R., Fleiß, E., Stern, T., 2021. Mind the gap: Towards a systematic circular economy encouragement of small and medium-sized companies. Journal of Cleaner Production 298, 126696. https://doi.org/10.1016/j.jclepro.2021.126696

International Society of Automation, 2010. ANSI/ISA-95.00.01-2010 (IEC 62264-1 Mod) Enterprise-Control System Integration - Part 1: Models and Terminology.

Joung, C.B., Carrell, J., Sarkar, P., Feng, S.C., 2013. Categorization of indicators for sustainable manufacturing. Ecological Indicators 24, 148–157. https://doi.org/10.1016/j.ecolind.2012.05.030

Kibira, D., Brundage, M.P., Feng, S., Morris, K.C., 2018. Procedure for Selecting Key Performance Indicators for Sustainable Manufacturing. Journal of Manufacturing Science and Engineering 140, 011005. https://doi.org/10.1115/1.4037439

Kim, J., Sovacool, B.K., Bazilian, M., Griffiths, S., Yang, M., 2024. Energy, material, and resource efficiency for industrial decarbonization: A systematic review of sociotechnical systems, technological innovations, and policy options. Energy Research & Social Science 112, 103521. https://doi.org/10.1016/j.erss.2024.103521

Kirk, J., Miller, M., 1986. Reliability and Validity in Qualitative Research. SAGE Publications, Inc., Newbury Park, California. https://doi.org/10.4135/9781412985659

Kristensen, H.S., Mosgaard, M.A., 2020. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? Journal of Cleaner Production 243, 118531. https://doi.org/10.1016/j.jclepro.2019.118531

Kuhn, T.S. (Thomas S., 1922-1996, author, 1970. The structure of scientific revolutions. Second edition, enlarged. Chicago : University of Chicago Press, © 1970. ©1962.

Kurdve, M., Shahbazi, S., Wendin, M., Bengtsson, C., Wiktorsson, M., 2015. Waste flow mapping to improve sustainability of waste management: a case study approach. Journal of Cleaner Production 98, 304–315. https://doi.org/10.1016/j.jclepro.2014.06.076

Larek, R., Brinksmeier, E., Meyer, D., Pawletta, T., Hagendorf, O., 2011. A discrete-event simulation approach to predict power consumption in machining processes. Prod. Eng. Res. Devel. 5, 575–579. https://doi.org/10.1007/s11740-011-0333-y

Lee, S., Seon, J., Hwang, B., Kim, S., Sun, Y., Kim, J., 2024. Recent Trends and Issues of Energy Management Systems Using Machine Learning. Energies 17, 624. https://doi.org/10.3390/en17030624

Leiden, A., Herrmann, C., Thiede, S., 2021. Cyber-physical production system approach for energy and resource efficient planning and operation of plating process chains. Journal of Cleaner Production 280, 125160. https://doi.org/10.1016/j.jclepro.2020.125160

Levitin, A., Redman, T., Laboratories, T.B., 1994. QUALITY DIMENSIONS OF A CONCEPTUAL VIEW.

Machado, C.G., Winroth, M.P., Ribeiro Da Silva, E.H.D., 2020. Sustainable manufacturing in Industry 4.0: an emerging research agenda. International Journal of Production Research 58, 1462–1484. https://doi.org/10.1080/00207543.2019.1652777

Maddikunta, P.K.R., Pham, Q.-V., B, P., Deepa, N., Dev, K., Gadekallu, T.R., Ruby, R., Liyanage, M., 2022. Industry 5.0: A survey on enabling technologies and potential applications. Journal of Industrial Information Integration 26, 100257. https://doi.org/10.1016/j.jii.2021.100257

Matsui, Y., 2001. Role of information systems in manufacturing firms: an empirical analysis for machinery, electrical & electronics, and automobile plants in Japan.

Moldavska, A., Welo, T., 2015. On the Applicability of Sustainability Assessment Tools in Manufacturing. Procedia CIRP 29, 621–626. https://doi.org/10.1016/j.procir.2015.02.203

Niiniluoto, I., 1993. The aim and structure of applied research. Erkenntnis 38, 1–21. https://doi.org/10.1007/BF01129020

Pande, B., Adil, G.K., 2022. Assessment of the current state of sustainability in a manufacturing firm. IJPPM 71, 1254–1276. https://doi.org/10.1108/IJPPM-04-2020-0151

Piscicelli, L., 2023. The sustainability impact of a digital circular economy. Current Opinion in Environmental Sustainability 61, 101251. https://doi.org/10.1016/j.cosust.2022.101251

Presley, A., Liles, D.H., 1998. THE USE OF IDEF0 FOR THE DESIGN AND SPECIFICATION OF METHODOLOGIES.

Qureshi, M.I., Md. Rasli, A., Jusoh, A., Kowang, T.O., 2015. Sustainability: A new manufacturing paradigm. Jurnal Teknologi 77. https://doi.org/10.11113/jt.v77.6661

Rao, R.V. (Ed.), 2007. Introduction to Decision Making in the Manufacturing Environment, in: Decision Making in the Manufacturing Environment: Using Graph Theory and Fuzzy Multiple Attribute Decision Making Methods. Springer London, London, pp. 3–6. https://doi.org/10.1007/978-1-84628-819-7_1

Robinson, S., Bhatia, V., 1995. Secrets of Auccessful Simulation Projects.

Roger G., S., Kimberly A., B., Mikko A., J., 2002. A resource-based view of manufacturing strategy and the relationship to manufacturing performance. Strategic Management Journal 105–117. https://doi.org/10.1002/smj.213

Rosen, M.A., Kishawy, H.A., 2012. Sustainable Manufacturing and Design: Concepts, Practices and Needs. Sustainability 4, 154–174. https://doi.org/10.3390/su4020154

Säfsten, K., Gustavsson, M., 2020. Research methodology : For engineers and other problem-solvers. Institutionen för beteendevetenskap och lärande, Linköpings universitet.

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., Kendall, A., 2019. A taxonomy of circular economy indicators. Journal of Cleaner Production 207, 542–559. https://doi.org/10.1016/j.jclepro.2018.10.014

Saliya, C.A., 2023. Research Philosophy: Paradigms, World Views, Perspectives, and Theories, in: Saliya, C.A. (Ed.), Advances in Knowledge Acquisition, Transfer, and Management. IGI Global, pp. 35–51. https://doi.org/10.4018/978-1-6684-6859-3.ch004

Sartal, A., Bellas, R., Mejías, A.M., García-Collado, A., 2020. The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. Advances in Mechanical Engineering 12, 1687814020925232. https://doi.org/10.1177/1687814020925232

Schmidt, M., Nakajima, M., 2013. Material Flow Cost Accounting as an Approach to Improve Resource Efficiency in Manufacturing Companies. Resources 2, 358–369. https://doi.org/10.3390/resources2030358

Shen, J., Cooley, V.E., 2008. Critical issues in using data for decision-making. International Journal of Leadership in Education 11, 319–329. https://doi.org/10.1080/13603120701721839

Shizuo Itoh, 2002. Plant Information System. Japan Tappi Journal 56, 1122–1125.

Smith, L., Ball, P., 2012. Steps towards sustainable manufacturing through modelling material, energy and waste flows. International Journal of Production Economics 140, 227–238. https://doi.org/10.1016/j.ijpe.2012.01.036

Snyder, H., 2019. Literature review as a research methodology: An overview and guidelines. Journal of Business Research 104, 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039

Swedish Research Council, 2017. Good research practice.

The European parliament and the council of the European Union, 2020. Official Journal of the European Union.

Thiede, S., Bogdanski, G., Herrmann, C., 2012. A Systematic Method for Increasing the Energy and Resource Efficiency in Manufacturing Companies. Procedia CIRP 2, 28–33. https://doi.org/10.1016/j.procir.2012.05.034

Thiede, S., Li, W., Kara, S., Herrmann, C., 2016. Integrated Analysis of Energy, Material and Time Flows in Manufacturing Systems. Procedia CIRP 48, 200–205. https://doi.org/10.1016/j.procir.2016.03.248

United Nations Department of Economic and Social Affairs, 2023. The Sustainable Development Goals Report 2023: Special Edition, The Sustainable Development Goals Report. United Nations. https://doi.org/10.18356/9789210024914

Venkata Rao, R., Patel, B.K., 2010. Decision making in the manufacturing environment using an improved PROMETHEE method. International Journal of Production Research 48, 4665–4682. https://doi.org/10.1080/00207540903049415

Vikhorev, K., Greenough, R., Brown, N., 2013. An advanced energy management framework to promote energy awareness. Journal of Cleaner Production 43, 103–112. https://doi.org/10.1016/j.jclepro.2012.12.012

Waltersmann, L., Kiemel, S., Stuhlsatz, J., Sauer, A., Miehe, R., 2021. Artificial Intelligence Applications for Increasing Resource Efficiency in Manufacturing Companies—A Comprehensive Review. Sustainability 13, 6689. https://doi.org/10.3390/su13126689

Weterings, R., Bastein, T., Tukker, A., Rademaker, M., de Ridder, M., 2013. Resources for our Future. Amsterdam University Press. https://doi.org/10.2307/j.ctt6wp6zb

Yin, R.K., 2009. Case Study Research: Design and Methods, Applied Social Research Methods. SAGE Publications.

Zhang, C., Chen, W.-Q., Ruth, M., 2018. Measuring material efficiency: A review of the historical evolution of indicators, methodologies and findings. Resources, Conservation and Recycling 132, 79–92. https://doi.org/10.1016/j.resconrec.2018.01.028

Zheng, J., Chen, A., Yao, J., Ren, Y., Zheng, W., Lin, F., Shi, J., Guan, A., Wang, W., 2022. Combination method of multiple molding technologies for reducing energy and carbon emission in the foundry industry. Sustainable Materials and Technologies 34, e00522. https://doi.org/10.1016/j.susmat.2022.e00522

APPENDIX
The Method Library

Method No.	Methods	Type of study					Applied level			Sustainability dimensions			Improvement field			Research area		Base approach								Focused resource flow					Connection with production information systems							Connection with standard			
		MTD	ID	N/A	SCS	MCS	MP	LCM	FAC	ENV	ECO	SOC	MSD	OM	TC	PPM	MT	LCX	SIM	LEAN	MFA	VSM	EME	EXE	IM	MAT	ENE	WAT	WAS	SER	ERP	MES	BOM	SCADA	MAN	SD	UDCM	GS	RS	OS	US
M01	A carbon accounting method based on multilevel material flow analysis (Billy et al., 2022)	X			X				X	X	X		X	X		X					X					X			X						X	X	X		X		
M02	Sustainability evaluation method and index (Zhang et al., 2021)	X	X		X		X			X				X			X						X			X	X	X	X	X					X	X	X				X
M03	Resource efficient process planning method (Denkena et al., 2022)	X			X		X				X			X			X		X							X	X		X								X				X
M04	Combination method of multiple molding technologies - Foundry (Zheng et al., 2022)	X			X		X			X					X		X		X							X	X										X				X
M05	A cyber physical production systems approach for process planning (Leiden et al., 2021)	X			X		X	X		X	X			X		X		X	X							X	X				X	X			X						X
M06	Industrial Metabolism Analysis (Wenjie, 2021)			X	X			X		X			X	X		X									X	X	X	X	X								X			X	
M07	Mathematical modelling for energy efficiency method (Goffin et al., 2021)	X			X			X			X			X			X		X								X								X						X
M08	Emergy-Based Conversion Efficiency Modelling (Sun et al., 2019)	X			X		X	X			X			X			X						X			X	X		X	X			X		X		X				X

Method No.	Methods	Type of study					Applied level			Sustainability dimensions			Improvement field			Research area		Base approach								Focused resource flow					Connection with production information systems							Connection with standard			
		MTD	ID	N/A	SCS	MCS	MP	LCM	FAC	ENV	ECO	SOC	MSD	OM	TC	PPM	MT	LCX	SIM	LEAN	MFA	VSM	EME	EXE	IM	MAT	ENE	WAT	WAS	SER	ERP	MES	BOM	SCADA	MAN	SD	UDCM	GS	RS	OS	US
M09	Resource value mapping (Papetti et al., 2019)	X			X		X	X	X		X			X		X						X				X	X	X	X						X		X				X
M10	Emergy-based evaluation method (Liu et al., 2018)	X			X		X	X	X	X	X		X	X		X							X			X	X		X	X					X		X				X
M11	Green performance mapping tool (Kurdve & Bellgran, 2021)	X				X		X		X		X	X	X		X				X						X	X										X				X
M12	Waste flow mapping (Kurdve et al., 2015)	X			X			X	X		X		X	X		X						X				X			X						X	X	X	X			
M13	Simulation based energy-resource measurement and improvement (Katchasuwanmanee et al., 2016)	X			X		X	X	X		X			X		X			X								X										X				X
M14	An exergy-based approach to resource accounting (Khattak et al., 2016)	X			X			X	X		X			X		X								X			X								X	X	X				X
M15	A value system framework developed for industrial water management (Walsh et al., 2016)	X			X				X		X			X		X					X							X									X	X			
M16	Energy efficiency benchmarking (Spiering et al., 2015)	X			X		X				X			X			X		X								X							X							

Method No.	Methods	Type of study					Applied level			Sustainability dimensions			Improvement field			Research area		Base approach								Focused resource flow					Connection with production information systems							Connection with standard			
		MTD	ID	N/A	SCS	MCS	MP	LCM	FAC	ENV	ECO	SOC	MSD	OM	TC	PPM	MT	LCX	SIM	LEAN	MFA	VSM	EME	EXE	IM	MAT	ENE	WAT	WAS	SER	ERP	MES	BOM	SCADA	MAN	SD	UDCM	GS	RS	OS	US
M17	Material flow cost accounting (Wang et al., 2017)			X	X			X	X		X			X		X					X					X	X		X								X	X			
M18	Energy Consumption Analysis for machine tools online fault-monitoring (Emec et al., 2016)	X			X		X				X			X			X		X								X										X			X	
M19	Discrete-event simulation approach for energy consumption prediction (Larek et al., 2011)	X			X		X				X			X			X		X								X										X				X
M20	Discrete event simulation for energy efficiency assessment (De Oliveria Gomes et al., 2013)	X			X			X			X		X	X		X			X								X										X				X
M21	Cross-functional factory modelling (Despeisse et al., 2013)	X			X				X		X		X	X		X			X							X	X	X	X								X				X
M22	Environmental impact modelling (Kellens et al., 2012)	X			X		X			X	X			X		X		X								X	X		X								X	X			
M23	Exergy analysis for energy efficiency (Taheri et al., 2014)			X	X		X				X			X		X								X		X	X										X				X
M24	Impact assessment of embodied water in manufacturing systems (Mousavi et al., 2015)	X			X			X	X	X	X			X		X		X	X									X							X	X	X				X

Method No.	Methods	Type of study					Applied level			Sustainability dimensions			Improvement field			Research area		Base approach								Focused resource flow					Connection with production information systems							Connection with standard			
		MTD	ID	N/A	SCS	MCS	MP	LCM	FAC	ENV	ECO	SOC	MSD	OM	TC	PPM	MT	LCX	SIM	LEAN	MFA	VSM	EME	EXE	IM	MAT	ENE	WAT	WAS	SER	ERP	MES	BOM	SCADA	MAN	SD	UDCM	GS	RS	OS	US
M25	Eco-efficiency assessment (Li et al., 2012)	X			X		X			X				X			X	X	X							X	X		X							X	X				X
M26	Qualitative MEW process flow maps (Smith & Ball, 2012)	X			X				X		X			X		X					X					X	X		X						X		X				X
M27	An advanced energy management framework (Vikhorev et al., 2013)	X			X				X		X			X		X			X								X					X								X	
M28	Ecology model at factory level (Despeisse et al., 2012)	X			X				X	X	X		X	X		X			X		X					X	X	X	X								X	X			
M29	A generic material, energy, and waste flow model (Ball et al., 2009)	X			X				X	X	X			X		X			X		X					X	X		X								X	X			
M30	A methodology to assess cyber physical production systems' potential in production from environmental point of view (Thiede, 2018)	X			X		X	X	X	X	X			X		X		X								X	X		X								X	X			
M31	Energy portfolio (Thiede et al., 2012)	X			X		X	X	X		X			X		X			X								X										X				X
M32	Optimisation approaches for machining time, machining deviation and machining energy consumption reduction (Hu et al., 2018)	X			X		X				X			X			X		X								X			X							X				X

Method No.	Methods	Type of study					Applied level			Sustainability dimensions			Improvement field			Research area		Base approach								Focused resource flow					Connection with production information systems							Connection with standard			
		MTD	ID	N/A	SCS	MCS	MP	LCM	FAC	ENV	ECO	SOC	MSD	OM	TC	PPM	MT	LCX	SIM	LEAN	MFA	VSM	EME	EXE	IM	MAT	ENE	WAT	WAS	SER	ERP	MES	BOM	SCADA	MAN	SD	UDCM	GS	RS	OS	US
M33	Energy supply operation optimization approaches in manufacturing plant (Feng et al., 2016)	X			X				X		X			X		X			X								X										X				X
M34	Energy value-stream mapping method (Müller et al., 2014)	X			X				X		X		X	X		X						X					X										X				X
M35	A framework for material flow assessment in manufacturing systems (Gould & Colwill, 2015)	X			X		X	X	X		X			X		X					X					X											X				X
M36	A method integrating analysis of energy, material and time (Thiede et al., 2016)	X			X				X	X	X			X		X		X			X	X				X	X										X	X			X
M37	A method to analyse electric energy consumption (Rodrigues et al., 2018)	X				X	X				X			X		X			X								X									X	X				X
M38	Overall energy demand approach (Denkena et al., 2020)	X			X			X	X		X			X		X			X								X										X				X

REFERENCES

Ball, P. D., Evans, S., Levers, A., & Ellison, D. (2009). Zero carbon manufacturing facility—Towards integrating material, energy, and waste process flows. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *223*(9), 1085–1096. https://doi.org/10.1243/09544054JEM1357

Billy, R. G., Monnier, L., Nybakke, E., Isaksen, M., & Müller, D. B. (2022). Systemic Approaches for Emission Reduction in Industrial Plants Based on Physical Accounting: Example for an Aluminum Smelter. *Environmental Science & Technology*, *56*(3), 1973–1982. https://doi.org/10.1021/acs.est.1c05681

De Oliveria Gomes, V. E., De Oliveira Gomes, J., & Grote, K.-H. (2013). Discrete Event Simulation Inserted into Kaizen Event to Assess Energy Efficiency. In A. Y. C. Nee, B. Song, & S.-K. Ong (Eds.), *Re-engineering Manufacturing for Sustainability* (pp. 499–503). Springer Singapore. https://doi.org/10.1007/978-981-4451-48-2_81

Denkena, B., Dittrich, M.-A., & Onken, L. (2020). Environmental evaluation of process chains. *Procedia CIRP*, *88*, 265–269. https://doi.org/10.1016/j.procir.2020.05.046

Denkena, B., Wichmann, M., Kettelmann, S., Matthies, J., & Reuter, L. (2022). Ecological Planning of Manufacturing Process Chains. *Sustainability*, *14*(5), 2681. https://doi.org/10.3390/su14052681

Despeisse, M., Ball, P. D., Evans, S., & Levers, A. (2012). Industrial ecology at factory level – a conceptual model. *Journal of Cleaner Production*, *31*, 30–39. https://doi.org/10.1016/j.jclepro.2012.02.027

Despeisse, M., Oates, M. R., & Ball, P. D. (2013). Sustainable manufacturing tactics and cross-functional factory modelling. *Journal of Cleaner Production*, *42*, 31–41. https://doi.org/10.1016/j.jclepro.2012.11.008

Emec, S., Krüger, J., & Seliger, G. (2016). Online Fault-monitoring in Machine Tools Based on Energy Consumption Analysis and Non-invasive Data Acquisition for Improved Resource-efficiency. *Procedia CIRP*, *40*, 236–243. https://doi.org/10.1016/j.procir.2016.01.111

Feng, L., Mears, L., Beaufort, C., & Schulte, J. (2016). Energy, economy, and environment analysis and optimization on manufacturing plant energy supply system. *Energy Conversion and Management*, *117*, 454–465. https://doi.org/10.1016/j.enconman.2016.03.031

Goffin, N., Jones, L. C. R., Tyrer, J., Ouyang, J., Mativenga, P., & Woolley, E. (2021). Mathematical modelling for energy efficiency improvement in laser welding. *Journal of Cleaner Production*, *322*, 129012. https://doi.org/10.1016/j.jclepro.2021.129012

Gould, O., & Colwill, J. (2015). A framework for material flow assessment in manufacturing systems. *Journal of Industrial and Production Engineering*, *32*(1), 55–66. https://doi.org/10.1080/21681015.2014.1000403

Hu, L., Tang, R., Liu, Y., Cao, Y., & Tiwari, A. (2018). Optimising the machining time, deviation and energy consumption through a multi-objective feature sequencing approach. *Energy Conversion and Management*, *160*, 126–140. https://doi.org/10.1016/j.enconman.2018.01.005

Katchasuwanmanee, K., Cheng, K., & Bateman, R. (2016). Simulation based energy-resource efficient manufacturing integrated with in-process virtual management. *Chinese Journal of Mechanical Engineering*, *29*(6), 1083–1089. https://doi.org/10.3901/CJME.2016.0714.080

Kellens, K., Renaldi, Dewulf, W., & Duflou, J. R. (2012). Environmental Impact Modeling of Discrete Part Manufacturing Processes. In D. A. Dornfeld & B. S. Linke (Eds.), *Leveraging Technology for a Sustainable World* (pp. 557–562). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-29069-5_94

Khattak, S. H., Greenough, R., Korolija, I., & Brown, N. (2016). An exergy based approach to resource accounting for factories. *Journal of Cleaner Production*, *121*, 99–108. https://doi.org/10.1016/j.jclepro.2015.12.029

Kurdve, M., & Bellgran, M. (2021). Green lean operationalisation of the circular economy concept on production shop floor level. *Journal of Cleaner Production*, *278*, 123223. https://doi.org/10.1016/j.jclepro.2020.123223

Kurdve, M., Shahbazi, S., Wendin, M., Bengtsson, C., & Wiktorsson, M. (2015). Waste flow mapping to improve sustainability of waste management: A case study approach. *Journal of Cleaner Production*, *98*, 304–315. https://doi.org/10.1016/j.jclepro.2014.06.076

Larek, R., Brinksmeier, E., Meyer, D., Pawletta, T., & Hagendorf, O. (2011). A discrete-event simulation approach to predict power consumption in machining processes. *Production Engineering*, *5*(5), 575–579. https://doi.org/10.1007/s11740-011-0333-y

Leiden, A., Herrmann, C., & Thiede, S. (2021). Cyber-physical production system approach for energy and resource efficient planning and operation of plating process chains. *Journal of Cleaner Production*, *280*, 125160. https://doi.org/10.1016/j.jclepro.2020.125160

Li, W., Winter, M., Kara, S., & Herrmann, C. (2012). Eco-efficiency of manufacturing processes: A grinding case. *CIRP Annals*, *61*(1), 59–62. https://doi.org/10.1016/j.cirp.2012.03.029

Liu, C., Cai, W., Jia, S., Zhang, M., Guo, H., Hu, L., & Jiang, Z. (2018). Emergy-based evaluation and improvement for sustainable manufacturing systems considering resource efficiency and environment performance. *Energy Conversion and Management*, *177*, 176–189. https://doi.org/10.1016/j.enconman.2018.09.039

Mousavi, S., Kara, S., & Kornfeld, B. (2015). Assessing the Impact of Embodied Water in Manufacturing Systems. *Procedia CIRP*, *29*, 80–85. https://doi.org/10.1016/j.procir.2015.01.001

Müller, E., Stock, T., & Schillig, R. (2014). A method to generate energy value-streams in production and logistics in respect of time- and energy-consumption. *Production Engineering*, *8*(1–2), 243–251. https://doi.org/10.1007/s11740-013-0516-9

Papetti, A., Menghi, R., Di Domizio, G., Germani, M., & Marconi, M. (2019). Resources value mapping: A method to assess the resource efficiency of manufacturing systems. *Applied Energy*, *249*, 326–342. https://doi.org/10.1016/j.apenergy.2019.04.158

Rodrigues, G. S., Espíndola Ferreira, J. C., & Rocha, C. R. (2018). A novel method for analysis and optimization of electric energy consumption in manufacturing processes. *Procedia Manufacturing*, *17*, 1073–1081. https://doi.org/10.1016/j.promfg.2018.10.078

Smith, L., & Ball, P. (2012). Steps towards sustainable manufacturing through modelling material, energy and waste flows. *International Journal of Production Economics*, *140*(1), 227–238. https://doi.org/10.1016/j.ijpe.2012.01.036

Spiering, T., Kohlitz, S., Sundmaeker, H., & Herrmann, C. (2015). Energy efficiency benchmarking for injection moulding processes. *Robotics and Computer-Integrated Manufacturing*, *36*, 45–59. https://doi.org/10.1016/j.rcim.2014.12.010

Sun, H., Liu, C., Chen, J., Gao, M., & Shen, X. (2019). A Novel Method of Sustainability Evaluation in Machining Processes. *Processes*, *7*(5), 275. https://doi.org/10.3390/pr7050275

Taheri, K., Gadow, R., & Killinger, A. (2014). Exergy Analysis as a Developed Concept of Energy Efficiency Optimized Processes: The Case of Thermal Spray Processes. *Procedia CIRP*, *17*, 511–516. https://doi.org/10.1016/j.procir.2014.01.060

Thiede, S. (2018). Environmental Sustainability of Cyber Physical Production Systems. *Procedia CIRP*, *69*, 644–649. https://doi.org/10.1016/j.procir.2017.11.124

Thiede, S., Bogdanski, G., & Herrmann, C. (2012). A Systematic Method for Increasing the Energy and Resource Efficiency in Manufacturing Companies. *Procedia CIRP*, *2*, 28–33. https://doi.org/10.1016/j.procir.2012.05.034

Thiede, S., Li, W., Kara, S., & Herrmann, C. (2016). Integrated Analysis of Energy, Material and Time Flows in Manufacturing Systems. *Procedia CIRP*, *48*, 200–205. https://doi.org/10.1016/j.procir.2016.03.248

Vikhorev, K., Greenough, R., & Brown, N. (2013). An advanced energy management framework to promote energy awareness. *Journal of Cleaner Production*, *43*, 103–112. https://doi.org/10.1016/j.jclepro.2012.12.012

Walsh, B. P., Cusack, D. O., & O'Sullivan, D. T. J. (2016). An industrial water management value system framework development. *Sustainable Production and Consumption*, *5*, 82–93. https://doi.org/10.1016/j.spc.2015.11.004

Wang, Y.-X., Kuo, C.-H., Song, R., Hu, A., & Zhang, S.-S. (2017). Potentials for Improvement of Resource Efficiency in Printed Circuit Board Manufacturing: A Case Study Based on Material Flow Cost Accounting. *Sustainability*, *9*(6), 907. https://doi.org/10.3390/su9060907

Wenjie, L. (2021). Industrial Metabolism Analysis and Green Optimization of a Painting Production Line. *E3S Web of Conferences*, *248*, 02057. https://doi.org/10.1051/e3sconf/202124802057

Zhang, C., Wang, C., Liu, C., Zhu, G., Li, W., & Gao, M. (2021). Data-driven sustainability evaluation of machining system: A case study. *The International Journal of Advanced Manufacturing Technology*, *117*(3–4), 775–784. https://doi.org/10.1007/s00170-021-07779-9

Zheng, J., Chen, A., Yao, J., Ren, Y., Zheng, W., Lin, F., Shi, J., Guan, A., & Wang, W. (2022). Combination method of multiple molding technologies for reducing energy and carbon emission in the foundry industry. *Sustainable Materials and Technologies*, *34*, e00522. https://doi.org/10.1016/j.susmat.2022.e00522