Applied Energy 390 (2025) 125877

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy management and industry 4.0: Analysis of the enabling effects of digitalization on the implementation of energy management practices

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HIGHLIGHTS

- Novel framework better integrating synergies between EnMPs and I4.0 technologies.
- Increased awareness offered on the roles of I4.0 technologies and EnMPs in manufacturing.
- Several areas of impact were identified and analyzed for selected I4.0 technologies and EnMPs.
- Data collection and analysis are the most implemented I4.0 technologies for EE.

ARTICLE INFO

Keywords:
Energy management
Energy efficiency
Industry 4.0
Smart factory
Digitalization
Manufacturing
Decarbonization

ABSTRACT

Manufacturing industries face significant challenges in reducing final energy use and improving Energy Management Practices (EnMPs). Industry 4.0 (I4.0) technologies provide transformative opportunities to address these challenges, yet their integration with EnMPs remains underexplored. This study aims to fill this gap by reviewing I4.0 solutions applied in manufacturing and assessing their impact on companies' Energy Management strategies. Specifically, the study develops a Smart Factory framework, categorizes I4.0 technologies into four clusters (system, infrastructure, service, and process) and identifies nine key Areas of Impact. The framework systematically maps these technologies to assess their effects on Energy Management. This model is validated and applied in two Swedish firms manufacturing respectively automotive components and heavy machinery, and machine tool accessories. Results indicate that EnMPs affect multiple areas, while their most notable impact is observed in the area of 'awareness', 'connectivity & integration', and 'visualization'. Similarly, I4.0 technologies enhance EnMPs by improving energy monitoring, performance evaluation, and energy-efficient process design. Internet of Things emerged as a critical enabler, facilitating real-time energy data collection and analysis, while Artificial Intelligence and Big Data Analytics provided predictive capabilities to optimize energy use and prevent inefficiencies. Simulation tools and Virtual Reality supported process visualization and design optimization, while Advanced Robotics enhanced flexibility and reduced operational energy waste. Energy-aware production scheduling, predictive maintenance, and the design of energy-efficient systems were the most significantly impacted practices. This framework demonstrates how I4.0 technologies can enable the transition towards smarter, energy-efficient manufacturing, contributing to industrial decarbonization and sustainability goals. By

Abbreviations: EnM, Energy Management; EnMPs, Energy Management Practices; EE, Energy Efficiency; CPS, Cyber-Physical System; IoT, Internet of Things; AI, Artificial Intelligence; BDA, Big Data Analysis; CS, Cyber Security; AR, Augmented Reality; AM, Additive Manufacturing; AoIs, Area of Impacts; IT, Information Technology; M, Million; EEMs, Energy Efficiency Measures; I4.0, Industry 4.0; VR, Virtual Reality; SF, Smart Factory; SM, Smart Manufacturing; NEBs, Non-Energy Benefits; IIoT, Industrial Internet of Things; SIM, Simulation; ARobs, Autonomous Robots; KPI, Key Performance Indicator; BC, Blockchain; M2M, Machine to Machine; MWh, Megawatt hour.

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https://doi.org/10.1016/j.apenergy.2025.125877
Received 20 September 2024; Received in revised form 14 March 2025; Accepted 4 April 2025
Available online 10 April 2025

providing actionable insights, the framework equips researchers and practitioners with a systematic approach to integrating digital technologies and energy management strategies, bridging a critical gap in the literature.

1. Introduction

Energy management (EnM) stands as a cornerstone of industrial transformation, with energy efficiency (EE) acting as a critical enabler for achieving operational excellence, sustainability, and long-term competitiveness [1]. In manufacturing, EE is far more than a supplementary measure, it is an essential strategy for addressing the dual challenges of rising energy costs and stringent environmental regulations [2]. The integration of EE into core industrial operations drives profound changes across production systems. It optimizes resource utilization [3], reduces waste [4], enhances productivity [5], and extends equipment lifespans [6], providing improvements to operational performance [2,6]. Beyond these immediate benefits, streamlined energy use delivers significant cost savings while reducing environmental impacts, making EE a cornerstone of sustainable industrial practices [7,8].

Crucially, EnM with EE as a key component, enhances resilience by enabling industries to adapt to volatile energy markets and comply with evolving regulations [9]. A sound EnM strategy can be applied in firms through EnMPs adoption [10,11]. Indeed, an effective EnM strategy is based on an organizational structure that can raise the importance of energy in the business and achieve results through overseeing people, resources, and planning [12,13]. Each firm needs to find its application within the definition of EnM strategies, according to its context (e.g., firm size and type) [14,15]. However, EE and EnM are not valued enough yet [16,17]. As previous studies discussed, firms experience difficulties in effectively implementing EnM [18] due to a number of barriers including economic [12], technical [14], information [19,20], and organizational [21,22].

Concurrently, the industrial sector is amidst a transformative era often referred to as the fourth industrial revolution, or Industry 4.0 (I4.0) [23]. This revolution encompasses a suite of technologies, including cyber-physical systems (CPS), the Internet of Things (IoT), Artificial Intelligence (AI), Big Data (BD), Blockchain, Cyber security (CS), Augmented reality (AR), Virtual reality (VR); all aimed at enhancing the efficiency of industrial processes [24,25]. Within this context, EnM in the manufacturing industry has undergone a rapid paradigm shift, driven by the need to transition towards smart and sustainable factories. These factories, characterized by greater flexibility and enhanced sustainability, lie at the heart of Industry 4.0, leveraging advanced digital technologies to optimize energy use and operational efficiency [5,26]. Recent studies have delved into how these I4.0 technologies can optimize manufacturing processes, with scholars asserting their potential to enhance the utilization of industrial production resources, across the upstream and downstream segments of the industrial value chain [26-28]. In fact, researchers have argued that the benefits of I4.0 technologies extend beyond mere productivity gains [29], manufacturing agility [30], encompassing process innovation [31], improved collaboration [32], adopt circular economy approach [32-34], environmental sustainability [35], and energy transition [36]. However, despite these advancements, the integration of industrial EnMPs and I4.0 remains an unexplored area in the literature. In fact, there are very little studies that have thoroughly investigated the nexus between EnMPs and I4.0 within the manufacturing context. Looking at EnMPs and I4.0 together is utmost critical since both EnMPs and I4.0 share the similar objective, which is enhancing the efficiency at manufacturing level, albeit with distinct trajectories.

Nonetheless, scholars have started to explore the impact of digital manufacturing solutions for EE in industry, yet research in this area is far from being mature. Kunkel et al. shed light on the correlation between energy indicators and I4.0 in the Chinese manufacturing sector, though their analysis has not focused at the operational-level impacts [37]. Ghobakhloo et al. have delved into the concept of I4.0 in relation to energy sustainability [38]. Similarly, Hasan and Trianni explored the effects of I4.0 on Energy Efficiency Measures (EEMs) performance at the operational level, although the study has not encompassed the full spectrum of I4.0 technologies [6]. Introna et al. explored how Industry 4.0 technologies could address the requirements of ISO 50001 (EnM systems), although lacking a systematic conceptualization of the relationships between I4.0 and specific EnMPs contextualized in the smart factory; moreover, any real-world business contexts application is lacking, to the detriment of the framework applicability [39]. Furthermore, while scholars have investigated energy use prediction [40], monitoring [41], and technology innovation models [37,38,42] integrating I4.0 technologies, there remains a notable gap in research addressing the I4.0 technologies with the adoption of comprehensive EnMPs in the Smart Factory (SF) [44] context. Specifically, there is a lack of studies looking at how I4.0 technologies intersect with EnMPs and, in turn, impact various areas of the manufacturing environment. This gap highlights the need for a more in-depth investigation into how these technologies could reshape EnMPs and influence broader manufacturing processes. Given the growing relevance of both I4.0 and EnMPs, a thorough investigation of all the I4.0 technologies, their combinations and interactions in the SF context, and a systematic analysis of their enabling effects on a defined set of EnMPs is crucial.

Considering the initial background, the aim of this study is to address the main adopted I4.0 technologies and how they can enable EM through their effects on EnMPs. To do so, the study develops an initial framework to illustrate the synergies between EnMPs and I4.0 technologies within the manufacturing context. To the best of author's knowledge, this study is a novel attempt to develop a framework integrating EnMPs and I4.0 in the SF context. In fact, the study presents two distinct contributions in terms of novelty. ***First***, it offers a comprehensive investigation integrating EnMPs and I4.0 technologies at manufacturing context describing all the interconnected features between EnMPs and I4.0. ***Second***, it proposes a framework integrating EnMPs and I4.0 technologies in a smart manufacturing context.

In the broader context of the study's contribution, the findings are poised to make a critical impact on both academia and industry. The outcomes of the study could support academia and industrial companies with increased knowledge and awareness on the roles of digital and smart technologies in the manufacturing context and lead them to improve investments in digitalization strategies and interventions; moreover, further insights on energy use reduction in manufacturing could be derived, decreasing the industrial reliance on energy supplies. With this more nuanced understanding, industries will be better positioned to optimize their operational performance, thus fostering long-term sustainability in both manufacturing practices and broader business operations.

The remainder of the paper is structured as follows: Section 2 offers the literature background of the study highlighting the research gaps. The research methods are presented in Section 3. Section 4 discusses the different features of the framework followed by its empirical demonstration in Section 5. Section 6 and 7 respectively present the discussion and conclusions of the study.

2. Literature background

The literature review examined two primary research streams. Whilst the first stream centred on EnMPs and EEMs, the second stream focused on I4.0 technologies and the implementation of SF manufacturing frameworks. In this regard, it should be noted that the concept of "industry 4.0" is relatively recent [45]. Furthermore, for the purpose of this study, we have adopted a narrative literature review [46] to showcase the main concepts and technologies, as summarized in Table 1.

2.1. Energy management frameworks and productivity benefits

The first stream encompasses the development of EnM frameworks, emphasizing productivity benefits and focusing on selected cross-cutting sectors. Studies have also focused on developing maturity focused and characterization frameworks. For instance, Pye and Mckane [47], Skumatz and Dickerson [48], Mills and Rosenfeld [49] have highlighted the multiple benefits stemming from EnM, proposing a nexus between EnM and production benefits. Likewise, Cagno et al. [50] and Nehler and Rasmussen [51] have argued about the non-energy benefits (NEBs) with regards to industrial EEMs. Although, these efforts have addressed only a few operational attributes. Furthermore, scholars have focused on developing EnM frameworks highlighting maturity aspects [47–49] and EnMPs assessment framework [11]. Nevertheless, previous studies have largely overlooked the broader array of EnMPs and relevant connection with cross cutting technologies. On the other hand, whilst scholars have also looked into the status of EnMPs at energy intensive industries [55-56], SMEs [19], with further investigation to the barriers and drivers to EnMPs [12,22,57], research has limited to an analysis of traditional EnMPs, overlooking the application of recent technologies, such as I4.0 technologies, for EnM.

Furthermore, in this stream, researchers have mainly focused on characterizing the EEMs and looking at the impact of EEMs on production resources and operational performances. For instance, Fleiter et al. [58], Trianni et al. [59] developed EEMs characterization-based framework, although neglecting the comprehensive impact of EEMs at industrial context. Likewise, Hasan et al. [3], Trianni et al. [60] argued about the impact of EMS and EEM on production resources. More recently, Cagno et al. [2] discussed the impact of EEMs at operational level, albeit with a limited focus on traditional EM activities. Moreover, the studies have narrowly discussed EEMs, overlooking the diverse array of industrial EEMs applicable across various technology domains.

2.2. Industry 4.0 technologies and smart factory for energy management

The second stream of literature has focused on I4.0 technologies, with authors contributing to the development of algorithm-based models and optimization strategies. For example, Büchi et al. [61] and Soori et al. [62] have concentrated on integrating models for various industries. Conversely, Kulatunga et al. [63], Peralta et al. [64], Shrouf and Miragliotta [1] have discussed the technical features of I4.0 and their impact on production systems. However, what concern is that EM is not discussed comprehensively. In fact, while the literature has explored specific I4.0 technologies and contributions towards framework development, a notable concern arises from the predominant focus of studies on technical features, neglecting the decision-making perspective on which specific technology best supports industry needs, especially in managing EnMPs and EEMs.

Furthermore, in this stream of research, the literature has explored the concept of smart factory (SF), with a particular focus on defining the attributes of SF integrated with I4.0 technologies. However, earlier studies have overlooked how EnMPs could be integrated into the context of smart factories. For example, Wang et al. [65] characterized smart factories considering aspects such as production modularity and manufacturing agility, yet little attention was given to the nexus between EnMPs and relevant technologies. Similarly, Jang et al. [44] proposed a fuzzy set-based framework that addressed financial and efficiency-related issues, but EnMPs was not thoroughly discussed. Likewise, Park et al. [66] and Canas et al. [67] developed SF framework integrating I4.0 technologies, yet the scientific evidence regarding how energy management could be effectively managed within these systems remains inconclusive, and there is a lack of broader consideration of I4.0 technologies.

Chen et al. proposed a CPS-based smart factory framework emphasizing a physical domain composed of machines and people, and a digital twin body composed of models and services (information and control information), but with limited focus on energy management [68]. Also, Ryalat et al. introduced a smart factory framework integrating CPS and IoT, validated through a drilling process case study, but energy management is not directly addressed [69]. Additionally, Park et al. described an AI-based smart factory framework for Korean SMEs that incorporates intelligent production and modularization but does not explicitly address energy considerations [70]. Ma et al. introduced a digital twin and big data-driven framework for sustainable smart manufacturing in energy-intensive industries, explicitly targeting energy efficiency by integrating product lifecycle management, real-time data, and energy-saving decision-making [71]. A novel framework by Favi et al. developed a framework that integrates Energy Material Flow Analysis, Life Cycle Assessment, and Multi-Criteria Decision Making to assess and optimize energy and material flows in manufacturing plants using I4.0 technologies [40]. It focuses on modelling the system, evaluating environmental and economic KPIs, and optimizing production scenarios, effectively supporting plant managers in managing energy and material flows sustainably. However, while these frameworks explore various aspects of smart factory design, including sustainability, optimization, and technological integration, none explicitly connect with or integrate EnMPs as a systematic approach. This significant gap underscores the need for a framework that bridges smart factory development and energy management to address sustainability goals comprehensively.

2.3. Research gaps

The summary of literature presented in Table 1 has highlighted several significant observations and delineated relevant research gaps.

Firstly, upon examination of the studies, it is evident that a diverse array of research has concentrated on EnMPs (e.g., frameworks, applications). Additionally, studies have investigated the impact of EnM on production resources. Conversely, other research has delved into I4.0 technologies, delineating discrete attributes of SF.

Secondly, EnMPs have not been comprehensively integrated within the manufacturing context although scholars have underscored the role of energy as a critical resource, emphasizing its profound impact on production systems. By delving deeper into the specific effects of EnMPs, particularly within the intricate fabric of manufacturing operations, a deeper understanding can be attained. Such an understanding holds the potential to significantly enrich the decision-making process concerning the adoption of EnMPs within industrial settings.

Thirdly, the literature has extensively deliberated on algorithms and models integrating I4.0 technologies. In fact, scholarly discourse has rapidly burgeoned within this domain, particularly emphasizing aspects such as production efficiency, agility, and optimization techniques. However, scant attention has been devoted to exploring the nexus between I4.0 and EnMPs. The integration of EnMPs with I4.0 is of crucial importance, given that one of the primary objectives of I4.0 technologies is to enhance efficiency. Notably, EnMPs and I4.0 represent two distinct pillars, each with the overarching aim of improving operational efficiency, albeit through divergent trajectories.

Fourthly, previous studies have predominantly concentrated on presenting various attributes of SF. However, in this pursuit, studies have primarily emphasized technology integration. Nevertheless, research that comprehensively integrates EnMPs with I4.0 within the SF context whilst keeping focus on EE is far from mature yet. Indeed, investigating the synergies between EnMPs and I4.0 within the SF context is of utmost importance. Such an investigation would yield invaluable insights into the optimization of energy flows throughout the production process, thereby enhancing our understanding of sustainable manufacturing practices.

Table 1
Summary of selected studies highlighting EMP, EE, I4.0, and SF *Legend: ✓✓ (Broader consideration); ✓ (Partial consideration); × (No consideration).

Researchers and year	Focused area				Study description	Remark	References
	EnMPs	EEMs	I4.0	SF			
Pye and Mckane (2000)	✓✓	✓	×	×	The framework is focused on highlighting NEBs stemming from EM; incorporates different sets of cost (e.g. environment, production, capacity)	Whilst the study discusses EnMPs broadly, I4.0 technologies, and SF are little discussed.	[47]
Worrell et al. (2003)	✓✓	✓	×	×	Productivity benefits stemming from EnM are discussed; financial benefits are highlighted; other benefits are attributed into seven categories (i.e. waste minimization, production enhancement).	Lack of focus on I4.0 technologies.	[72]
Christoffersen et al. (2006)	✓✓	×	×	×	Highlights the EnMPs at the Danish industries; discusses energy policy, energy savings target, strategies towards EnMPs.	Very little discussion around I4.0 technologies, and SF.	[73]
Sorrell (2007)	✓	✓	×	×	Energy services contracts framed into three areas consists of scope, depth, and finance. Customer perspective is focused.	I4.0 technologies are not discussed; SF concept is not included.	[74]
Ates and Durakbasa (2012)	✓✓	×	×	×	The model is aimed to assess the degree of EnM applications. Proposition of minimum requirements; inclusion of energy manager in the requirement.	I4.0 technologies and SF are not discussed.	[75]
Fleiter et al. (2012)	✓	✓✓	×	×	A characterized based model for EEM is developed. Considered attributes are relative advantage, payback time, initial expenditure, NEBs, technical context, impact scope, sectoral applicability etc.	I4.0 and SF are not discussed.	[58]
Antunes et al. (2014)	✓	✓	×	×	EE and EnM standards are highlighted, in particular USO 50001. EM activities are divided into five maturity levels taking inspiration from Plan-Do-Check-Act cycle.	No focus at I4.0, SF.	[53]
Trianni et al. (2014)	✓	✓✓	×	×	EEMs are characterized based on multiple attributes including economic, energy, environmental, production, activity type, acceptance, involvement, distance to process, and frequency.	I4.0 dimensions are left unaddressed.	[59]
Introna et al. (2014)	✓✓	✓	×	×	EnM maturity-based model; model is divided into five stages consists of “initial”, “occasional”, “planning”, “managerial”, and “optimal”.	No focus on I4.0 technologies, SF.	[54]
Trianni et al. (2018)	✓✓	✓	×	×	Assessment based model is developed characterizing EnMPs. Considered attributes are types of EnMPs, EE improvement, target of EnMP, development stage, adoption methods, organization involvement.	Limited discussion around I4.0 technologies, and SF.	[11]
Sa et al. (2015)	✓✓	✓	×	×	EnM strategies are highlighted; five categories of strategies are discussed including reliability, efficiency, low cost, funding, and awareness.	The study mostly focuses on EnMPs; no discussion around I4.0 technologies.	[76]
Bendetti et al. (2015)	✓✓	✓	×	×	Three areas are considered consisting of “scope”, “intangibility of the contract”, and “degree of risk”.	No focus on I4.0 technologies.	[77]
Kindström and Ottosson (2016)	✓	✓	×	×	Energy services are categorized into four steps including information, analysis, activities, and performances; service ladder concept is integrated.	Discussion around I4.0 technologies are limited.	[78]
Wang et al. (2016)	×	×	✓	✓✓	SF is characterized by integrating big data-based feedback. Main characteristics are supervisory control system, cloud, industrial network, and physical resources.	No discussion around EnM.	[65]
Ghobakhloo (2020)	×	✓	✓✓	×	Interpretive structural modelling techniques are utilized to develop the model; sixteen attributes are considered (e.g. production modularity, supply chain digitization, manufacturing agility, cost reduction).	Discussion around EnMPs is limited.	[27]
Büchi et al. (2020)	×	✓	✓✓	×	Develops a concept of openness to I4.0 technologies; six opportunity typologies are integrated; considered attributes are breadth and depth.	Whist the study argues about I4.0 technologies, the is lack of argument integrating I4.0 and EnMPs, and EE.	[61]
Hasan et al. (2022)	✓	✓	×	×	Impact of EnMPs/ energy services on production resources (e.g., machine, labor, waste, capital) and productivity features (e.g., resource efficiency, operation time) are characterized.	I4.0 technologies are not considered.	[3]
Cagno et al. (2022)	✓	✓	×	×	EEMs are characterized into 15 categories (e.g., lead time, process quality, flexibility, inventory, plant layout, occupational safety & health, water, material, emission, waste, customers).	Whilst the study discusses the EEMs, there is very limited argument about I4.0 technologies and SF, specifically how EEMs are linked to I4.0 in SF context.	[2]
Hasan et al. (2023)	×	✓	✓	×	The role of I4.0 technologies is explored with consideration of EEMs performance; production resources are considered; operational performances (e.g. throughput, reliability, operation cost, labor effectiveness) are integrated.	Much focused on EEMs, key SF attributes are neglected.	[6]
Soori et al. (2023)	×	×	✓	✓	IoT is discussed with regards predictive maintenance, asset tracking, inventory management, quality control, production process monitoring, safety monitoring, supply chain optimization.	Lack of discussion on EnMPs and EE.	[79]
Soori et al. (2024)	×	✓	✓	✓	I4.0 technologies are discussed with regards to virtual manufacturing.	Whilst the study discusses EE, I4.0, and SF, there is limited discussion on EnMPs.	[62]

(*continued on next page*)

Table 1 (*continued*)

Researchers and year	Focused area				Study description	Remark	References
	EnMPs	EEMs	I4.0	SF			
Masood et al. (2023)	×	×	✓	✓	Blockchain-based framework is developed; embedded with data driven intrusion detection system.	Lack of focus on comprehensive suite of I4.0 technologies; no focus on EM.	[80]
Luca Silvestri (2021)	×	×	✓	✓	Computational fluid dynamics is highlighted with regards to optimize manufacturing process. Big data, Simulation, cloud computing are highlighted.	Whilst the study argues about specific I4.0 technologies, it has very little focus on EnMPs.	[81]
Valero et al. (2022)	×	×	✓✓	✓	Highlights the roles of I4.0 technologies in smart manufacturing context, termed Link4Smart. Horizontal integration and vertical integration are discussed.	No discussion on EnMPs.	[82]
Cañas et al. (2022)	×	×	✓	✓✓	The developed framework is integrated with production planning & control with I4.0 technologies; six different layers that consist of asset, integration, communication, information, functional, and business.	While discussing I4.0 and SF, little focus has been given to integrate EE, and EMP in the study.	[67]
Jang et al. (2023)	×	×	✓	✓	Develops a fuzzy set configuration helping to adopt SF; four paths including govt. support, entrepreneurial spirit, efficiency expectation, and financial preparedness.	Lack of focus on EnM, EE. Moreover, I4.0 technologies are not comprehensively focused.	[44]
Park et al. (2023)	×	×	✓	✓	AI focused framework for the SMEs; main attributes are informatization, automation related characteristics.	No discussion around EnMPs, and EE.	[66]
Park and Choi (2024)	×	×	✓	✓✓	The relationship between regional characteristics and smart factories adoption is discussed for Korean industries.	The study focuses mostly on I4.0 technologies and SF; lack of discussion on EnMPs.	[83]

In essence, this study advances the current scholarly discourse by delving into EnMPs, EE, I4.0 technologies, and SF within the manufacturing sphere. To drive this investigation forward, a novel framework is developed integrating EnMPs and I4.0 within the framework of smart factories. Section 4 presents the features of this framework, offering a comprehensive understanding of its attributes.

3. Research methods

To examine how I4.0 technologies can facilitate EnM through EnMPs, a structured framework comprising three interconnected areas was developed. The study began by exploring the concept of SF, focusing on the identification and analysis of relevant I4.0 technologies and their attributes within the SF context (Area 1). The analysis then shifted to the empowered organizational domains and smart capabilities - referred to as Areas of Impact (Area 2) - that these SF technologies could influence or enable. Lastly, the study evaluated how SF attributes, through their interaction with the Areas of Impact, affect or enable a defined set of EnMPs (Area 3).

The steps underpinning the development and application of the framework integrating EnMPs and I4.0 technologies within the SF context are illustrated in Fig. 1. Taking inspiration from previous studies

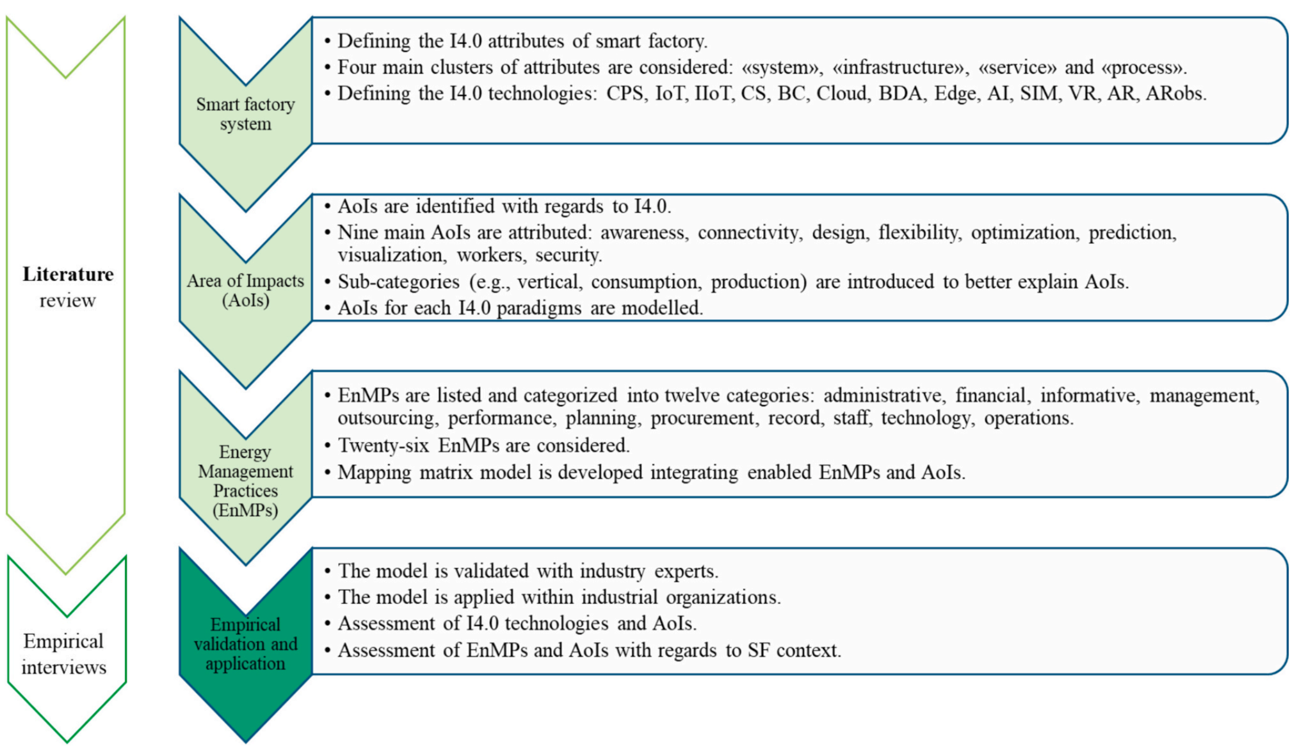

Fig. 1. Research methods adopted in the study.

[2,58], the process began with a literature review aimed at defining the framework and providing a first theoretical validation, based on previous contributions, which was later enforced by an empirical testing on field through case studies [85-87].

Literature review was preferred as the initial step because it allows for a broad and in-depth exploration of existing knowledge, facilitating the identification of relevant concepts, technologies, and relationships that form the foundation of the framework. The review was conducted adopting a narrative non-systematic approach, allowing more flexibility and the freedom to explore a wider range of sources, including academic papers but also industry reports, and grey literature. Compared to systematic reviews, non-systematic ones are indeed better suited for synthetizing concepts and ideas into new frameworks due to their adaptability and integrative nature [84]. The search of academic papers was conducted using academic databases (such as Scopus, Google Scholar, and Web of Science), with no specific limitations nor being confined to strict inclusive criteria, given the non-systematic nature of the analysis. This approach allowed for an extensive exploration of the literature, necessary when multiple perspectives need to be accounted, albeit at the expense of the reliability of the outcome. To address this limitation, the theoretical validation of the framework was complemented by an empirical application, as discussed in Section 5.

The analysis focused on two primary directions: (i) the identification and characterization of I4.0 technologies and attributes, along with their empowering capabilities and organizational impacts; and (ii) their influence on and enabling role in an organization's EM system, represented through a defined set of EnMPs. Taking inspiration from previous literature, the attributes of I4.0 technologies are classified into four macro-categories, namely: system, infrastructure, service, and process, each further subdivided to ensure a comprehensive evaluation. Following this, the Areas of Impacts (AoIs) are delineated, drawing upon the identified attributes linked to I4.0. This process involves considering nine distinct areas, with attention directed towards ensuring a thorough examination of the fundamental aspects of I4.0 technologies in relation to EE. The following step includes a meticulous selection of EnMPs. By taking inspiration from Trianni et al. [11] and Hasan et al. [3], Appendix A lists the considered EnMPs in this study. Differently from previous studies which have discussed a detailed list of EnMPs and energy management services, this study has rather opted to focus on the critical EnMPs within the manufacturing context to showcase the applicability of the framework's main components and their relevance to manufacturing operations.

In the later phase, selected EnMPs are mapped in accordance with the AoIs within the SF context. The AoIs are the main characteristics and aspects of a manufacturing company that are impacted by the attributes of I4.0 technologies. This approach provides a scientifically rigorous understanding of the nexus between EnMPs, I4.0 technologies, and EE within the SF framework. After the design and theoretical validation, the framework was empirically validated and applied within industrial settings, particularly in Swedish industries. While applying the model, we carefully opted for the approach taken by previous research [59], where the focus has been on the practical application of the framework in industries rather than highlighting the validation part separately. This approach has been beneficial for two main reasons. Primarily, by concentrating on the practical application of the framework, we were able to ascertain its real-world effectiveness in assessing AoIs with regards to EnMPs and I4.0 within manufacturing industries. Second, by incorporating the validation of selected EnMPs, our approach facilitated a deeper assessment of the framework's alignment with contemporary technological trends and industry standards. This ensured that the framework not only addressed current EM challenges but also remained relevant and future-proof amidst rapid advancements in digitalization.

While discussing the framework during application, the questions were organized as semi-structured interviews, which allowed sufficient flexibility during the discussions, repeatability and comparability between the different sessions [76–78] and contextualization of findings, for the benefit of the reliability of results. Additionally, validity is ensured by the selection of the interviewed companies, which are large organizations with experience in Industry 4.0, where the respondents possess a broad knowledge and general understanding of the topic under investigation. The first questions were designed to collect the relevant information on the context of each company, such as the identification of the main activities performed, the role of the interviewees, the level of digitalization and the digitalization strategy of the interviewed or served manufacturing companies, and the technologies and services adopted or provided.

The data collected through the interviews were cross-referenced with secondary data, when available, to confirm their reliability. After the identification of the context, the second part of the interviews allowed to focus on the core topics of the investigation, i.e., the completeness of the framework and the relationship intercurrent between SF attributes and I4.0 technologies, and their effects and impacts on a defined set of EMPs, through a detailed analysis. During this part of the discussion, the AoIs were presented, then the list of practices was carefully evaluated, addressing in each case the enabling technologies and AoIs and their effects. For the purposes of ensuring the validity of the research, the framework was presented to respondents prior to formulating the questions, and its clarity was assessed from their perspective. The process did not proceed further until the respondent demonstrated a clear understanding of both the framework and the research objectives. Moreover, the empirical findings were compared with those obtained through the theoretical validation, as detailed in Section 5, strongly improving the reliability of results.

4. The smart factory framework

4.1. Attributes of the framework

The I4.0 attributes enable new capabilities in the smart manufacturing context, spanning production, organization, management, and network levels. In this study, the clustering of I4.0 attributes into '*System*', '*Infrastructure*', '*Service*', and '*Process*' was specifically developed to align with the functional and operational roles of I4.0 technologies within industrial environments [79,80]. The value of this clustering lies in its ability to reveal the dynamic interrelationships between technologies, helping to identify synergies, and dependencies. As I4.0 encompasses a diverse range of technologies- from IoT and artificial intelligence to robotics and big data analytic - understanding how these technologies interact in practice is essential for achieving the intended benefits of digital transformation [1]. Categorizing these technologies into functional clusters, such as '*System*', '*Infrastructure*', '*Service*', and '*Process*' thus offers a much-needed framework for examining the specific roles each technology plays in enhancing efficiency, decision-making, and operational agility [90]. Moreover, the clustering approach allows for a deeper, more nuanced understanding of the operational impact of these technologies. For example, the distinction between 'Infrastructure' and 'Service' helps highlight the difference between the physical technologies enabling automation and the digital services, such as predictive maintenance and AI-driven optimization, that enhance performance outcomes [91]. This is crucial for industries that are seeking not just technological adoption but strategic integration, ensuring that each technology serves its intended purpose while complementing others within the broader industrial ecosystem [26]. Detailed descriptions of the attributes are presented in Table 2.

Whilst taking a closer look at the cluster level, for instance, at the *system* level, I4.0 technologies play a critical role in transforming traditional manufacturing operations, altering them into interconnected and intelligent systems [9,92]. More precisely, in a SF environment, Cyber-Physical Systems (CPS) facilitate predictive maintenance by continuously monitoring equipment conditions and autonomously scheduling maintenance tasks pre-emptively to prevent failures [65]. Moreover, Internet of Things (IoT) devices integrated into production

Table 2
Attributes of SF system.

I 4.0 attributes cluster	I 4.0 technologies	Industry 4.0 attributes description	Reference
System	CPS, IoT, and IIoT	Interconnection and enhanced communication between objects, equipment, machines (M2M communication), workers departments, and facilities at all levels of the factory and outside the physical boundaries of the factory (suppliers, consumers logistics) also in real-time.	[9,92,104–106]
		Decentralization with data collected from equipment, machines processes, and items, and sent back once analyzed to make informed self-decisions.	[38,106]
		Real time capabilities such as monitoring at process, machine, factory levels of operations, production processes, performances power consumption, materials consumption and supplies presence, position of workers, energy flows, pollutants, and communications.	[1,101,106–109]
	CS	Security for shared information and data, and in terms of robustness against malicious events or faults in all the paradigms (IoT, CPS, BDA, Cloud, Edge, VR and AR, AM) of the SF.	[80,110,111]
		Integrity of communicated information in terms of accuracy, consistency, and reliability of data through systems, physical components, and about the products lifecycle.	[110,112]
		Availability of stored or shared files.	[111,112]
		Confidentiality of personal privacy and intellectual property-related information among vertical and horizontal integration.	[110]
Infrastructures	BC	Security and transparency of transactions, operations, peer-to- peer trading, negotiations, data sharing and contracting outside the boundaries of the enterprise (e.g., with stakeholders, suppliers, other enterprises) by recording them immutably.	[89,92,94,107]
		Decentralization of decision-making, management information, and knowledge, which can be useful for auditors, agencies, and organizations.	[105,113]
		Traceability of data once shared, of data from smart products, of transactions, operations, peer-to-peer trading (e.g., verify origins of acquired resources), negotiations, and contracting outside the boundaries of the enterprise.	[89,92,94]
		Real-time data sharing with suppliers and customers, related to consumption patterns, products to be manufactured, contracts related information, resources flow and tracking of products and supplies with increased accuracy.	[89,92,94,114]
	Cloud	Data storage and sharing of information inside the enterprise, and with decentralized factories, suppliers, and buyers.	[92,115,116]
		Energy intelligence for optimized	[93,94]

(continued on next page)

Table 2 (*continued*)

I 4.0 attributes cluster	I 4.0 technologies	Industry 4.0 attributes description	Reference
		processes parametrization and configuration, allowing the elimination of traditional processes and digitalization of resources.	
Services	BDA	Mining and trends detection of data collected with systems and tools. Data are analyzed, translated in indicators, and compared so that they acquire value and transparency is increased.	[9,27,92,117,118]
		Predictive capabilities based on the analysis of consumption behaviors, resources demand trends, and parameters, leading to informed decision making and improved solutions.	[89,107,119,120]
		Near-real time data analysis of production processes and operations status, with consequent informed decision making that allow immediate interventions.	[100,121–123]
	Edge	Data analysis and monitoring close to the source permitting analytics at each sensor, sending alert warnings, and improving response time.	[124]
	AI	Prediction capabilities with smart algorithms for optimal decision making about supplies, consumption, maintenance, and logistic systems	[29,95,106,107,125]
		Autonomation and optimization of machines with deep and machine learning, such that they become self-aware and self-regulating.	[95,117,126]
		Data-driven planning of resource uses and production scheduling.	[127–130]
		Advanced design for buildings and products.	[131,132]
	SIM and VR	Monitoring through virtual representations and modelling of products and processes that can be continuously updated to spot problems and rapidly define solutions.	[95,122,133,134]
		Visualization of performances, steps of the production processes, resources flow, products, information, and parameters are enhanced through augmented representation of reality.	[89,95,107,135]
		Modelling and prototyping of products, production lines, processes, shop floor setups, and the entire enterprise to produce statistics and recommendations without stopping the production.	[89,95,107,120,134,136]
		Smart working for maintenance operations and training of employees.	[134–136]
	AR	Visualization of performances, steps of the production processes, resources flow, products, information, and parameters are enhanced through augmented representation of reality.	[106,107,137,138]
		Smart working for maintenance operations and training of workers.	[136,137]
Process	AM	Enhanced resources consumption, reduced need for raw materials and resources, material wastes, and product stocks, and chances to implement re-manufacturing.	[107,123,128,139]

(continued on next page)

Table 2 (*continued*)

I 4.0 attributes cluster	I 4.0 technologies	Industry 4.0 attributes description	Reference
		Improved engineering and design of product, equipment, and processes, with also chances to realize collaborative design.	[140–142]
		Improved production customization due to the possibility of realizing different shapes and configurations and increased.	[92,142]
	ARobs	Flexibility is improved because they can be used in several configurations, hence allowing enhanced customization.	[38,128,143]
		Quality and accuracy are increased as well as speed and reduced downtimes.	[102,144]
		Integration with human workers is due to the fact that they can be used in harsh environments, reducing human workloads, and autonomously reconfigurable without the need of human interventions.	[6,144]

machinery gather and transmit real-time data on operational performance. This data empowers decision-makers with valuable insights, facilitating more informed decision-making and optimized resource allocation at the system level [93]. Similarly, earlier studies [88,92] have discussed the contribution of I4.0 technologies on *infrastructure* level. Notably, technologies such as blockchain or cloud technologies play important roles in reshaping company infrastructure. Blockchain enhances data security and transparency through decentralized ledger systems, ensuring transaction integrity and supply chain traceability [95]. On the other hand, cloud computing offers scalable, cost-effective data storage and processing solutions, facilitating seamless resource access and collaboration. These technologies optimize infrastructure management, operational efficiency, and enable rapid adaptation to evolving business requirements [89,90].

Services represent another important cluster within the SF, wherein I4.0 technologies exert significant implications. Several scholarly studies have scrutinized this nexus, shedding light on the critical impact of I4.0 on service levels within manufacturing operations [91,92]. However, when it comes to energy related services, Ghobakhloo et al. [27], Delgado-Gomes et al. [100], Yu et al. [43] have argued about the transformative potential of AI, Big data analytics (BDA) driven maintenance systems in SF highlighting its role in pre-emptively identifying equipment failures, thus effectively reducing downtime and optimizing energy utilization. Besides, the integration of AR-enabled remote maintenance solutions further enhances service efficiency, enabling technicians to promptly diagnose and rectify issues.

Scholars have also highlighted the impact on *process* levels stemming from I4.0 technologies. This encompasses a wide array of operations, including production workflows, supply chain management, and quality control measures [6,101]. For instance, the integration of advanced robotics systems enables greater flexibility in production lines, allowing for rapid reconfiguration and adaptation to changing demands [102]. Additionally, I4.0 technologies contribute to improving quality control measures by leveraging real-time data analytics and machine learning algorithms [103]. This facilitates the early detection of defects, enhances product consistency, and ensures compliance with stringent quality standards.

Indeed, each system, infrastructure, service, and process, presents specific attributes and characteristics according to its nature. Although, the combined applications of solutions with their respective attributes are expected to act on defined aspects of the manufacturing production. These affected aspects are in this study called AoIs, and their enhancement allow the transformation of plants from traditional realities to smart ones. So, the Attributes and the consequent AoIs are derived from the analysis and evaluation of the novel capabilities.

4.2. Areas of impacts (AoIs)

The term AoIs encompasses the various facets influenced by a specific action, initiative, and technology. Table 3 presents the detailed AoIs of SF. Whilst identifying the AoIs, it is imperative to thoroughly look all relevant domains to determine the complex interactions stemming from I4.0 technologies. Notably, this approach is underscored by earlier scholarly contributions, which have argued the necessity of comprehensive assessments. For instance, the adoption of energy-efficient technologies transcends mere energy savings at the manufacturing level, showcasing multiple effects across various areas [72]. Besides, recent studies [3,60] argued about the impact on production resources concerning EEMs.

Thus, the integration of I4.0 technologies demands thorough scrutiny concerning its potential impact on industrial landscapes, as it implies a critical transformation across diverse domains. In this study, the AoIs are derived from the attributes delineated in the earlier section 4.1. As previously mentioned, while identifying the AoIs, particular attention has been paid to understand the key aspects associated with I4.0 and energy management. Nine AoIs are considered (see Table 3), which are *awareness* [92], namely the increased knowledge thanks to data gathering and information collection; *connectivity and integration* [109,145]; *design* [120]; *flexibility* [41,120]; *optimization* [120,146]; *prediction* [62,147]; *visualization* [148,149]; *workers* [6,140]; and finally, *security* [43,150] in information and data sharing.

When considering the linkage of enabling interactions between each I4.0 technology and respective AoIs, it is critical to comprehend the complex relationship between I4.0 technologies and AoIs. Table 4 presents the enabling interactions between each I4.0 technology and corresponding AoIs. Through the systematic presentation of data in tabular form, readers are provided with a coherent comprehension of how each I4.0 technology impacts different areas in the organizations. For instance, Medojevic et al. highlighted awareness as a significant AoI, attributed to the heightened understanding and knowledge surrounding I4.0 technologies. However, what is crucial is that this awareness extends beyond mere recognition and necessitates proactive maintenance, optimization, and process control in manufacturing. Similarly, connectivity and integration emerge as prominent AoIs associated with I4.0. On the contrary, Javied et al. [109] and Bornschlegl et al. argues that the interconnectedness facilitated by I4.0 technologies often enhances connectivity both vertically and horizontally within organizational structures. However, it is imperative to acknowledge that alongside the benefits, I4.0 heightened security concerns regarding shared information. In this context, Ordieres-Meré et al. [105] and Li et al. [107]

Table 3
Areas of Impacts of SF.

AoIs	Sub-AoIs	Description	References
Awareness		Increased knowledge thanks to data gathering and information collection, data monitoring, analysis, interpretation, modelling, and trends detection also in near real-time.	[1,151]
Connectivity and Integration	Internal/ Vertical External/ Horizontal	Interconnection of systems and people within (internal) and outside (external) the physical boundaries of the factory (e.g., networks of companies or supply chain) for enhanced communication and data sharing. Human workers, human workers-machines, machines, and facilities are integrated at all levels (vertical) and with all agents (horizontal) for enhanced collaboration.	[9,92]
Design		Advanced and efficient development, design, and creation of products, facilities, and processes.	[1,89,110]
Flexibility		In terms of the high flexibility of processes, the agility of production, and improved consideration of information coming from customers during production (customization) and/or suppliers (reaction in real-time).	[89,104,121]
Optimization	Consumption Production Procurement	Consumption trends, resources and supplies procurement, and production processes and activities.	[89,104,126]
Prediction	Consumption Production Procurement	Future consumption needs, future resources and supplies, and planning and scheduling of future events.	[107,152]
Visualization	Displaying Representation	Visual representation and virtualization of machines, equipment, physical systems, facilities, and processes (e.g., digital twins). Display of collected and/or elaborated data and flows.	[29,121,153]
Workers		New roles and required skills, and improved working conditions due to automation and changes in operating activities.	[6,127]
Security		In sharing information, transactions, and data both within and outside the boundaries of the enterprise.	[94,105,154]

underscore the domain of security as a significant impact of I4.0 technologies. In Table 4, the enabling interactions of I4.0 technologies and AoIs are reported.

4.3. Energy management practices and SF impacts

In this section, the enabling effect of the AoIs on EnMPs is presented. The detailed results of the enabling effect of the AoIs on EnMPs are summarized in Table 5.

The investigation was performed by deducing the interconnections

Table 4
Summary of the AoIs for each I 4.0 technologies. "X " = AoIs identified by previous literature for the considered I 4.0 technologies.

I4.0 attributes	I4.0 technologies.	AoIs									References
		Awareness	Connectivity and Integration	Design	Flexibility	Optimization	Prediction	Visualization	Workers	Security	
Systems	IoT	X	X					X			[1,92,101,105–107,123]
	CPS	X	X					X			[1,101,106–109]
	CS									X	[110]
Infrastructures	BC		X							X	[89,92,94,107]
	Cloud	X	X								[92,115,116]
Services	BDA	X						X			[9,27,92,117,118]
	Edge	X	X			X	X				[124]
	AI	X			X	X	X				[29,95,106,107,125]
	SIM, VR	X		X	X	X	X	X	X		[89,95,107,120,134,136]
	AR	X		X	X			X	X		[106,107,137,138]
Processes	ARobs				X	X			X		[6,96,107,142]
	AM			X	X	X					[140–142]

Table 5
Summary of AoIs and EnMPs relations. "X" = AoIs identified by previous literature for the considered EnMPs.

Type of practice	Energy Management Practices	AoIs									References
		Awareness	Connectivity and Integration	Design	Flexibility	Optimization	Prediction	Visualization	Workers	Security	
Administrative	Energy cost allocation	X									[9,38,92,151]
	Energy demand budgeting	X					X				[38,101,123]
Financial	Acquisition/management of financing and incentives	X									
	Adoption of energy performance contracting for energy-efficiency									X	[158]
Engineering	Energy efficient building/facility design	X	X	X				X			[6,120]
	Energy efficient product design	X	X	X	X			X		X	[159,160]
	Energy efficient system/process/equipment design	X	X	X	X			X			[9,105,121]
Informative	Internal communication regarding energy topics	X	X					X		X	[26,107]
	Marketing energy efficiency actions and results to external stakeholders	X	X					X		X	[3,161]
Management	Energy management position covered by an external consultant		X								[11]
Outsourcing	Outsourcing of engineering and project design		X							X	[3]
	Outsourcing of operation and maintenance activities	X	X							X	[3,118]
Performance	Identification of energy-efficiency opportunities	X	X			X		X			[2,60,162]
	Measurement of energy use	X	X					X		X	[89,107,120]
	Monitoring and evaluation of energy performance	X	X				X	X			[100,163]
Planning	Energy-aware production scheduling	X	X		X		X	X			[89,106]
	Maintenance planning						X	X			[2]
Procurement	Procurement of delivered energy through energy service contracts		X							X	[3,164]
	Optimize energy procurement based on energy data	X	X			X	X				[66,147]
Record	Documentation and record management regarding energy use	X	X								[56,165,166]
	Energy audit	X	X								[3,167]
Staff	Energy efficiency training for employees	X	X					X	X		
	Definition of energy responsibilities	X	X								[168]
Technology & operation	Demand side management techniques	X					X				[169,170]
	Energy-efficiency based maintenance	X						X			[3,171]
	Energy recycling	X						X			[99]

between the AoI and the EnMPs from the literature, in view of the novel capabilities of the SF. Scholars have argued about multiple interconnections between EnMPs and AoIs in academic discourse. Patros et al. [31] and Shrouf and Miragliotta [52] highlighted the nexus between EnMPs and awareness within the context of SF context. Indeed, improved data availability and collection of the whole environment, buildings, working equipment, processes, and products allow making effective data-based decisions on new products design, process planning, and scheduling.

More importantly, data facilitates informed decision-making regarding EEMs, resource allocation, and the optimization of energy use patterns. At the heart of this process lies the integration of awareness (data collection), visualization, and design (data elaboration and application), where advanced data analysis techniques enable the extraction of actionable insights [155]. For what concerns the performance practices, awareness given by real-time monitoring and analysis allows the evaluation and comparison between machines and equipment [156]. The chance to share information at all levels allowed by connectivity, integration, and security lead to optimization measures across departmental boundaries, and outside the company [43]. Similarly, Visualization such as digital copies of facilities and their elements can be used for benchmarking and to present relevant information to decision-makers [157].

5. Empirical demonstration

Upon preliminary validation through discussions among industry and academic experts, the proposed framework has been applied in two manufacturing companies located in Sweden: a component manufacturer for automotive industry and a hard metal cutting inserts manufacturer for the metalworking industry. The companies are presented below. In the following, the application in two large manufacturing with energy-intensive activities is presented, given the relevance of EE activities and digitalization within their facilities.

5.1. Company a

The company manufactures components with transmissions and axles for reloaders articulates and haulers; the performed processes are turning, washing, gear, hardening, and others. The site presents a large logistic area for material transport, a paint shop, several assembly lines for the various products, and an advanced heat treatment centre. In detail, on-site there are 235 machines employed for turning, washing, gear machines, hardening, and other activities. The site presents a large logistic area for the material transport, a paint shop, and several assembly lines for the various products, and an advanced heat treatment centre for product and component quality. Besides, globally, the company has 14 plants and more than 14,600 employees, net sales of euro 8.1 M in 2020 and operating income of euro 1.0 M in 2020. Global total energy use is around 372,000 MWh/year for all the operational facilities.

As reported by the interviewee (responsible for the I4.0 strategy), the journey to digitalise the manufacturing sites has started in the latest years across the different sites of the company. The main motive is the need to implement lean production techniques, since they observed that other businesses presented profitable results from their application. In particular, the focus areas of the digitalisation journey are automation and support of manual labor, autonomous control of manufacturing, IT and data security, operations data collection, operations data usage, advanced manufacturing technologies, model based manufacturing, and smart governance.

The I4.0 solutions applied on-site are adopted at pilot and first installation phase. The implementation of an IIoT platform for the collection of data from production recently started with the goal of balancing the different energy use KPIs, overall equipment effectiveness, and prevent over storage and overproduction to reduce wastes of energy. The IIoT platform is not controlling equipment, but just monitoring, analysing, and prescribing different actions and is applied at core production processes in the plant for the machining phase. The platform is applied in combination with advanced analytics programs and machine learning. On site, cybersecurity is highly valued, and the company is currently working on the segmentation of the network inside the factory to improve security system protection. For what concerns data storage, the goal is to avoid excessive storage in cloud environments due to prohibitive costs, thus local servers are also employed (e.g., 30 days of data are stored in cloud and 10 years of data in local servers).

Simulation tools, particularly discrete event simulation, are harnessed for projects impacting factory flows, such as simulating assembly lines and complex factory processes. Additionally, virtual reality is increasingly employed, particularly in the virtual prototyping of products. It plays a crucial role in the early verification of assembly, painting, and service processes. Besides, augmented reality, while currently in a pilot phase in the assembly area, serves multiple functions. It facilitates standardized photos and quality inspections. Moreover, it is integrated with artificial intelligence to enable smart classes and smart glasses for remote employee support. Notably, the logistic area benefits from the employment of forty-five robots for automated material transport. Similarly, autonomous guided robots are strategically deployed in assembly lines. Furthermore, there's ongoing testing for their potential application in machining processes. However, it's worth noting that onsite additive manufacturing is not practiced. Instead, external collaborations are sought for prototyping metal parts.

In Table 6 are summarized the effects that the adopted I4.0 solutions have on the AoIs, as stemmed from the discussion. A high share of the expected results is confirmed. However, what concerns that, it is expected to improve the optimization area since the implemented IIoT has the goal of optimizing processes and energy use. Besides, the flexibility area could not be verified for the AI technology that has been reported to be mainly used for advanced analytics purposes and in combination with AR.

Whilst looking at the EMPs, those most impacted and enabled in terms of confirmed and added interconnections belong to performance and staff categories (see Table 7). Notably, within the manufacturing context, the aspects of awareness, connectivity and integration, and visualization have witnessed significant enhancements. During discussion, production managers highlighted few important aspects. For example, concerning the measurement of energy usage, the production manager acknowledged increased awareness facilitated by data obtained through the IoT. This data not only improved understanding but also enhanced visualization of energy flow within the production environment. Moreover, it aided in identifying machines consuming energy and when they do so, enabling more targeted optimization efforts. Similarly, concerning AI, the integration of AI technologies has proven beneficial. For instance, AI-driven analytics have enabled predictive maintenance strategies, leading to reduced downtime and energy wastage. Additionally, AI algorithms have optimized energy use patterns by dynamically adjusting production schedules based on energy pricing and demand fluctuations. The detailed connections between the AoIs and EnMPs are elaborated in Table 7.

5.2. Company B

Manufacturer B plant is one of the largest facilities in the world for the manufacture of cutting tools such as boring bars and cemented carbide inserts, with around 1400 employees, making it a LE. Thus, tools for metal cutting, drills, mills, turning tools are produced in two subplants, one dedicated to holders' production, and another to produce hard inserts from wool fragments. The activities performed there are EI, and the high amount of consumed energy is measured at machines and plant levels. On site there are two production areas for tool and inserts manufacturing, respectively. The plant consists of 40 five-axis machining centres with turning machining centres supported by a

Table 6
Manufacturer A: Summary of I 4.0 technologies adopted and AoIs. Colours are used to determine whether it validates the framework (green), provides empirical addition to the framework (orange), or it lacks empirical validation (red).

I4.0 technologies	AoIs								
	Awareness	Connectivity and Integration	Design	Flexibility	Optimization	Prediction	Visualization	Workers	Security
IoT	X	X			X		X		
CS									X
BDA	X						X		
Cloud	X	X							
AI	X			X	X	X			
SIM, VR	X		X	X	X	X	X	X	
AR	X		X	X			X	X	
ARobs				X	X			X	

Table 7
Manufacturer A: Summary of EnMPs, adopted I4.0 technologies and AoIs summary. Colours are used to determine whether it validates the framework (green), provides empirical addition to the framework (orange), or it lacks empirical validation (red).

Type of practice	Energy Management Practices	AoIs								
		Awareness	Connectivity and Integration	Design	Flexibility	Optimization	Prediction	Visualization	Workers	Security
Administrative	Energy cost allocation	IoT, BDA, Cloud, AI, SIM, VR, AR				IoT, AI, SIM, VR				
	Energy demand budgeting									
Engineering	Energy efficient building/facility design									
	Energy efficient product design									
	Energy efficient system/process/equipment design									
Financial	Acquisition/management of financing and incentives									
	Adoption of energy performance contracting for energy-efficiency	IoT, BDA, Cloud, AI, SIM, VR, AR		SIM, VR, AR	X			IoT, BDA, SIM, VR, AR		
Informative	Internal communication regarding energy topics	IoT, BDA, Cloud, AI, SIM, VR, AR	IoT, Cloud					IoT, BDA, SIM, VR, AR		
	Marketing energy efficiency actions and results to external stakeholders	X								
Management	Energy management position covered by an external consultant									
Outsourcing	Outsourcing of engineering and project design									X
	Outsourcing of operation and maintenance activities	IoT, BDA, Cloud, AI, SIM, VR, AR	IoT, Cloud							CS
Performance	Identification of energy-efficiency opportunities	IoT, BDA, Cloud, AI, SIM, VR, AR	IoT, Cloud					IoT, BDA, SIM, VR, AR		
	Measurement of energy use	IoT, BDA, Cloud, AI, SIM, VR, AR	IoT, Cloud					IoT, BDA, SIM, VR, AR		
	Monitoring and evaluation of energy performance	IoT, BDA, Cloud, AI, SIM, VR, AR	IoT, Cloud					IoT, BDA, SIM, VR, AR		
Planning	Energy-aware production scheduling									
	Maintenance planning	IoT, BDA, Cloud, AI, SIM, VR, AR					V	IoT, BDA, SIM, VR, AR		
Procurement	Procurement of delivered energy through energy service contracts									
	Optimize energy procurement based on energy data									
Record	Documentation and record management regarding energy use									
	Energy audit									
Staff	Energy efficiency training for employees	IoT, BDA, Cloud, AI, SIM, VR, AR	IoT, Cloud					IoT, BDA, SIM, VR, AR	SIM, VR, AR, ARobs	
	Definition of energy responsibilities	IoT, BDA, Cloud, AI, SIM, VR, AR	IoT, Cloud					IoT, BDA, SIM, VR, AR		
Technology & operation	Demand side management techniques		IoT, Cloud							
	Energy-efficiency based maintenance							X		
	Energy recycling		IoT, Cloud							

'X'= Lacks empirical validation

'X' = Lacks empirical validation.

turn-mill cell. The production is EI and produces heat.

The interviewee (Production engineer involved in OEE projects) deemed the company to be an early adopter of I4.0 solutions and a strong research program is performed in the hardware and software areas of I4.0. At the beginning of their transition, 3D models and programs started to be employed to run and control machines autonomously. OEE systems are employed in the automated environment to identify malfunctions and abnormal behaviors, so that information can be used to prescribe solutions and optimize production. For example, at the facility a wide variety of similar products are produced, and the production can be automatically adapted according to the requests reducing time and wastes. Recently a new tool was developed to trace sustainability performances, assessing how the working environment, buildings, media, infrastructure, and production function behave. In detail, IoT with measuring systems and sensors and BDA are applied for the collection of data from machines, that are stored both on local server and cloud platforms where they are analyzed. Similarly, simulation is adopted for the visualization and design of programs, to enhance design of tools and production processes, and to identify eventual failures or problems. On the other hand, VR is applied to create models of machines along with ARobs, smart machines, and AM in production process. Finally, to date they are researching AI to optimize the toolpath creation.

The effects that the adopted I4.0 solutions have on the AoIs are summarized in Table 8. A high share of the expected results could be validated, and the IoT technology was reported to enable *prediction*, since it is applied for the collection of data used in predictive and preventive activities (e.g., maintenance). Lastly, due to the low level of information dragged on ARobs and AM, it was not possible to verify all the impact area, for the same reason the *flexibility* area was not validated for AI, since *flexibility* is expected to be enhanced, thanks to the combined adoption of AM and AI that leads to customization.

Regarding the ways in which I4.0 technologies enable EnMPs, from the validation results is possible to assess that the enhanced AoIs (Awareness, Connectivity and Integration, Visualization) are the most impacting in terms of energy-related performances, and their effects are expected to boost energy management and efficiency in companies by enabling almost all the practices mentioned by the interviewees, that are a great share of the evaluated set. Indeed, for what concerns the clusters of practices, the most enabled are *technology & operations*, *performance*, *engineering*, and *staff* related.

When examining the relationship between EnMPs and AoIs, it becomes evident that certain areas, particularly performance and records, are significantly affected (see Table 9). During the application of the framework, the production engineer recognized the enabling impact of IoT and AI in identifying EE opportunities. In fact, through IoT devices integrated into the production system, the company is collecting real-time data on energy use, equipment performance, and operational parameters. Subsequently, AI algorithms analyze this data to uncover inefficiencies and patterns, further identifying equipment malfunctions of excessive energy usage.

Furthermore, when examining the record, the integration of IoT has significantly enhanced the energy audit process, providing detailed insights. In fact, through the utilization of IoT devices integrated within facilities, energy audits benefit from detailed data inputs, enabling a thorough assessment of energy use patterns. Similarly, with regards to simulation, IoT is also aiding the companies to design more efficient production systems. By visualizing data tailored to specific needs and standard nodes, simulation tools empowered by IoT enable companies to gain deeper insights into their operations, identify potential bottlenecks, and optimize resource utilization for enhanced performance. The detailed results of the enabled EnMPs and AoIs are reported in Table 9.

6. Discussion

The academic significance of this study lies in its contribution built upon three critical factors mainly. First, the study investigates the complex characteristics of I4.0 technologies keeping focus on industrial adoption context. Second, it pioneers an innovative assessment of I4.0 technologies intertwined with EnMPs, considering its broader perspective beyond technical factors. Third, it delves into the crucial question of how I4.0 technologies can serve as catalysts for effective EnMPs implementation, pushing the discourse forward for the SF. To substantiate these claims, the study has meticulously developed a SF framework that integrates I4.0 technologies and a diverse array of EnMPs.

The framework proposed and validated in this study contributes to the discussion over SF models by explicitly integrating EnMPs into the design and operation of smart manufacturing systems, assessing impacts from the perspective of the decision-maker, with a systematic approach towards EnM By contrasting our work to previous research in the area, we note that existing frameworks focused on various aspects such as cyber-physical systems, big data analytics, and digital twins, yet lacking a systematic approach to energy management. This is the case of e.g., Chen et al. who emphasized virtual-real fusion and digital twins without a dedicated focus on energy optimization [68]. Similarly, scholars discussed reconfigurable manufacturing and vertical integration, respectively, with only peripheral mentions of energy efficiency [172,173]. Also, the proposed framework has specific reference to the SF context, thus building up on extant contributions which have offered a purely theoretical attempt to link I4.0 technologies and EnM [39]. The framework developed in this study distinguishes itself by systematically embedding EnMPs directly into the smart factory architecture, ensuring that energy efficiency is not an afterthought, rather a core component of the manufacturing process. This integration facilitates real-time monitoring and optimization of final energy use, aligning with sustainability goals and reducing operational costs. By bridging the gap between SF development and EnM, this framework contributes to the advancement of sustainable manufacturing practices and offers a comprehensive solution that addresses both technological innovation and environmental responsibility.

Here, it is worth noting that while ISO 50001 provides a structured

Table 8
Manufacturer B: Technologies and AoIs summary. Colours are used to determine whether it validates the framework (green), provides empirical addition to the framework (orange), not possible to be validated (ash) or it lacks empirical validation (red).

I4.0 technologies	AoIs								
	Awareness	Connectivity and Integration	Design	Flexibility	Optimization	Prediction	Visualization	Workers	Security
IoT	X	X				X	X		
CPS									
CS									X
BDA	X						X		
Cloud	X	X							
Edge									
BC									
AI	X			X	X	X			
SIM, VR	X		X	X	X	X	X	X	
AR									
ARobs				X	X			X	
AM			X						

Table 9
Manufacturer B: EnMPs and AoIs summary. Colours are used to determine whether it validates the framework (green), provides empirical addition to the framework (orange), or it lacks empirical validation (red).

Type of practice	EnMPs	AoIs								
		Awareness	Connectivity and Integration	Design	Flexibility	Optimization	Prediction	Visualization	Workers	Security
Administrative	Energy cost allocation									
	Energy demand budgeting									
Engineering	Energy efficient building/facility design	IoT, BDA, Cloud, AI, SIM, VR	IoT, Cloud							
	Energy efficient product design	IoT, BDA, Cloud, AI, SIM, VR	IoT, Cloud							
	Energy efficient system/process/equipment design	IoT, BDA, Cloud, AI, SIM, VR	IoT, Cloud							
Financial	Acquisition/management of financing and incentives			SIM, VR, AR				IoT, BDA, SIM, VR		
	Adoption of energy performance contracting for energy-efficiency			SIM, VR, AR				IoT, BDA, SIM, VR		
Informative	Internal communication regarding energy topics	IoT, BDA, Cloud, AI, SIM, VR	IoT, Cloud					IoT, BDA, SIM, VR		
	Marketing energy efficiency actions and results to external stakeholders									
Management	Energy management position covered by an external consultant									
Outsourcing	Outsourcing of engineering and project design									
	Outsourcing of operation and maintenance activities									
Performance	Identification of energy-efficiency opportunities	IoT, BDA, Cloud, AI, SIM, VR	IoT, Cloud					IoT, BDA, SIM, VR		
	Measurement of energy use	IoT, BDA, Cloud, AI, SIM, VR	IoT, Cloud					IoT, BDA, SIM, VR		
	Monitoring and evaluation of energy performance	IoT, BDA, Cloud, AI, SIM, VR	IoT, Cloud					IoT, BDA, SIM, VR		
Planning	Energy-aware production scheduling		X							
	Maintenance planning	IoT, BDA, Cloud, AI, SIM, VR					IoT, AI, SIM, VR	IoT, BDA, SIM, VR		
Procurement	Procurement of delivered energy through energy service contracts									X
	Optimize energy procurement based on energy data									
Record	Documentation and record management regarding energy use	IoT, BDA, Cloud, AI, SIM, VR	IoT, Cloud					IoT, BDA, SIM, VR		
	Energy audit	IoT, BDA, Cloud, AI, SIM, VR	IoT, Cloud					IoT, BDA, SIM, VR		
Staff	Energy efficiency training for employees	IoT, BDA, Cloud, AI, SIM, VR	IoT, Cloud					IoT, BDA, SIM, VR	Sim, VR, ARobs	
	Definition of energy responsibilities							IoT, BDA, SIM, VR		
Technology & operation	Demand side management techniques									
	Energy-efficiency based maintenance									
	Energy recycling		IoT, Cloud							

'X'= Lacks empirical validation

'X' = Lacks empirical validation.

and standardized framework for EnM – ensuring continuous improvement through a systematic cycle of planning, implementation, monitoring, and review – its primary focus remains on management processes, compliance, and periodic assessment [13,174]. In contrast, the framework developed in this study goes beyond static evaluations by embedding EnMPs directly into the operational and technological layers of smart factories, leveraging the multiple areas of impact stemming from the synergies of EnMPs and I4.0 technologies. Rather than relying solely on structured reporting and iterative improvements, this framework takes a broader perspective by examining the combined impacts of EnMPs and I4.0 technologies, with a particular emphasis on their synergies at the manufacturing operational level. Importantly, this does not diminish the relevance of ISO 50001. Rather, the integration of its systematic methodology with the digitalized, real-time approach can create a more robust and future-ready energy management system, bridging the gap between organizational control and technological advancement in industrial energy management.

Starting from highlighting the complex nature of I4.0 and EnMPs, several critical points can be discussed. However, what concerns that while assessing the characteristics, technologies, and layouts of the SF, the most applied technologies are IoT, cloud, AI, SIM and VR. The findings from the two studied companies provide practical examples of how I4.0 technologies can be applied to enhance EnM, while also illustrating variability in their adoption and utility, further confirming the need to move beyond the purely theoretical models proposed in past literature (e.g., [39, 175-180]). In Company A (automotive components), an IoT platform was implemented to enable data collection, facilitating energy optimization and balancing key performance indicators. Advanced analytics and machine learning tools were employed to optimize factory flow and improve EE, supported by simulation tools and virtual reality for prototyping and production process optimization. Additionally, autonomous guided robots and automated transport robots were utilized for logistics and assembly, aligning with the emphasis in the literature on the efficiency gains achievable through robotics [105]. However, while these technologies have demonstrated utility in Company A, additive manufacturing was notably absent, consistent with previous research regarding its limited diffusion [6].

In contrast, Company B (hard metal cutting inserts) applied IoT and Big Data analytics extensively for real-time energy monitoring and predictive maintenance, showcasing the role of digital technologies in enhancing operational awareness and proactive decision-making. Virtual reality and augmented reality supported production design and process optimization, while sustainability performance assessment tools were integrated to align operational practices with broader environmental goals. This contrasts with the literature's focus on flexibility, as Company B's use of sustainability metrics emphasizes a more structured approach to leveraging I4.0 for climate goals [6].

The results align with prior studies in demonstrating the contribution of I4.0 to various aspects of industrial manufacturing, such as production management [89,90], quality improvement through lean practices [91,92], and circular economy approaches [93,94]. Nevertheless, it is essential to note that not all I4.0 technologies are equally applicable to EnM. In fact, recent research [6] has accentuated this issue, highlighting discrepancies in the applicability of I4.0 technologies for increased EE. For example, additive manufacturing and autonomous robots have been lauded for their potential to enhance production process, facilitate the creation of high-quality products, and waste minimization [95,96]. However, the lack of significant adoption of additive manufacturing and the limited implementation of augmented reality beyond pilot phases in the studied companies highlight ongoing barriers, such as low digital maturity and sectoral applicability, which have been emphasized in previous research [6], [105,106]. While Company A leveraged advanced robotics, these tools were used primarily for logistics and assembly rather than broader EnM tasks, further supporting the argument that the utility of I4.0 technologies is highly context-dependent [5,97,98].

Whilst having a deeper look at I4.0 technologies, the incorporation of Blockchain technologies, and Cloud Manufacturing are notably deficient in the current industrial contexts, including at the studied companies. An important observation arises regarding the underlying cause – "*a deficiency in the driving force for data sharing*". Crucially, the successful adoption of these advanced technologies hinges upon robust incentives driving collaborative data exchange [181]. Moreover, scholarly investigations highlight the indispensable nature of flawless integration and interconnectivity with external entities for the effective implementation of these transformative paradigms [9,117]. Therefore, the resolution of challenges pertaining to information sharing and the cultivation of a collaborative ethos emerge as important prerequisites to fully harnessing the potential of blockchain, and cloud manufacturing within the industrial landscape [41].

On a separate note, regarding the digitalization process in the studied companies, two gaps are perceived when dealing with the relationships with energy topics. It is possible to call the first gap a "strategy gap" since it consists of the difference between the strategy promoted at a high management level and the one applied in practice on-site. From the discussions with the studied manufacturing companies, it was evinced that companies present detailed roadmaps for their digital transformation at high management level, while it is harder to perceive it as a topic discussed and implemented in daily operations. However, Company A seems to be more invested in the digitalization of the production plant, even if the practical applications are still at pilot and study phases confirming the existence of a delay between the actual digitalization process and the ideal one. Indeed, respondents from the studied companies highlighted that in several cases when they approach I4.0 tools and services the aim is to solve daily issues. The second gap can be defined as an "implementation gap" since there is a difference between the literature findings and the level of digitalization effectively applied in the studied companies.

It is evinced that implementation of I4.0 technologies could create synergies in enabling EnMPs, and it was seen in the studied companies that the most adopted technologies today are aimed at improving secure data collection, value extraction, representation of useful insights, and data sharing within the plant. Consequently, the improved areas of impact are Awareness, Connectivity and Integration, and Visualization This confirms findings seen also in the literature [9,92], where internal knowledge is improved with data and information gathering, monitoring, interpretation, modelling, and trends detection in near real-time; interconnection and enhanced communication between objects, equipment, machines, and workers in the factory also in real-time are enhanced [9,92,182]and representation of machines, physical systems, and processes, display of data and flows are improved [1,183].

When a group of practices is enabled, many of them are interconnected, and considering the synergies that arise can accelerate the transition towards leaner and smarter production. This approach not only fosters energy-related actions but also promotes greater awareness of energy management practices. In fact, given the enabling effect that I4.0 presents on EnM strategies, an interesting outcome of the validation process is the intercurrent circularity between the need to digitalize and to improve EE. Usually, due to the diverse optimization targets, digitalization is the starting point while improved EE is an outcome of the digital transition [41,43]. In some cases, EE enhancement is an expected result of the modernization process, but it is not the main driver for digitalization, except for manufacturing companies that use vast amounts of energy (e.g., steel sector) [163].

On the other hand, the need to implement enhanced energy-related data collection and analysis techniques in industries also drives more and less specific digitalization advances [127]. In general terms, investigated firms seem to have built company-wide digitalized infrastructures and consequently enhanced the availability of information about energy aspects, not accessible before [184]. Today, the increased interest regarding energy topics and the need to decrease consumption are between the main drivers to improve digitalization efforts, thus creating a circularity in the relation between driving and driven agents.

Here, it is also important to note that the alignment between AoIs and EnMPs can be influenced significantly by a company's maturity level in I4.0 technologies, as pointed out by [185] and by [13] on EnMPs. This was seen also in the studied companies. Companies at different stages of technological advancement and EM implementation may demonstrate varying degrees of integration between AoI and EnMPs. Those with a higher maturity level in I4.0 technologies are likely to possess more sophisticated tools and systems for collecting, analysing, and acting upon energy-related data [147]. This higher maturity level was seen in Company A, which has adopted a broader range of tools and focuses on advanced analytics, robotics, and simulation for optimizing both energy and logistics. Conversely, companies at lower maturity levels in I4.0 technologies may encounter barriers when attempting to harness technology-driven solutions to enhance their EM practices. This challenge could be more relevant for Small and Medium Enterprises (SMEs), as they inherently differ in organizational structure, resource allocation, and operational constraints when compared to larger industries [19].

Another important point to share that manufacturers often strive to improve operations output and energy use, and use the given solutions for EE, management, and reduced consumption purposes [153]. Although EE enhancement is a common side-effect of digitalization [186], it is not a primary driver [102,103]. Due to the numerous optimization targets, digitization is typically the starting point, with enhanced EE resulting from the transformation [187-189]. Anyway, EE and management are critical parts of smart and efficient manufacturing for firms. In fact, keeping track of energy usage has been vital in recent years, thus the need for more detailed data and employees' participation in the optimization process has become a driving force for further innovation, which can now lead to improved process control through data collection and analysis. To date, the increased interest in energy topics and the need to decrease consumption are between the main drivers to improve digitalization efforts, thus creating a circularity in the relation between driving and driven agents.

This research offers significant theoretical and practical implications for advancing EnMPs through I4.0 technologies in manufacturing. Theoretically, the study bridges a key gap by integrating EnMPs and I4.0 technologies, presenting a novel framework that links technological clusters (System, Infrastructure, Service, and Process) with energy management Areas of Impact. This framework contributes to understanding how digital technologies can drive energy efficiency and highlights the role of organizational digital maturity in shaping technology adoption. Additionally, the study emphasizes the circular relationship between digitalization and energy efficiency, providing a new perspective on industrial decarbonization and underlining the context-dependent nature of technology adoption across sectors.

Practically, the validated framework serves as a roadmap for industrial decision-makers, offering tailored strategies for leveraging I4.0 technologies like IoT, simulation tools, and AI to achieve energy efficiency. It supports companies in enhancing their sustainability efforts. The research also underscores the role of technologies like AR and VR in workforce training, fostering collaboration between humans and machines. With its adaptability across diverse industrial contexts, the framework offers scalable solutions for global manufacturers, empowering them to harmonize digital transformation with sustainability goals.

7. Conclusions and further research

Understanding how I4.0 technologies can synergise with EnMPs and identifying key areas of impact within SF is critical for achieving substantial EE improvements. To address this issue, a novel framework has been developed in this study to provide an assessment of how I4.0 technologies and EnMPs can be integrated effectively in the SF context. The study provides compelling evidence of the synergies between EnMPs and I4.0 technologies within the framework of SF. These synergies are especially pronounced in key areas such as awareness, connectivity, integration, and data visualization, each of which plays a crucial role in transforming energy management in industrial settings. However, the true significance of this study lies in its framework's ability to assess the impact of EnMPs specifically within the context of I4.0 technologies at the SF level. This capability is particularly critical in operational setting, where the interplay between advanced technologies and EnMPs can drive substantial improvements in energy efficiency and further support industrial decarbonization initiatives through effective digitization.

The ability to assess these impacts equips industrial decision-makers with the essential tools to make informed choices about technology adoption. By understanding how EnMPs can be integrated with I4.0 technologies, industrial decision-makers can identify strategies that not only enhance energy efficiency but also align with their decarbonization strategies. In fact, this study highlights the critical role that the integration of EnMPs and I4.0 technologies plays in facilitating meaningful progress towards decarbonization and sustainable practices in the manufacturing sector.

Despite the novel contribution, the study has three main limitations. First, the definition of the I4.0 attributes and of the AoIs in the smart factory is an attempt to categorize very wide. However, it is evident that while defining the attributes and cluster of I4.0 technologies, which are fast-changing concepts and continuously evolving. Besides, it should be emphasized that this developed clustering is not presented as a definitive but rather as a preliminary framework intended to frame how these attributes could be explored in relation to industrial applications. Thus, this study offers an initial but grounded attempt to structure the myriad dimensions of I4.0 in a way that is both scientifically informed and practically relevant for industrial transformation. Second, certain I4.0 technologies, such as augmented reality (AR) and additive manufacturing, were only partially explored due to their low adoption levels in the studied companies. This reflects a broader challenge in achieving comprehensive validation of the framework across all technological clusters and AoIs. And the final limitation constitutes of limited number of cross-examined companies, representing different manufacturing sectors and levels of digital maturity, and the specific geographical area in the validation phase, since not all the technologies are implemented and consequently validated. Hence, while this provides initial evidence of its applicability, the limited sample size restricts generalizability to other industries and geographic regions.

However, from the results and the main limitations, future research suggestions have emerged. First, broader validation of the framework is needed across a larger and more diverse sample of companies, including different industries and regions. This would enhance its robustness and provide a more comprehensive understanding of the contextual factors influencing technology adoption. Second, an analysis of the implementation barriers that lead to the presence of the “strategy” and “implementation” gaps is suggested to identify the causes that hinder the practical adoption of I4.0 tools and technologies in companies. Third, a study on how to overcome EnMPs barriers and strengthen drivers could lead to further interesting results about the effect of I4.0 on EM strategies. Such a study should include exploring the integration of underutilized I4.0 technologies, such as AR and additive manufacturing, into energy management practices Moreover, an analysis aimed at simultaneously tackling the implementational barriers that delay the adoption of EnMPs and I4.0 technologies could lead to further results on the digitalization process, the EnM aspects, and their reciprocal interactions. Besides, the most promising and adopted I4.0 technologies should be furtherly analyzed and investigated, to better understand the potential benefits and drawbacks that they could bring in the manufacturing context in terms of energy management, also in quantitative terms. Furthermore, form these analysis new insights regarding the direct connection between the technologies and the practices could be derived, which were just mentioned in the present research due to the width of the studied topics and considered technologies. Finally, we suggest research into the more recently defined term Industry 5.0 also involving the actual utilizers of the digital innovations.

CRediT authorship contribution statement

Enrico Cagno: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Davide Accordini:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patrik Thollander:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mariana Andrei:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **A S M Monjurul Hasan:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Formal analysis. **Sonia Pessina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Andrea Trianni:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, 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.

Acknowledgements

We would like to express our gratitude to the industry respondents for giving their time to answer our questions.

Appendix A

List of EnMPs considered in the study [3,11].

Type of practice	Energy Management Practices
Administrative	Energy cost allocation
	Energy demand budgeting
Financial	Acquisition/management of financing and incentives
	Adoption of energy performance contracting for energy-efficiency
Engineering	Energy efficient building/facility design
	Energy efficient product design
	Energy efficient system/process/equipment design
Informative	Internal communication regarding energy topics
	Marketing energy efficiency actions and results to external stakeholders
Management	Energy management position covered by an external consultant
Outsourcing	Outsourcing of engineering and project design
	Outsourcing of operation and maintenance activities
Performance	Identification of energy-efficiency opportunities
	Measurement of energy use
	Monitoring and evaluation of energy performance
Planning	Energy-aware production scheduling
	Maintenance planning
Procurement	Procurement of delivered energy through energy service contracts
	Optimize energy procurement based on energy data
Record	Documentation and record management regarding energy use
	Energy audit
Staff	Energy efficiency training for employees
	Definition of energy responsibilities
Technology & operation	Demand side management techniques
	Energy-efficiency based maintenance
	Energy recycling

Data availability

Data will be made available on request.

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