Review of resource efficiency assessments in manufacturing: An integration model for production information systems

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Review of resource efficiency assessments in manufacturing: An integration model for production information systems

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ABSTRACT

Resource efficiency is core for the competitiveness of manufacturing companies in their transition towards responsible consumption and production. But academia and industry still lack thorough knowledge about effective resource efficiency assessment methods and opportunities offered by industrial digitalization to implement these methods. This study systematically reviewed and categorized resource efficiency assessment methods in the manufacturing sector. A method library with 43 selected assessment methods was created based on a criterion for effective implementation. Subsequent analysis shows the wealth and diversity of existing assessment methods. However, the results also indicated that the methods are rarely connected to production information systems and standards, therefore hindering their effectiveness in industrial use cases. This paper proposes an integration model to help industrial users in selecting relevant and useable resource efficiency assessments based on data availability. This model aims to overcome the barriers to implementation identified in this systematic review. Future research will focus on consolidating the integration model through industry collaboration while also addressing emerging resource efficiency methods and standards.

1. Introduction

With the increasing emphasis on sustainable development, many manufacturers are seeking opportunities to improve their sustainability performance while simultaneously upholding exceptional quality and productivity. Resource efficiency—which illustrates the economic output generated per unit of natural resources—has come to be a determinant of competitiveness and sustainable growth in most industries (Giljum and Polzin, 2009). On the United Nations 2030 Agenda, the manufacturing industry will potentially contribute to Sustainable Development Goal (SDG) 12—responsible consumption and production—by taking actions towards better resource efficiency in production. According to the Sustainable Development Goals Report 2023, the material footprint per capita in high-income countries is still ten times that of low-income countries, which urged the European Union (EU) to make resource efficiency a top policy priority (Wilts and O'Brien, 2019). In 2020, the European Union introduced the EU taxonomy, creating an EU-wide classification system for environmentally sustainable economic activities (Lucarelli et al., 2020). Under the new regulation that sets out six climate and environmental objectives (Radley-Gardner et al., 2020), EU manufacturing companies are more motivated to make decisions aligned with environmental sustainability. In addition to regulatory pressures, many large manufacturing companies have started reporting on resource efficiency performance at the enterprise level, mainly in response to external stakeholders in the value chain, including end customers. But rather than focusing solely on reporting, the competitive and globalized markets demand that time and other organizational resources be given priority in order to identify improvement (Aqlan, 2018).

A deeper understanding of resource efficiency performance at the micro-levels (Duflou et al., 2012) of manufacturing systems (factory, line, process, etc.) has been identified as an essential capability (Kristensen and Mosgaard, 2020) in leading the transition towards a circular economy and sustainable resource consumption (Ghisellini et al., 2016). There has been a lot of study done on the development of resource efficiency assessment; however, those assessment methods do not always satisfy the demands of industry. In a review of factory sustainability assessment methods, four key characteristics were identified to be beneficial: generic applicability, rapid assessment, application at the factory level, and a holistic view of sustainability (D. Chen et al., 2013). But her study also showed that none of the 12 examined methods met these practical requirements. The needs of different types of

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organizations also vary. Fast improvement is especially important for small and medium-sized enterprises (SMEs) because they have limited resources in terms of personnel, time, and capital compared with large companies (Thiede et al., 2013; Trianni et al., 2013). However, limited understanding of resource efficiency assessment methods and their effective implementation in manufacturing can be provided due to the focus on generic sustainability, the small sample of methods, and the specific user group, like SMEs.

Industrial digitalization offers new opportunities for resource efficiency assessment. Digital technologies are contributing positively to environmental sustainability in manufacturing by increasing resource and information efficiency (X. Chen et al., 2020). But a review of empirical studies also pointed out that industrial digitalization should better support environmental impact analysis by addressing issues with data availability, transparency, access, and analysis (Despeisse et al., 2022). Production information systems, which link the physical production and data layer in manufacturing companies (Li et al., 2016), are increasingly reliant on digital technology to support thorough data inventory management. Hence, to guarantee data supply for resource efficiency improvement, the first step is to integrate assessment methods into production information systems.

Motivated by all these factors, researchers and industrial participants both recognized the need for resource efficiency assessments with improved input data. Therefore, this review aims to fill the knowledge gap in understanding effective resource efficiency assessment methods and to pinpoint how these methods can contribute to environmentally sustainable manufacturing by integrating production information systems.

The research question (RQ) guiding the analysis was ***"How can production information systems*** support ***resource efficiency assessments in manufacturing companies?"*** Accordingly, this study was guided by three objectives:

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

The article is structured in six sections. This section presents the research background, the research question, and three objectives. Section 2 describes the research methodology that guides the systematic review of the literature and the selection of effective resource efficiency assessments to build the method library (the first objective). Section 3 presents a bibliometric analysis of literature search and results from literature coding. The results are then discussed in Section 4, which also includes the enabling and hindering factors in the implementation of resource efficiency assessment (the second objective). The proposed integration model is introduced in Section 5 (the third objective). Finally, Section 6 concludes with a summary of the study and suggests directions for further work.

2. Methodology

A systematic literature review was performed (Snyder, 2019). The review of publications containing resource efficiency assessment methods and industrial implementation was performed in four stages: search, screening, coding, and analysis. Accordingly, Section 2.1 outlines the initial search string, screening exclusion and inclusion criteria, and the complementary snowballing search (Wohlin et al., 2022). Section 2.2 introduces the labels used for coding and designing literature analyses. In Section 2.3, the study's scope and limitations are discussed.

Fig. 1 provides an overview of this thorough literature review. In the initial search, 555 publications were discovered. After a two-step selection process, 36 publications were chosen to serve as core papers for a backwards snowballing, and 17 were retained. The resulting sample of 53 papers was further coded for detailed analysis. Finally, the final sample was converted into a library of 43 methods for practical usage, with duplicates deleted (where many articles utilized the same methods).

2.1. Initial search, screening, and snowballing

The literature search aimed at finding scientific publications discussing resource efficiency assessment in a manufacturing setting, with a focus on methods, tools, strategies, indicator development, and use cases. For this purpose, "resource efficiency" was selected as the umbrella keyword, combining with resource flow keywords "material," "energy," and "waste." These alternative resource flow keywords are very commonly emphasized in studies in regard to material efficiency

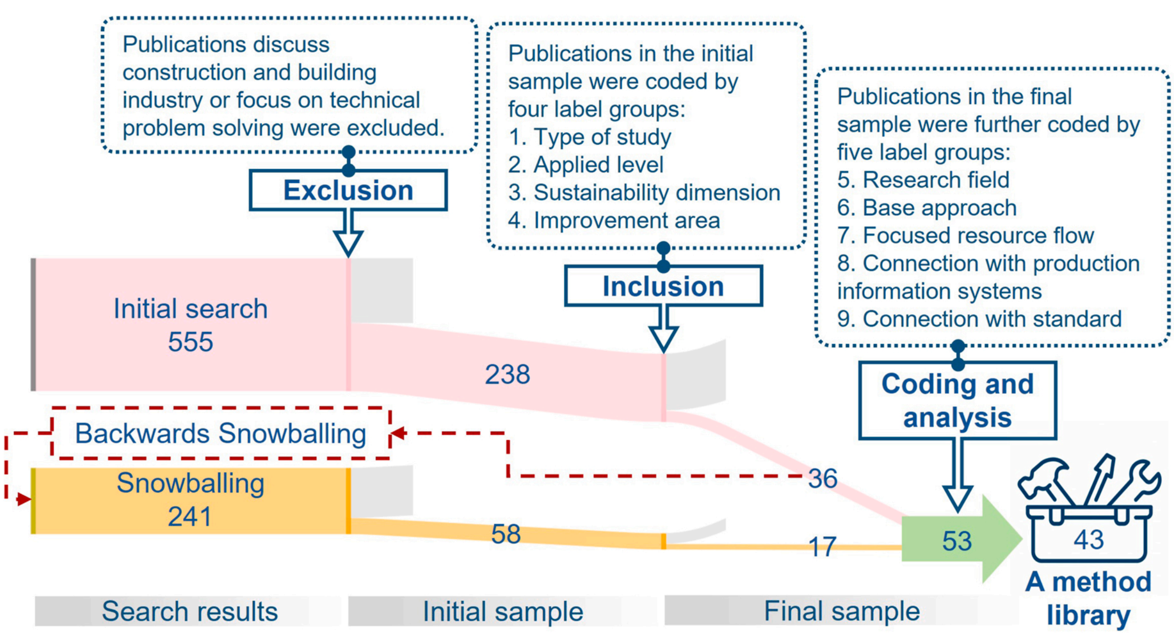

Fig. 1. An overview of the review process.

(Schmidt and Nakajima, 2013; Zhang et al., 2018), energy saving (Abdelaziz et al., 2011), and waste flow mapping (Kurdve et al., 2015) in manufacturing factories. Besides the "method" for resource efficiency assessments, alternative keywords "indicator," "tool," "approach," and "measure" were also included in the string to cover more studies regarding assessing resource efficiency performance. Finally, the research aimed at studies in the manufacturing sector with improvement intentions regarding sustainability, green manufacturing, and environmental impact.

Therefore, the string "(("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*))" was applied to the title, abstract, or keywords in the initial search within Scopus. All English-written articles, conference papers, and reviews published in journals and conferences from 1997 to 2025 were included in the search results.

To further identify relevant publications, the exclusion was developed based on the subject area and research objectives. Publications were excluded if they were not relevant to the purpose of the study, thereby narrowing down to studies only focusing on resource efficiency assessment method development and use cases in the manufacturing sector. Papers that discussed the construction sector or focused on technical problem solutions (such as tooling path optimization) were excluded.

Afterwards, effective resource efficiency assessment methods were identified from the initial sample by applying the inclusion criterion, in response to the first objective. Table 1 shows four label groups developed from the three main characteristics of an effective resource efficiency method: applicability, scope, and impacts.

The first label group was formed to investigate the applicability of resource efficiency assessment methods. Papers were labelled by their purpose first, depending on what they developed. Having at least a single case study was the requirement to demonstrate the applicability of methods or indicators developed in publications. As a result, studies that discussed new methodologies or indicators but provided no examples of application were eliminated since they did not serve the goal of this systematic review.

The second label group aimed to find effective resource efficiency assessment methods that fit the scope of the study. Five levels of scope in manufacturing were distinguished, from individual device to value chain, in a systematic energy and resource-saving approach study (Duflou et al., 2012). In the context of this study, a resource efficiency assessment method needs to be feasible in factories; therefore, three desired applied levels were machine, cell, and factory.

The third and fourth label groups verified the impacts of methods or indicators developed in literature. Effective resource efficiency assessment methods should support manufacturing companies' sustainability performance from the sustainability triple bottom line: economy, environment, and society (Elkington, 1994; Purvis et al., 2019). This study also addressed the quantitative assessment of sustainability impacts. Papers that only described potential impact were not included. Furthermore, effective resource efficiency methods can improve sustainability performance from different lenses. The most common improvement area in manufacturing is process improvement, for example, continuous improvements by optimizing processing parameters. Improvements from the manufacturing strategy perspective can be strategic changes regarding internal and external stakeholders, such as raw material suppliers and production planning. The other improvement area is technology change, where technical solutions can also lead to a leap in sustainability performance.

After applying exclusion and inclusion, a total of 36 publications were kept. To increase the coverage of resource efficiency assessment methods and to capture additional papers, the backwards snowballing method was used to enrich the sample with highly relevant papers that may have been missed in the initial search (Wohlin et al., 2022). All open-access publications cited by the 36 papers were extracted. The same exclusion and inclusion were applied to 241 papers, and 17 papers went into the final sample.

Table 1
Label groups 1–4 for effective resource efficiency assessment methods identification (inclusion).

Label group	Abbreviation	Definition
1. Type of study (applicability)		
Method development	MED	New resource efficiency assessment methods developed
Indicator development	IND	New resource efficiency indicator developed
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)		
Process improvement	IMP	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

2.2. Coding and analysis

On top of the four label groups from Table 1, five additional label groups were developed for coding and in-depth analysis of the final sample: research area, base approach, focused resource flow, connection with standards, and connection with production information systems (shown in Table 2). In total, each publication from the final sample was coded in nine label groups.

The coded publications directly contributed to the study's first objective, which identified effective resource efficiency assessment methods. Based on the coding, an in-depth analysis was performed for publications in label groups "type of study" and "applied level." Cross analysis was also used to dig deeper into publications' distribution between label groups, with focuses on "base approaches," "connection with production information systems," and "connection with standards." This hybrid aimed to pin potential correlations between different attributes of methods found in literature and, therefore, also to uncover enabling and hindering factors in assessment method development and implementation.

2.3. Scope definition and limitations

A review study must have a clear scope and make cautious decisions to ensure feasibility and credibility. The review was scoped based on two factors: a literature search and screening.

To perform a study in the field of sustainability performance, this review started with a broad initial search through carefully selected keywords to cover more relevant publications. The backwards snowballing also served this purpose to enrich the final sample and double-check if any core papers on the topic were missing. In the snowballing, only open-access scientific publications were kept because the screening required full papers. Publications with limited information would not contribute positively to the study's validity or the purpose of performing a snowballing search.

This review followed strict inclusion criteria, excluding papers on resource efficiency assessment methods that lacked case studies. While theory-based methods may have potential, case studies that show practical use in production are aligned with the beneficial characteristics for factory assessment tools: generic applicability and rapid assessment (D. Chen et al., 2013). However, this may have excluded useful

Table 2
Additional labels for groups 5–9 for coding.

Label groups	Abbreviation	Definition
5. Research field		
Production management	PM	Generic production and manufacturing systems management
Manufacturing processes	MP	Specific manufacturing processes such as machining
6. Base approach		
Life cycle assessment	LCA	Assessment of environmental impact throughout a system's life cycle
Simulation or modelling	SIM	Modelling production or manufacturing processes to analyse system performance, test scenarios, and optimize operations without disrupting real-world workflows
Lean management	LEAN	A management philosophy that aims to maximize value and minimize waste by improving efficiency and eliminating non-value-adding activities in production systems
Material flow analysis	MFA	A method that quantifies the flows and stocks of materials within a defined system to understand resource use, losses, and opportunities for efficiency improvement
Value stream mapping	VSM	A visual tool used in LEAN to map the flow of materials and information through a process, identifying bottlenecks and waste
Emergy	EME	Emergy measures the total energy used (direct and indirect) to produce a product or service, expressed in units of a single energy type, usually solar energy equivalents
Exergy	EXE	Exergy assesses the useable energy within a system, highlighting inefficiencies by quantifying energy quality losses during transformations
Industrial metabolism	INDM	Industrial metabolism analyses material and energy flows within industrial systems
7. Focused resource flow		
Material	MAT	Material flow in manufacturing systems, such raw material consumption
Energy	ENE	Energy flow in manufacturing systems, such as 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, labour 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 materials	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 standards		
Global standard	GS	Globally recognized standards
Regional standard	RS	Standards used in specific regions, such as the EU standard
Other standards	OS	Other hierarchy of standards
Unspecified standard	US	/

theory-driven methods, so reducing the final sample size. Future iterations can address this by introducing and testing more methods, as well as using user feedback to guide further development.

3. Results

The Results starts with a bibliometric analysis of both the initial and the final samples (Donthu et al., 2021). The next sections present findings of in-depth analysis and cross analyses on 53 publications from the final sample. The method library is presented in Appendix A.

3.1. Bibliometric analysis

Fig. 2 shows the number of publications each year from 1995 to 2025 for both the initial and final samples. In the initial sample, publications on the topic "resource efficiency assessment in manufacturing" began to rise in 2010 and have maintained a high volume of articles each year. By the end of May in 2025, 15 publications had been identified in the initial sample, nearly matching the volume of 2018 and 2020. The trend in the initial sample reveals that resource efficiency assessment in manufacturing is a popular issue. However, the number of publications in the final sample, which indicates how many of these publications provided effective resource efficiency assessment methods, was found to be low throughout the whole period.

The keyword *"resource efficiency"* was not the default choice in reviewed publications. Fig. 3 illustrates the top keywords used by publications from both the initial and final samples.

Among the 296 publications in the initial sample, 105 used the exact keyword "resource efficiency". Studies on energy may use different

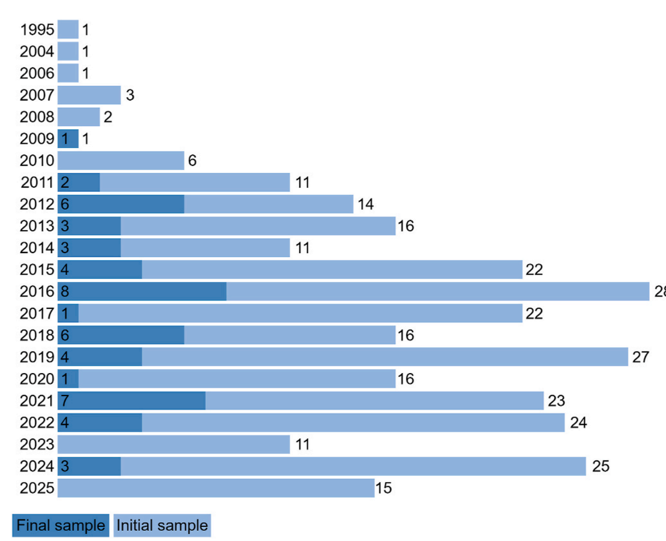

Fig. 2. Number of publications per year in the initial sample and final sample.

keywords, such as "*energy efficiency" or "energy management"* (Lee et al., 2024; Vikhorev et al., 2013). *"Resource efficiency"* can serve as a high-level terminology. For example, *"resource efficiency"* was used in an discrete-event simulation approach, despite a clear emphasis on energy consumption prediction (Larek et al., 2011). In the initial sample, it was discovered that studies used a variety of keywords with similar definitions, such as *"resource efficien*"* (e.g., *resource efficient production* in Fig. 3). A method named as *"resource-efficient manufacturing" (REM)* was used as a process for manufacturers to reduce production costs and maximize profits (Gould and Colwill, 2015).

The terminology around *production information systems* is found to be inconsistent as well. Some researchers highlighted the development of *manufacturing information systems* to facilitate energy consumption analysis, where data management can be a foundational part of information handling (Vikhorev et al., 2013). The term *"manufacturing IT systems"* was also used when the authors were trying to define an information source for resource flow model parameterization (Leiden et al., 2021).

3.2. Results in-depth analysis focus on individual label groups

3.2.1. Applicability

Fig. 4 illustrates the applicability of resource efficiency assessment methods in 296 publications from the initial sample, according to the presence of case studies. The study found 228 papers lacked case studies for the new methods developed; 64 publications conducted a single case study, and only 4 publications included multi-case studies.

This included a step further to assess the validation of the methods in the library. The tool named green performance mapping (GPM) was a best practice of method demonstration (Kurdve and Bellgran, 2021). Researchers developed the method with users from the automotive industry and then tested it in pharmaceutical and several different manufacturing industries over a period of nine years. Eight different case studies repute the GPM tool for being engaging, visual, and easy to use on different manufacturing system levels for users to identify and prioritize environmental perspectives. Another method for analysing and optimizing electricity consumption in manufacturing processes also had a multi-case study (Rodrigues et al., 2018). The method was demonstrated in the small-size food processing industry with two companies that share common characteristics such as high manual workload, seasonal production volume, and limited financial resources.

Applicability of resource efficiency assessment methods can also be enhanced by conducting single case studies within specific research areas. The method for energy and carbon emission reduction was initiated from the needs of the foundry industry (Zheng et al., 2022), where the proposed method was validated in the actual production situation of the foundry enterprise. However, if a method aims for a larger scope but only a small number of cases are chosen, the applicability of the method may potentially be limited. A multinational electronic appliance company served as the place for case studies for the method Resource value mapping, which was developed to assess the resource efficiency of manufacturing systems in general (Papetti et al., 2019). Though the case study was thorough, it was limited to illustrating how the method could be used in industries other than energy-intensive businesses.

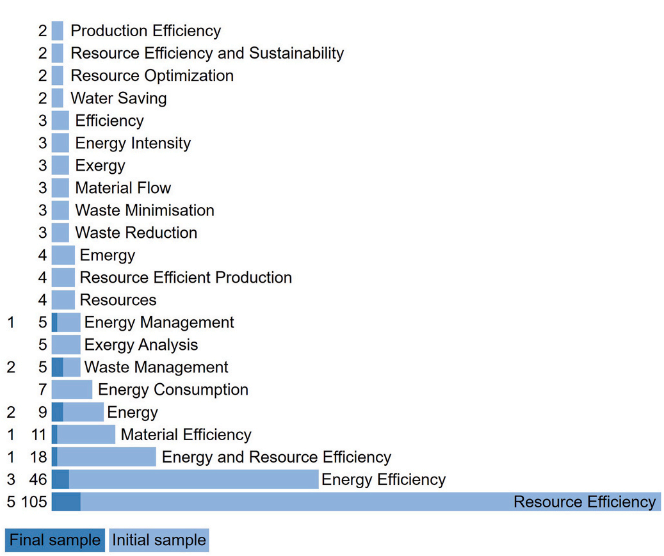

Fig. 3. Keywords used by publications in initial sample and final sample.

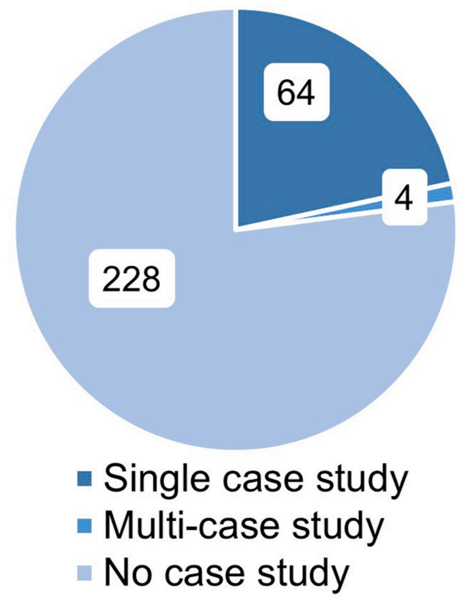

Fig. 4. The number of publications with single case studies, multi-case studies, and no case studies in the initial sample.

3.2.2. Applied level

Methods for resource efficiency assessment from the final sample covered all three applied levels defined in label group 2: machine, cell, and factory, with 27, 25, and 27 publications, respectively (shown in Fig. 5.)

Among 27 publications at the machine level, 15 researched dedicatedly at this level. These studies mainly focused on manufacturing processes, for example, in machining system (Larek et al., 2011; Zhang et al., 2021), moulding processes (Spiering et al., 2015; Zheng et al., 2022) and discrete part manufacturing (Kellens et al., 2012). These

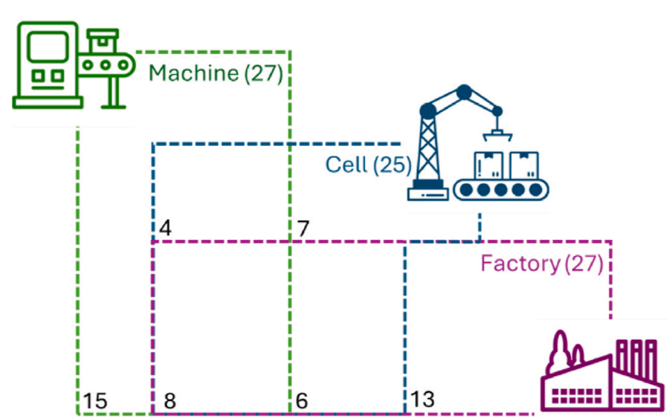

Fig. 5. Applied level coverage of resource efficiency assessment methods in the final sample.

research also had different targets for improvement, including electricity consumption reduction (Rodrigues et al., 2018; Spiering et al., 2015; Taheri et al., 2014), strategic lubricant usage (Campitelli et al., 2019), prolonged tool lifetime (Emec et al., 2016) and machining time optimization (Hu et al., 2018). Besides, there were three publications that researched in production management field at machine level for laser cutting (Kellens et al., 2012), thermal spray (Taheri et al., 2014), and small-size food processing (Rodrigues et al., 2018).

All 13 publications dedicated to factory-level resource efficiency assessments have laid their focus on production management. Many among these studies modelled factories, therefore multiple resource flows can be combined in one assessment method (Ball et al., 2009; Despeisse et al., 2013; Smith and Ball, 2012). There are also studies with chosen resource flows at the factory level. For instance, a study had industrial water as the objective (Walsh et al., 2016) and several publications focused on energy management for factory-level resource efficiency (Feng et al., 2016; Müller et al., 2014; Vikhorev et al., 2013).

3.3. Results from cross analyses

3.3.1. Base approaches used by resource efficiency assessment methods

The 53 resource efficiency assessment methods from publications included in the final sample are coded using the base approaches used in method development. The columns of Fig. 6 show how many times each base approach was used. The heat map also illustrates the distribution of base approaches against the other six label groups separately.

The most utilized base approach in the final sample is simulation and modelling of production systems. Life cycle assessment-relevant approaches and material flow mapping were also frequently used for developing assessment methods for resource efficiency. More conventional approaches, such as lean and value stream mapping, were mentioned multiple times, indicating a close link between resource efficiency assessment and traditional production management. emergy, exergy, and industrial metabolism received less attention because they are relatively new to the manufacturing industry.

Energy flow was extensively simulated and modelled in industrial systems. Some studies simulated energy flows separately since energy calculation was identified as the main impact contributor in specific use cases, such as laser welding and injection moulding. Simulations of energy flow can also be combined with material and waste flow for holistic economic calculation in a generic model (Ball et al., 2009).

Material flow analysis was the leading choice for resource efficiency assessment at the factory level. The life cycle assessment methodology was used in thirteen articles, with a noticeable emphasis on environmental sustainability. Resource efficiency assessment methods can also start with combined base approaches. For example, a cyber-physical production systems approach for process planning used life cycle assessment together with simulation and modelling of production systems to better cover environmental and economic impact dimensions (Leiden et al., 2021).

3.3.2. Connection with production information systems

The heat map in Fig. 7 illustrates the pattern of connections between resource efficiency assessment methods from the final sample and production information systems from other two label groups' perspectives.

As shown in the first column, more than half of the resource efficiency assessment methods did not specify data collection in applications. This indicated a low overall maturity regarding integrating data requests from resource efficiency assessments and data management in manufacturing companies, despite the level of manufacturing systems. Among the eight base approaches, resource efficiency assessment methods developed based on simulation and life cycle assessment have relatively closer connections with data sources but still rely a lot on manual data collection and secondary data.

Four methods from the library have clearly pointed out the connections, either for one-time data collection or continuous data acquisition: In a cyber-physical production systems approach, the study objective was controlled by a manufacturing execution system (MES) connected to an enterprise resource planning system (ERP). The assessment therefore used data extracted from these systems as well as manually acquired data (Leiden et al., 2021). In Spiering's energy efficiency benchmarking method, real-time data and historical data can be collected through measurement devices and supervisory control and data acquisition (SCADA) systems (Spiering et al., 2015). In the method of sustainability evaluation in machining processes developed, a basic database was created for Emergy conversion efficiency. Consumption data on energy, materials, services, and wastes were collected from different production documents, such as the production plan, BOM, and real-time monitoring (Sun et al., 2019). Installation of commercial energy management systems such as automatic monitoring and targeting (AMT) systems and energy management systems was recommended for efficient data collection (Vikhorev et al., 2013).

Even if partially or not connected to production information systems, resource efficiency assessments can acquire data from or be complemented by other data sources, such as those manually collected by production personnel and secondary documents, or in a combined way. In a method called resource value mapping, manual data was collected by researchers during site visits to serve the case studies (Papetti et al., 2019).

3.3.3. Connection with standards

In coding the publications from the final sample, connections with standards were included to evaluate how much the resource efficiency method development process has been integrated with global, regional, or other types of standards. Fig. 8 illustrates the status, delivering a main message that only a few methods from the final sample have well-built

Base approach		Applied level			Type of study				Improvement area			Sustainability dimension			Research field		Focused reource flow				
		MAC	CELL	FAC	MED	IND	SCS	MCS	IMP	STRA	TECH	ENV	ECO	SOC	PM	MP	MAT	ENE	WAT	WAS	SER
LCX	13	8	7	5	8	1	12	1	11	4	0	13	7	0	9	2	11	9	4	7	0
SIM	23	12	9	9	23	0	22	1	22	3	1	9	20	0	13	8	10	22	3	8	0
LEAN	1	0	1	0	1	0	0	1	1	1	0	1	0	1	1	0	1	1	0	0	0
MFA	10	2	4	10	8	0	10	0	10	2	0	4	10	0	10	0	9	6	2	6	0
VSM	4	1	2	4	4	0	4	0	4	2	0	1	4	0	4	0	3	3	1	2	0
EME	3	3	2	1	3	1	3	0	3	1	0	2	2	0	1	2	3	3	1	3	3
EXE	5	2	1	3	4	0	5	0	4	1	0	2	3	0	3	0	3	5	0	0	0
IND	1	0	1	0	0	0	1	0	1	1	0	1	0	0	1	0	1	1	1	1	0

Fig. 6. The distribution of the base approaches against applied level, type of study, improvement area, sustainability dimension, research field, and focused resource flow.

Connection with Production Information Systems		Applied level			Base approach							
		MAC	CELL	FAC	LCX	SIM	LEAN	MFA	VSM	EME	EXE	INDM
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
SCADA	0	0	0	0	0	0	0	0	0	0	0	0
BOM	1	1	1	0	0	0	0	0	0	1	0	0
MAN	14	7	8	8	4	3	0	2	2	3	2	0
SD	13	6	4	6	6	5	0	1	1	1	2	0
UDC	47	25	23	24	10	20	1	10	4	3	4	1

Fig. 7. The connection to production information systems against the applied level and base approach.

Connection with standards		Applied level			Base approach							
		MAC	CELL	FAC	LCX	SIM	LEAN	MFA	VSM	EME	EXE	INDM
GS	13	6	6	8	6	3	0	6	2	0	0	0
RS	2	0	0	2	1	0	0	1	0	0	0	0
OS	4	2	1	1	0	3	0	0	0	0	0	1
US	35	19	18	17	7	17	1	4	3	3	6	0

Fig. 8. The connection to standards against applied level and base approach.

connections with standards among all three applied levels and various base approaches.

In resource efficiency assessment method development, thirteen methods from the final sample referred to global standards, all from the International Organization for Standardization (ISO). The Environmental Management Standard ISO 14001 was widely used as a guideline standard, despite the type of base approach (Ball et al., 2009; Despeisse et al., 2012; Kurdve et al., 2015). The general framework from ISO 14051 was used to develop resource efficiency assessment methods based on material flow analysis (Walsh et al., 2016; Wang et al., 2017). The method "environmental impact modelling for discrete part manufacturing processes" mentioned ISO14955-1, a standard still under development about environmental evaluation of machine tools (Kellens et al., 2012). In two methods where LCA was used as the base approach, the new international standards for life cycle assessment, ISO 14040 and ISO 14044, were cited (Thiede, 2018; Thiede et al., 2016). From the user's perspective, only one method referred to the European Union Emission Trading Scheme (EU ETS) in elaborating the need for new assessment methods for carbon accounting (Billy et al., 2022).

Other specific standards were also adopted in resource efficiency assessment method development, mainly in detailed assessment steps. For instance, the industrial metabolism analysis followed standardized steps for industrial metabolism analysis, though it was not a universal standard yet (Wenjie, 2021). The standard IEC61508-part4 was mentioned to emphasize why machine condition monitoring would serve the method's purpose (Emec et al., 2016). A standard for industrial data called MTConnect was used in machine tool energy data monitoring (Vikhorev et al., 2013).

4. Discussion

This chapter compares the review to previous reviews on resource efficiency, as discussed in Section 4.1. Section 4.2 goes into further detail about how to effectively implement resource efficiency assessment methods. Section 4.3 presents a list of enabling and hindering factors in resource efficiency assessment method development and implementation.

4.1. *Positioning this review in resource-efficient manufacturing*

Several reviews have already explored resource efficiency and related practices in the manufacturing industry, each offering valuable insights into specific aspects such as resource efficiency metrics, cleaner production methods, and energy assessment. Hernandez and Cullen, for instance, reviewed various resource efficiency metrics and evaluated them using the RACER methodology (Relevance, Acceptance, Credibility, Easiness, Robustness) (Hernandez and Cullen, 2019). In 2024, a review was conducted for cleaner production methods and innovative industrial processes, providing a detailed evaluation of current practices and identifying gaps in research and implementation (Manikandan et al., 2024). Many studies also looked at energy efficiency particularly. Various energy assessment methods and tools were examined and classified into energy analysis, evaluation, and energy-saving measures (Menghi et al., 2019). Renna and Materi classified energy studies by manufacturing system types (e.g., single machine, flow shop, job shop) and discussed energy-saving policies (Renna and Materi, 2021).

These reviews often approach the topic from a broad scope or focus on a single resource flow, while the present study seeks to provide a comprehensive review of RE assessment methods by applying different labels in the coding. This review also focuses particularly on usability, compatibility with industrial data, and decision-making support potential of assessment methods for resource efficiency. This review's analysis and discussion can supplement and expand on the current body of work by offering a more factory-based and application-oriented perspective. Meanwhile, gaps identified in previous reviews, such as the need for holistic analysis and improved data collection, are addressed.

4.2. Effectiveness of resource efficiency assessment method implementation

The effectiveness of resource efficiency assessment methods was examined from the applicability, applied level, and impact dimensions during this review's screening. Furthermore, this section provides additional interpretation of the resource efficiency assessment's implementation from data management, organization, and compliance perspectives, with reference to its connections with production information systems and standards.

4.2.1. Integrating production information systems for resource efficiency assessment

In the method library, simulation and modelling-based resource efficiency assessment methods have a stronger relationship with production information systems in terms of data management. One explanation would be that manufacturing system simulation is more closely associated with industrial digitalization, where the value of data is generally acknowledged. Resource efficiency assessment methods developed from conventional production management techniques, such as MFA (material flow analysis) and VSM (value stream mapping), still have a huge potential to be integrated with production information systems for data acquisition (Thiede et al., 2016).

In information system integrated resource efficiency assessment, some fundamental data quality-relevant issues, such as consistency, can be resolved (Levitin et al., 1994). Good integration in modern manufacturing systems can even allow data models with more advanced characteristics like security and understandability (Despeisse et al., 2023). It is advantageous to establish a resource efficiency data inventory that acts as a bridge between resource efficiency assessment methods and production information systems, as these two currently lack built-in connections. Studies in the field of circular manufacturing also indicated that the management and sharing of data and information are the most heterogeneous barriers in the adaptation of circular strategies (Acerbi et al., 2022). In the field of industrial digitalization, a concept of data value chain was proposed to systematically map and improve data flows so that industry more effectively selects and integrates digital technologies (Agerskans et al., 2022). Therefore, creating a data inventory for resource efficiency assessments shall be a collaborative effort with other research for smart sustainability performance management in production.

Resource efficiency assessment data inventory built by integrating production information systems can strongly back up cross-level assessments (Leiden et al., 2021). In practice, manufacturing companies usually start resource efficiency analysis with single machines since they are the basic unit of production systems with straightforward data incoming. It is also easier to work at the top value chain level, as the data involved can be pre-processed by other stakeholders. Resource efficiency assessments in between are essential in rebound effects prevention. For example, a survey study showed the gains from energy efficiency improvement could be partially offset by behavioural or systemic responses in other parts of manufacturing systems (Greening et al., 2000). Industrial symbiosis programs also highlighted the contribution to both environmental and economic sustainability from interconnected facility resource efficiency, for example, waste heat utilization and by-products used as resources (Chertow, 2000; Mirata and Emtairah, 2005). Therefore, researchers and industry must see the necessity of joint efforts in manufacturing resource efficiency management at the production cell, line, and facility level.

Manufacturing companies can also benefit from data visualization by integrating resource efficiency assessment with production information systems. Structured data inventory management makes performance monitoring timely and visible, which helps manufacturing companies, especially SMEs, with quick assessment and potential organizational culture change (Caldera et al., 2019). Interconnected resource efficiency assessments across production areas can enhance transparency for more instructive internal communication.

4.2.2. Connecting standards for resource efficiency assessment

Though regulations and standards about manufacturing resource efficiency are discussed a lot nowadays, the link between regulation studies and pragmatic resource efficiency assessment methods has not been built up. Enhanced standardization of resource efficiency assessment methods should be considered in future studies for both compliance and effective implementation.

In the development of resource efficiency assessment methods, the integration of standardized processes or instruction can significantly reduce the learning efforts required for industrial implementation. By providing clear guidelines, the standardized methods facilitate easier adoption by factory personnel, ensuring that resource efficiency becomes an integrated part of everyday production rather than a one-time event. Standardized methods are supposed to include specific steps for data collection, analysis, reporting, and acting, which can be uniformly applied across production lines and facilities (Gould and Colwill, 2015). This not only streamlines the assessment process but also helps build a culture of sustainability within the organization.

Furthermore, in practice, resource efficiency assessment methods that include processes and indicators aligned with existing standards or legislation are more likely to be adopted by industrial users for compliance purposes. For example, delivering a net reduction in greenhouse gas emissions is seen as a substantial contribution to the first environmental objective, "climate change mitigation," and improving water management and efficiency is required by the third objective, "the sustainable use and protection of water and marine resources," in EU taxonomy. Resource efficiency assessment methods following the instructions from regulation can simplify the reporting process for companies by directly using the same set of indicators for external reporting. Therefore, more time and organizational resources can be allocated to internal improvement actions. Standard assessment and reporting also help facilitate benchmarking against the industry's best practices, enabling companies to identify areas for improvement and implement the most advanced solutions.

4.2.3. Impact of resource efficiency assessment methods

While reviewing the impact of the resource efficiency assessment methods, a common logic was to quantify the economic impacts of focused resource flow, as the first step. Environmental impact was quantified afterwards by connecting secondary databases, such as the life cycle database for LCA. Only one publication introduced assessment methods that are able to quantify social sustainability on the production shop floor level in manufacturing companies (Kurdve and Bellgran, 2021). Currently, in the manufacturing sector, social sustainability is more emphasized at the company level or for the whole industry, mainly by means of social life cycle assessment (Petti et al., 2018). Studies evaluating the sustainability of fundamental manufacturing processes often excluded societal impact, though the authors recognized it as equally important (Mani et al., 2014). The potential for resource efficiency assessment methods to be feasible to measure social sustainability requires further investigation in method development.

In this study, papers reviewed rarely considered future iterations, such as Plan, Do, Check, Act cycle (Swamidass, 2000), for long-term resource efficiency performance management. As supportive tools, assessment methods should also guide users to deploy assessments in a more autonomous manner for continuous improvement.

4.3. Enabling and hindering factors

Based on the analysis and discussion around the initial sample and final sample, several enabling and hindering factors were identified, as summarized in Fig. 9. A best practice example from the method library

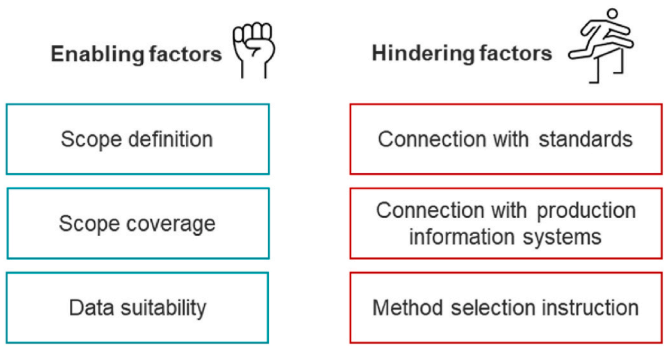

Fig. 9. Implementation factors (enabling and hindering) for resource efficiency assessment in manufacturing.

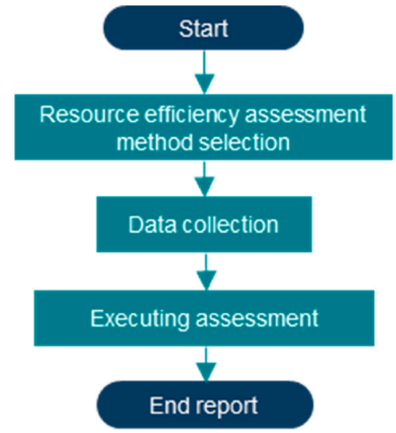

Fig. 10. The procedure for resource efficiency assessment generalized from the method library.

was provided in the followed texts. The implementation factors were later used as guidance to achieve the third objective of this study: creating an integration model for the production information systems (see Section 5).

The main enabling factors included

- Well-defined scope and impact of methods for application to align with the environmental goals. Best practice example: Cross-functional factory modelling (Despeisse et al., 2013).
- Broad coverage of resource flows, potentially through diverse base approaches. Best practice example: Sustainability evaluation method and index (Zhang et al., 2021).
- Production data suitability for resource efficiency assessments (manufacturers have data needed in resource efficiency assessments). Best practice example: Emergy-based evaluation method (Sun et al., 2019).

And the main hindering factors identified included

- Inadequate instruction in method selection and execution (for example, clear strategic alignment with companies' environmental goals and targets). Best practice example: Carbon accounting based on multilevel material flow (Billy et al., 2022).
- 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. Best practice example: Decarbonisation Index (DCI) for the automotive industry (Neef et al., 2024).
- 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). Best practice example: Cyber-physical production systems approach for process planning (Leiden et al., 2021).

5. The integration model

Reviewed studies were found to follow common steps while performing resource efficiency assessments, including several stages such as assessment preparation, data collection, and analysis (Sartzetaki et al., 2025). Fig. 10 illustrates the procedure generalized from reviewed assessment methods. While individual methods are proven to be effective to assess and potentially improve resource efficiency, it is still challenging for later users to identify which method should be selected for which environmental objectives (Fang et al., 2025). In addition, the methods generally rely on extensive data collection due to the insufficient connection to production information systems (Sun et al., 2019). While executing and reporting the assessment, insufficient connections to standards can limit the transferability of the results and regulatory compliance. Such common procedure can be useful for reporting purposes. However, it is time-consuming and challenging to reconduct the assessment for continuous monitoring and analysis. Reusing the assessment outcome for other purposes after reporting can also be hard.

In sustainable manufacturing research, there are new procedures developed for industrial users, mostly for indicator selection. For example, a procedure for selecting key performance indicators at the manufacturing process level was published in 2018 as manufacturers required better understanding and selection among the many indicator sets available (Kibira et al., 2018). Another study in 2019 specifically reviewed circular economy indicators from the literature and further designed a tool to help industrial users identify appropriate indicators based on their own cases and the indicators' characteristics. (Saidani et al., 2019). These new procedures were approved to be value-adding by enhancing the indicators' effectiveness. To improve the effectiveness of implementing resource efficiency assessment methods, this study developed an integration model with extended features (shown in Fig. 11).

In the preparation phase, the proposed model provides two different entry points for manufacturing companies: the company can choose feasible resource efficiency assessment methods in an opportunistic manner based on available data (bottom-up from resource efficiency data inventory), or the company can select resource efficiency assessment methods that align with strategic goals or sustainability compliance requirements (top-down from focused resource flows and targeted improvement areas). In both scenarios, the model assists manufacturing companies in maximizing the value of production data available and improving resource efficiency based on a data-informed selection of assessment methods.

To make a data-informed selection, resource efficiency assessment method selection and resource efficiency data inventory are separated. The 43 methods selected in this review serve as the preliminary method library. More information, such as listed data requirements from the method, instructions on method execution, and potential links to relevant standards and regulations, is continuously added to the method library. In parallel, the integration model includes a resource efficiency data inventory. Data currently available at manufacturing companies is examined and structured with reference to data requirements identified from the method library. Though current tests are conducted collaboratively between academia and industry, the data inventory should ideally be managed by users in accordance with their own data infrastructure in the long run. Afterwards, the readiness check determines whether to proceed with the selected method(s) by comparing data requirements from resource efficiency assessment method candidates and the resource efficiency data inventory. When the readiness check shows

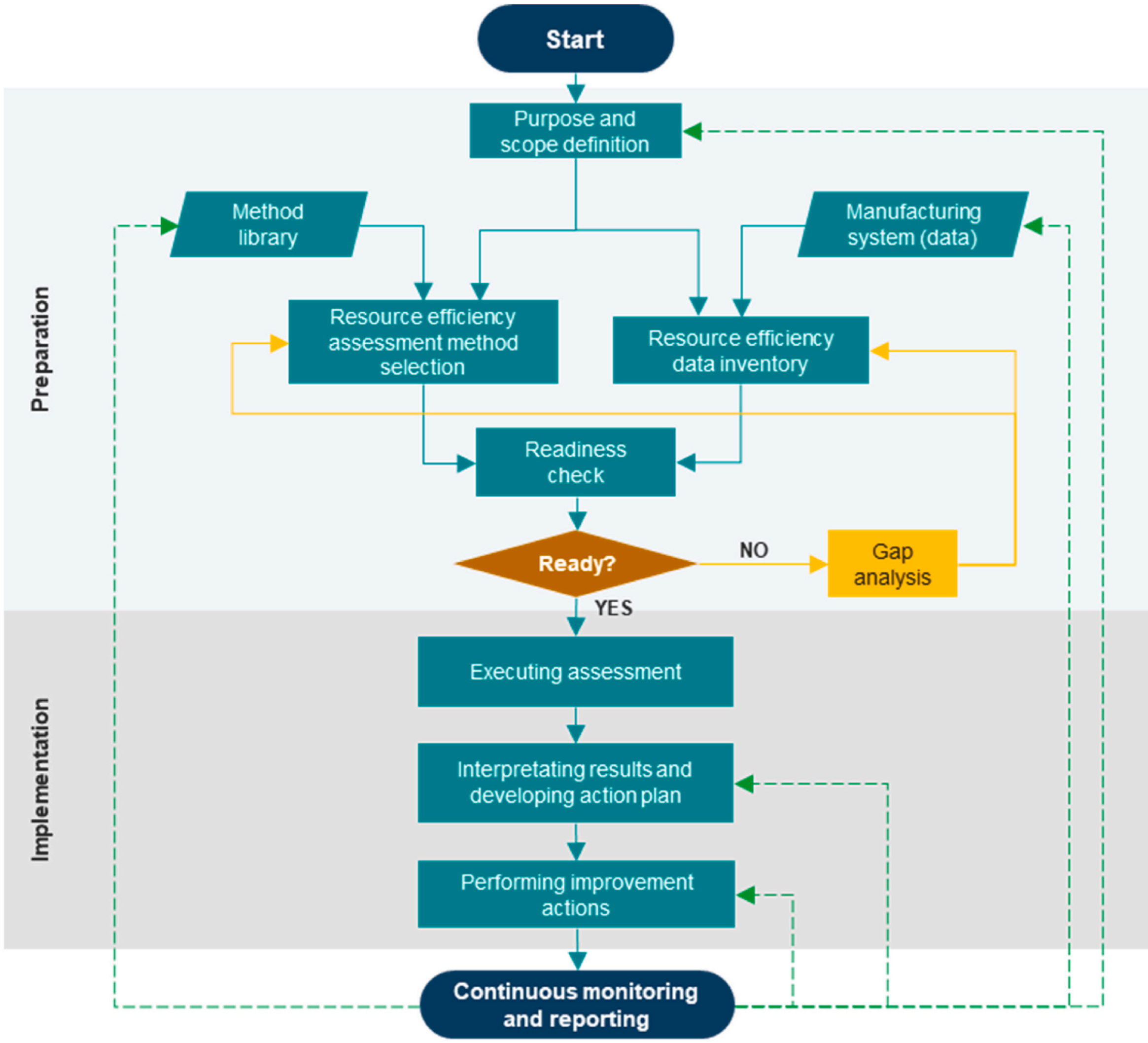

Fig. 11. The integration model for resource efficiency assessment.

any data gaps, immediate actions such as reviewing resource efficiency data inventory and reselecting methods are triggered, resulting in long-term actions like improving manufacturing data infrastructure for better data availability, collecting additional data by installing meters, filling data gaps using synthetic data or secondary data, etc.

The integration model moves on to the implementation phase if the readiness check shows a good match between data requirements from resource efficiency assessment method candidates and the resource efficiency data inventory. To emphasize resource efficiency improvement orientation, this integration model considers intermediate steps from execution to reporting, including interpretation of results, action plan development, and improvement actions themselves. This model also offers opportunities for iterations after implementation. The resource efficiency assessment report's outputs are used as input in earlier steps. For example, manufacturing companies may adjust their strategic objectives in subsequent resource efficiency assessment rounds. From a research standpoint, industry feedback is also essential in developing and updating the model to better meet industrial needs. For instance, populating the library with new methods compatible with diverse production information systems and standards encourages more industry partners to get on board.

Overall, the integration model shown in Fig. 11 is an expanded version of the common procedure shown in Fig. 10, with the intention to strengthen the enabling factors and overcome some of the hindering factors. Fig. 12 illustrates how the integration model further enhances enablers and tackles hindrances found in the literature.

As clear scope definition was identified as an enabling factor, this integration model maintains this enabler by guiding manufacturing users to define the scope of resource efficiency assessment at the beginning to ensure alignment with the companies' environmental objectives. Additionally, the model provides an embedded method library with methods that can cover different levels, from single machines to whole factories. Moreover, the integration model directs the development of a resource efficiency data inventory, where manufacturing data can be labelled by resource flows, resolutions, or other characteristics matching the requirement to implement specific resource efficiency assessment methods (readiness check). The inventory also supports data quality assessment and pre-processing the data (cleaning, formatting, etc.) prior to the resource efficiency assessment itself.

To address identified hindering factors, the method library and integration model consider the connection with standards in the review process. The step of understanding manufacturing systems aims to build possible connections with production information systems to ease data access and potentially connect to live data for real-time resource efficiency assessment. By giving users two possible entry points (top-down for specific environmental objectives or bottom-up based on data availability), the integration model also guides the choice of resource efficiency assessment method for a more strategic or opportunistic approach.

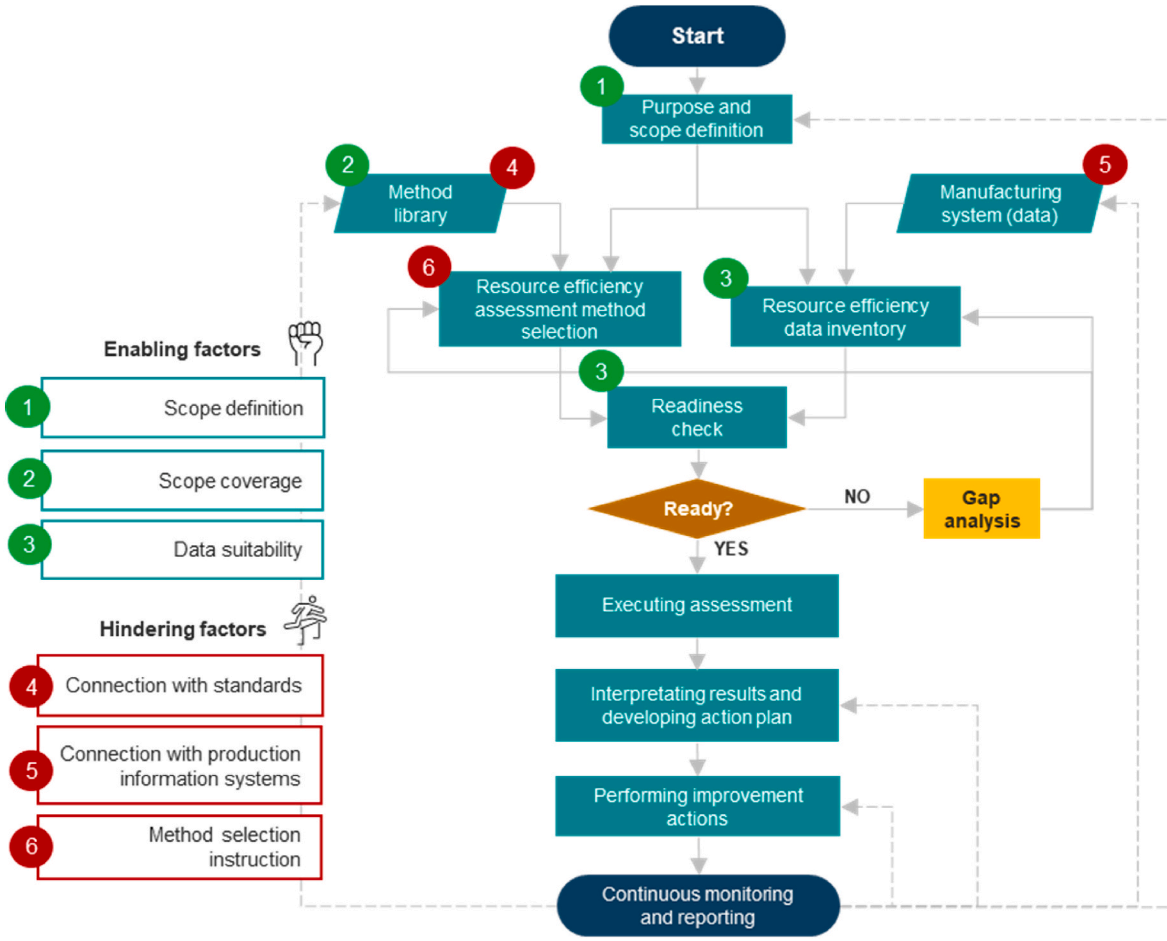

Fig. 12. Connections between the integration model and identified implementation factors.

6. Conclusion

Given the wide variety of methods available and the increasing availability of industrial data, developing new resource efficiency assessment methods or gathering extensive data is not necessarily the best solution to improve manufacturing resource efficiency. Integrating resource efficiency assessments into routine operations is critical to effectiveness.

This systematic review found that resource efficiency assessments were rarely connected to production information systems, which can support in many steps such as manufacturing data acquisition, data quality management, cross-level data sharing, and performance visualization. Furthermore, standardization, a critical enabler for compliance and implementation, is rarely connected with resource efficiency assessment methods in the development process. Another hindering factor that prevents resource efficiency assessment from being effective is a lack of awareness of interrelated resource efficiency assessments in manufacturing companies, as well as limited assessment applications. A method library was built from this systematic review, which was then used to create an integration model that included parallel steps and improvement iterations. This model can assist manufacturing companies in managing resource efficiency data inventories by locating and extracting necessary data from the production information systems.

The future research will focus on testing and consolidating the integration model. Manufacturing companies will be participating in the integration model's reflection and revision, as well as the development of potential additional features (for example, comparing individual methods) to improve the model's maturity. More future research directions identified from this review are to capitalize on the emergence of new resource efficiency assessment methods, standards, and regulations. Future reviews of theory-driven methods can expand the method library with new alternatives. Finally, taking social sustainability, efficient knowledge transfer, and upskilling into account in future resource efficiency assessment activities is critical in the human-centric Industry 5.0.

CRediT authorship contribution statement

Qi Fang: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mélanie Despeisse:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Björn Johansson:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. The method library

Table A
The method library with source and supportive labels for method selection.

Source	Method	Applied level			Sustainability dimensions			Focused resource flow				
Billy et al. (2022)	Carbon accounting based on multilevel material flow			FAC	ENV	ECO		MAT			WAS	
(Arguillarena et al., 2021; Burggräf et al., 2022; Campitelli et al., 2019; Rosebrock and Bracke, 2019)	Life Cycle Assessment-based resource efficiency assessment	MAC	CELL		ENV			MAT	ENE	WAT	WAS	
Zhang et al. (2021)	Sustainability evaluation method and index	MAC			ENV			MAT	ENE	WAT	WAS	SER
Denkena et al. (2022)	Resource-efficient process planning	MAC				ECO		MAT	ENE		WAS	
Zheng et al. (2022)	Combination method of multiple moulding technologies	MAC			ENV			MAT	ENE			
Wenjie (2021)	Industrial Metabolism Analysis		CELL		ENV			MAT	ENE	WAT	WAS	
Goffin et al. (2021)	Mathematical modelling for energy efficiency method		CELL			ECO			ENE			
(Liu et al., 2018; Sun et al., 2019)	Emergy-based evaluation method	MAC	CELL	FAC	ENV	ECO		MAT	ENE		WAS	SER
Papetti et al. (2019)	Resource value mapping	MAC	CELL	FAC		ECO		MAT	ENE	WAT	WAS	
Gharfalkar et al. (2018)	Operational resource effectiveness (OREft)	MAC	CELL			ECO		MAT	ENE	WAT	WAS	
Kurdve and Bellgran (2021)	Green performance mapping		CELL		ENV		SOC	MAT	ENE			
Kurdve et al. (2015)	Waste flow mapping		CELL	FAC		ECO		MAT			WAS	
Katchasuwanmanee et al. (2016)	Simulation-based energy-resource measurement	MAC	CELL	FAC		ECO			ENE			
(Bühler et al., 2018; Khattak et al., 2016, Taheri et al., 2014)	Exergy-based evaluation method	MAC	CELL	FAC	ENV	ECO		MAT	ENE			
Gould et al. (2016)	Material flow modelling for efficient production planning		CELL	FAC		ECO		MAT				
Walsh et al. (2016)	A value system framework for industrial water management			FAC		ECO				WAT		
Spiering et al. (2015)	Energy efficiency benchmarking	MAC				ECO			ENE			
Emec et al. (2016)	Energy consumption analysis for machine tools online fault monitoring	MAC				ECO			ENE			
(De Oliveria Gomes et al., 2013; Larek et al., 2011)	Discrete event simulation for energy efficiency	MAC	CELL			ECO			ENE			
Despeisse et al. (2013)	Cross-functional factory modelling			FAC		ECO		MAT	ENE	WAT	WAS	
(Kellens et al., 2012, 2014)	Environmental impact modelling	MAC			ENV	ECO		MAT	ENE		WAS	
Van Der Vorst et al. (2011)	Three-level resource consumption evaluation		CELL		ENV	ECO		MAT	ENE		WAS	
Li et al. (2012)	Eco-efficiency assessment	MAC			ENV			MAT	ENE		WAS	
Smith and Ball (2012)	Qualitative MEW process flow maps			FAC		ECO		MAT	ENE		WAS	
Vikhorev et al. (2013)	Energy management framework			FAC		ECO			ENE			
Despeisse et al. (2012)	Ecology model			FAC	ENV	ECO		MAT	ENE	WAT	WAS	
Ball et al. (2009)	A generic material, energy, and waste flow model			FAC	ENV	ECO		MAT	ENE		WAS	
Thiede (2018)	Assess cyber-physical production systems' environmental potential	MAC	CELL	FAC	ENV	ECO		MAT	ENE		WAS	
Thiede et al. (2012)	Energy portfolio	MAC	CELL	FAC		ECO			ENE			
Hu et al. (2018)	Optimization approaches machine time, machining deviation, and machining energy consumption	MAC				ECO			ENE			
Feng et al. (2016)	Energy supply operation optimization approaches in manufacturing plant			FAC		ECO			ENE			
Müller et al. (2014)	Energy value-stream mapping			FAC		ECO			ENE			
Gould and Colwill (2015)	Framework for material flow assessment	MAC	CELL	FAC		ECO		MAT				
Thiede et al. (2016)	Integrated analysis of energy, material, and time			FAC	ENV	ECO		MAT	ENE			
Rodrigues et al. (2018)	Analyse electric energy consumption	MAC				ECO			ENE			
(Weyand et al., 2021) (Wang et al., 2017)	Material flow cost accounting	MAC	CELL	FAC		ECO		MAT	ENE		WAS	
Denkena et al. (2020)	Overall energy demand approach		CELL	FAC		ECO			ENE			
Kellens et al. (2012)	Parametric environmental process models		CELL		ENV	ECO		MAT	ENE		WAS	
Wallrapp et al. (2024)	Material substitution approach	MAC	CELL	FAC	ENV	ECO						
Neef et al. (2024)	Decarbonisation Index (DCI) for the automotive industry			FAC	ENV			MAT				
Leisin and Radgen (2023)	Holistic assessment of decarbonisation pathways of energy-intensive industries	MAC			ENV			MAT	ENE			
Leiden et al. (2021)	Cyber-physical production systems approach for process planning	MAC	CELL		ENV	ECO		MAT	ENE			
Mousavi et al. (2015)	Impact assessment of embodied water		CELL	FAC	ENV	ECO				WAT		

Data availability

Data will be made available on request.

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