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Selecting sustainability indicators for smart product design based on industry 4.0/5.0 technologies: analysis and proposal of a methodological framework

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Abstract

Industry 4.0 deals with a digital revolution, integrating technologies like Virtual Reality, Augmented Reality, Digital Twin, and Robotics. This transformation unlocks opportunities in engineering, addressing sustainability challenges. Stakeholders use I4.0 technologies, including Industry 5.0, to measure sustainability indicators. This paper reviews I4.0 technologies for assessing sustainability, offering an SI framework in manufacturing and smart product design. Decision-makers can optimize environmental, social, and economic impacts in smart product design using this framework.

Keywords: sustainability, industry 4.0, smart products engineering, product design, circular economy

1. Introduction

The emerging concept of Industry 5.0 (I5.0) extends the boundaries of Industry 4.0 (I4.0) research, emphasizing three key pillars: resilience, sustainability, and the human aspect, aligning with the shift toward a circular economy (CE). CE aims to extend the life of products by exploiting end-of-life resources, reducing landfill waste, saving raw materials and limiting emissions (Rosa and Terzi, 2016; Ramirez-Peña et al., 2020). However, current production methods are unsustainable, causing environmental and societal harm throughout a product's life cycle. Adopting CE practices is essential for manufacturers to ensure marketplace competitiveness and achieve Sustainable Development (SD) goals (Gaha et al., 2013). To progress toward SD, measuring Sustainability Indicators (SI) is crucial, but choosing suitable indicators and determining measurement methods pose challenges for decision-makers (Andriankaja et al., 2015). Nevertheless, among the large variety of SI, which have been developed advanced by academics, companies, environmental agencies and governmental organizations (Jesinghaus, 2014) choosing the suitable ones, how measuring their performance, what level of sustainability should be considered and how to extract and structure the necessary measurement information becomes a major challenge for decision makers. The challenges in a dynamic environment of the fourth and fifth industrial revolutions include to manage a large amount of data, ensuring (cyber)security, to meet customer expectations for personalization and sustainability. Opportunities include creating smarter products, reducing costs, and enhancing operational efficiency through Internet of Things (IoT) and data analytics (Pereira Pessôa and Jauregui Becker, 2020). It should be noted that product development in the different design phases is important to identify the issues surrounding the use of associated I4.0 technologies, process, and methods. Technological evolution has seen the emergence since the mechatronic systems of the early 1960s, followed by the evolution of IoT and Cyber Physical Systems (CPS), towards a new evolution known as smart products or intelligent product (Guérineau et al., 2022). In this way, smart products can be adapted to better meet customer needs and constraints, thanks to the exchange of information and his adaptation of the context (Maass and Janzen, 2007). Understanding the development process of smart products is vital to limit their impact on environmental, societal, and economic aspects (Bricogne et al., 2016; Watz and Hallstedt, 2022). This article focuses on the design of smart products, emphasizing the integration of sustainability into product development processes. Hence, designers and manufacturers can benefit from the digital technologies within the I4.0, such as Virtual Reality (VR), Augmented Reality (AR), Digital twin (DT) or Robotics, which can be important enablers for industrial sustainability (Gaha et al., 2021; Mouflih et al., 2023). The Digital Thread (DTH) facilitates centralized data, information, and knowledge sharing, enabling a faster and cost-effective design process (Gaha et al., 2014; Marconnet et al., 2017; Pang et al., 2021). The main contribution of this article is therefore to determine the current state of considered SI for smart products in I4.0/I5.0, during these last ten years, and classify them in an organized, understandable, and usable manner and then develop a benchmark to track the most relevant data required for their measurements based on the I4.0 technologies. The proposed methodological framework aims to aid the selection of appropriate SI in smart product design, considering I4.0/I5.0 technologies and each stage of the product lifecycle. This approach facilitates data dissemination in the DTH, playing a crucial role in manufacturers' ecological transition.

2. Literature review methodology

To help designers, developing sustainable smart products within in industry 4.0/5.0, it's necessary to analyze related research. Therefore, we present a systematic literature review of trends and the various SI for the smart product (or intelligent product). Our main search engines being Google Scholar, Scopus, and ScienceDirect. However, due to limited commands on Google Scholar we consider only the databases Scopus and ScienceDirect. This choice is also based on the possibility to access papers. We started the literature review by collecting articles by searching on their titles, keywords and abstracts for keywords associated the three main themes (smart product, industry 4.0 (with I5.0) and sustainability indicators, see Figure 1). Then we proceeded by filtering based on three criteria: written in English; belongs to last ten years; availability restriction to full papers; and an in-depth investigation of the title, abstract, and full paper for relevance. The research methodology is based on the collect of data and metadata, identification of scientific articles and critical analysis of the field studied through a systemic procedure. From, the combination of the keywords of the three considered themes, we considered the four search strings (called S) that are shown in Figure 1.

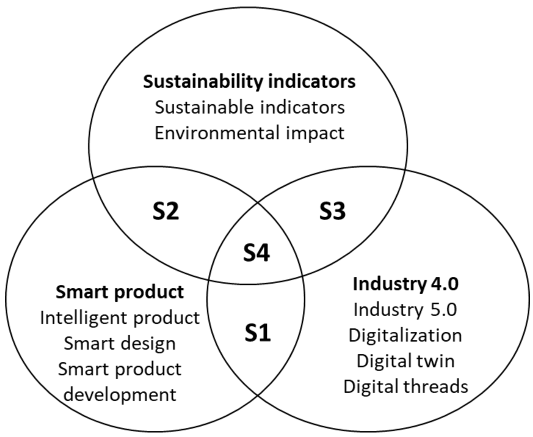

Figure 1. Selected keywords

3. Results and discussion

The results of our literature searches are summarized in Table 1. Filtering is based on reading the Title, Abstract or Keywords since 2013. Each search string has been categorized to represent the following

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keywords: S1 - Smart product and Industry 4.0, S2 - Smart product and Sustainability indicators, S3 - Sustainability indicators and Industry 4.0, S4 - Sustainability indicators of smart product and Industry 4.0. Therefore, to respond to our request, we obtained 33 articles.

Table 1. Search strings for each topic

Search strings	Topic	Results	After filtering results
S1: ("smart product" OR "intelligent product" OR "smart design" OR “smart product development”) AND ("industry 4.0" OR "industry 5.0" OR "digitalization" OR "digital twin" OR “digital threads”)	Smart product and Industry 4.0	137 (science direct) 332 (scopus)	**11 articles:** (Rauch et al., 2016; Nunes et al., 2017; Zheng et al., 2019; Romero et al., 2020; Zheng and Hong Lim, 2020; Boßlau, 2021; Cao et al., 2021; Sallati and Schützer, 2021; Carrera-Rivera et al., 2022; Ghobakhloo et al., 2022; Ehemann et al., 2023)
S2: ("smart product" OR "intelligent product" OR "smart design" OR “smart product development”) AND ("sustainability indicators" OR "sustainable indicators" OR "environmental impact")	Smart product and Sustainability indicators	11 (science direct) 26 (scopus)	**4 articles:** (Tchertchian and Millet, 2017; Liu et al., 2018; Riedelsheimer et al., 2020; Song et al., 2021)
S3: («sustainable indicators" OR "sustainability indicators") AND ("industry 4.0" OR "industry 5.0" OR "digitalization" OR "digital twin" OR “digital threads”)	Sustainability indicators and Industry 4.0	21 (science direct) 54 (scopus)	**12 articles:** (Joung et al., 2013; Chaim et al., 2018; Ndukwu et al., 2020; Enyoghasi and Badurdeen, 2021; Glatt et al., 2021; Gunduz et al., 2021; Kabzhassarova et al., 2021; Orošnjak et al., 2021; Riedelsheimer et al., 2021; Cetina-Quiñones et al., 2023; Contini et al., 2023; Longo et al., 2023; Ross et al., 2023)
S4: ("smart product" OR "intelligent product" OR "smart design") AND ("sustainability" OR "sustainable indicators" OR "environmental impact") AND ("industry 4.0" OR "digitalization" OR "digital twin" OR “digital threads”)	Sustainability indicators of smart product and Industry 4.0	19 (science direct) 23 (scopus)	**6 articles:** (Hallstedt et al., 2020; Lenz et al., 2020; Liu et al., 2020; Fraga-Lamas et al., 2021; Ghobakhloo et al., 2022; Popolo et al., 2022)

3.1. S1 - Smart product and Industry 4.0

Manufacturing companies, faced with rapid change, need to rethink their traditional business models for integrated Industry 4.0 (I4.0) solutions, essential to overcome the difficulties of analysis and innovation without holistic approaches (Boßlau, 2021). The development of smart products, which participate in decision-making and interact with information systems, aligns with the servitization of Smart Product-Service Systems (S-PSS or Smart PSS), with two objectives: to assess the impact of 4.0 technologies on business performance and to achieve Circular Economy (CE) goals objectives (Zheng et al., 2019). (Romero et al., 2020) highlight the fundamental issues in establishing a lifecycle management environment for Cyber-Physical Systems (CPS) and the benefits of using intelligent digital models, product avatars and digital shadows via the Digital Twin (DT), to integrate the DT concept and its applications into Product Lifecycle Management (PLM) and Digital Thread (DTH). Collaboration between stakeholders in the product lifecycle is essential for effective use of digital data and informed decision-making. Technological tools such as Augmented/Virtual Reality (AR/VR) are discussed for Smart Product Development (SPD) (Nunes et al., 2017). The transition from Lean Product Development (LPD) to SPD in Industry 4.0 focuses on reducing waste and integrating Industry 4.0 technologies for value-added activities. Collaboration management is vital to harnessing 4.0 technologies in detailed product design, knowledge management, risk management, digitization of data exchange, modeling and accelerating time-to-market, improving efficiency and speed in product development (Rauch et al.,

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2016). Industry 5.0, building on the technological foundations of Industry 4.0, focuses on resilience, environmental sustainability, and human centricity (Ghobakhloo et al., 2022). Smart product design in this evolution must prioritize user-centered design, considering user context in S-PSS design to enhance user experience and meet personalized and sustainable needs (Carrera-Rivera et al., 2022).

3.2. S2 - Smart product and sustainability indicators

The design phase is crucial to the sustainability of a smart product. Measuring and understanding deviations and impacts during this process is essential. According to (Song et al., 2021), ten criteria have been established to assess the sustainability of a Smart Product-Service Systems (S-PSS or Smart PSS), throughout its life cycle, encompassing economic, environmental, and social aspects. These criteria include "Total Cost for Smart PSS", "Reliability" aimed at improving the sustainability of product systems, improving "Ability to deliver services", and "Interactive Personalization" enabling tailor-made design of products and services. These criteria underline the importance of intelligent products and how their data can generate value-added services for the end-user. The concept of the digital twin (DT) is introduced, illustrating its role in collecting, managing and analyzing data from individual products across their lifecycles, using sustainability indicators. (Riedelsheimer et al., 2021) and (Tchertchian and Millet, 2017) discuss development methodologies for product systems and sustainability criteria for connected products. These criteria facilitate the verification and testing of energy savings, thanks to an optimization service that improves energy efficiency based on recommendations from users and operators. (Liu et al., 2018) discuss value co-creation and Smart PSS, presenting a structural model for Smart PSS, covering three business models: platform-oriented, use-oriented, and result-oriented. The authors analyze value dimensions, co-creation opportunities and the process of developing high-performance smart products. The Sustainability Indicators (SI) used are associated with the value dimensions for Smart PSS, including suitability, efficiency, maintainability, portability, ease of use, etc. In conclusion, collaboration between companies and consumers is important for the development of smart products that meet customer needs and create added value. The use of SI to measure and understand the progress of intelligent product development based on I4.0 technologies is therefore essential.

3.3. S3 - Sustainability indicators and Industry 4.0

In recent literature, "Sustainability Indicators" or "Sustainable Indicators" are frequently highlighted, marking the need to propose frameworks, tools, or methodologies for assessing product sustainability. Many studies focus on one or more of these indicators, such as CO2 emissions, recycling, and energy consumption, based on data collected via DTH at each stage of the life cycle, which can be static or dynamic. The assessment leverages technologies such as Big Data Analytics (BDA), Cloud Technology (CT), VR/AR, Artificial Intelligence (AI), Horizontal and Vertical System Integration, IoT, and Additive Manufacturing (AM) for sustainable manufacturing based on the 6Rs: Reduce, Recover, Reuse, Redesign, Remanufacture, Recycle (Enyoghasi and Badurdeen, 2021). This section focuses exclusively on sustainability indicators (SI), selecting papers that explicitly express these indicators. (Riedelsheimer et al., 2021) developed the DT-V model, including data from the planning, production, operation, and end-of-life phases of IoT-based products to monitor and optimize energy efficiency. Almost all the selected articles consider more than one sustainability indicator, with sustainability integration ranging from one life-cycle stage based on one indicator to multiple criteria in several stages. Researchers such as (Contini et al., 2023) have developed a "digital sustainability twin" to monitor sustainability in the ceramics industry, enabling informed decisions based on Key Performance Indicators (KPI). (Kabzhassarova et al., 2021) developed a checklist that identifies economic, environmental, and social indicators during production, highlighting the importance of technological integration for a sustainable, digitized enterprise. The supply chain represents an important field of research, including studies such as (Longo et al., 2023), who develop supply chain sustainability criteria based on DTH data. (Ross et al., 2023) exploit also machine learning to assess carbon emissions and other sustainability indicators in the machining process. In summary, the literature highlights the crucial importance of sustainability indicators and the integration of Industry 4.0 technologies to assess and improve the sustainability of products at every stage of their life cycle.

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3.4. S4 - Sustainability indicators of smart product and Industry 4.0

Smart products offer significant benefits, not least using their data to provide value-added services to end-users. The introduction of the digital twin (DT) concept is revolutionizing the collection, management, and analysis of data from individual products throughout their lifecycle. In Industry 5.0, these sustainability-focused products are referred to as Circular Intelligent Products (CIP), designed to minimize environmental impact over their entire lifecycle (Fraga-Lamas et al., 2021). Industry 5.0 technologies facilitate the design of CIPs, aiming to eliminate waste, pollution, and emissions, while extending their productive service life (Lenz et al., 2020). According to (Ghobakhloo et al., 2022), CIP can monitor and communicate their environmental footprint throughout their lifecycle, contributing to sustainability guided by Industry 5.0. This approach highlights environmental indicators such as waste reduction, energy consumption and emissions, while promoting social development, employment, equality and human agency as social indicators, and economic gains as an economic indicator. Smart products are closely linked to Industry 4.0 technologies, particularly in data exchange or transfer. (Popolo et al., 2022) point out that Industry 4.0 technologies offer interesting opportunities to address the sustainability challenges of smart products, by reducing operational costs, waste in value creation activities, promoting the use of cleaner energy and material resources, and improving working conditions and customer experience. They propose the integration of these technologies to apply aspects of sustainability when developing intelligent products, introducing the concept of "Product 4.0 (P4.0)" capable of monitoring and tracking its components for greater sustainability (repairability, waste reduction, recyclability, etc.). It is therefore crucial to integrate smart product development into product design and engineering to meet market requirements and guarantee product quality. (Hallstedt et al., 2020) carry out a literature review combining digitalization, sustainability and servitization, establishing links between these three themes. (Liu et al., 2020) develop fifteen sustainability assessment criteria for Smart PSS, covering economic, environmental, and social criteria.

4. Framework for selecting Key Sustainability Indicators while designing sustainable smart products in Industry 4.0/5.0

The migration from developing smart products to sustainable smart products based on sustainability indicators (Social, Environmental and Economic) that need be measured by Technologies of I4.0 presents a challenge, within the I5.0 which is an extension of the digital industrial revolution (I4.0), (Costa, 2024). In this paper, to help designers (mechanical, electronics and software designers) to eco-design their products, we propose a new eco-design framework for the development of smart products based on SI measured by technologies of industry 4.0/5.0. From the literature review we identified sustainable indicators (called Key Sustainability Indicators - KSI), as shown in Table 2, that can be considered at each eco-design stage and emphasized their importance. Moreover, we extracted the I4.0/50. technologies that can be used at each design stage, throughout its life cycle, to collect necessary data for measuring KSI. The proposed framework aims to show the feasibility of using these technologies to accompany designers in the development of smart sustainable products from the product definition phase to the detailed design phase based on the adequate KSI. This eco-design framework, which is iterative, is composed of the four stages, as shown in Figure 2:

- The first stage (I. Smart product design phase) initiates the collaborative design process within the Engineering Design Process, from mechanical, mechatronics and software sides, detailing the phases of product definition, conceptual framework mapping, embodiment design and detailed design refinement. It encompasses the definition of requirements, functionalities, and objectives, with an emphasis on strategic planning and functional diagrams. The conceptual phase transforms vague notions into concrete ideas, crucial for innovation. The embodiment phase coordinates efforts to turn the idea into an intelligent system, while the detailed design phase refines specifications for components and assemblies;
- The second stage (II. Sustainability framework), involves four sub-steps to identify the relevant indicators in the design phases. This stage comprises four essential sub-steps: (1) definition of the product life cycle, (2) identification of possible 4.0/5.0 industrial technologies, (3) integration of relevant regulations (and standards), and (4) selection of KSI to be measured. At

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each design stage, it is important to define possible I4.0/I5.0 technologies (e.g. Additive Manufacturing (AM), IoT, AI, Cobot/Robot (Automation), Cloud Technology (CT), Big Data Analytics (BDA), etc.), and considered regulations that can be used at each life cycle stage (Raw Material, Production, Use, Transport, and End of Life) to select the suitable KSI in the design context;

- The third stage (III. Assessment of Key Sustainability Indicators) proposes the assessment of the selected indicators on the product under development. The sub-steps involve (5) analysis and calculation of the KSIs, and (6) prioritization of these indicators to integrate the results into the product design. Depending on the results of the assessment, the designer may then consider it necessary to update the design with the selected KSI;
- The fourth stage (IV. Finished product), is the culmination of the process with (7) the sustainable design of the finished product, which integrates all the previous steps to produce a smart product that meets sustainability and functionality objectives.

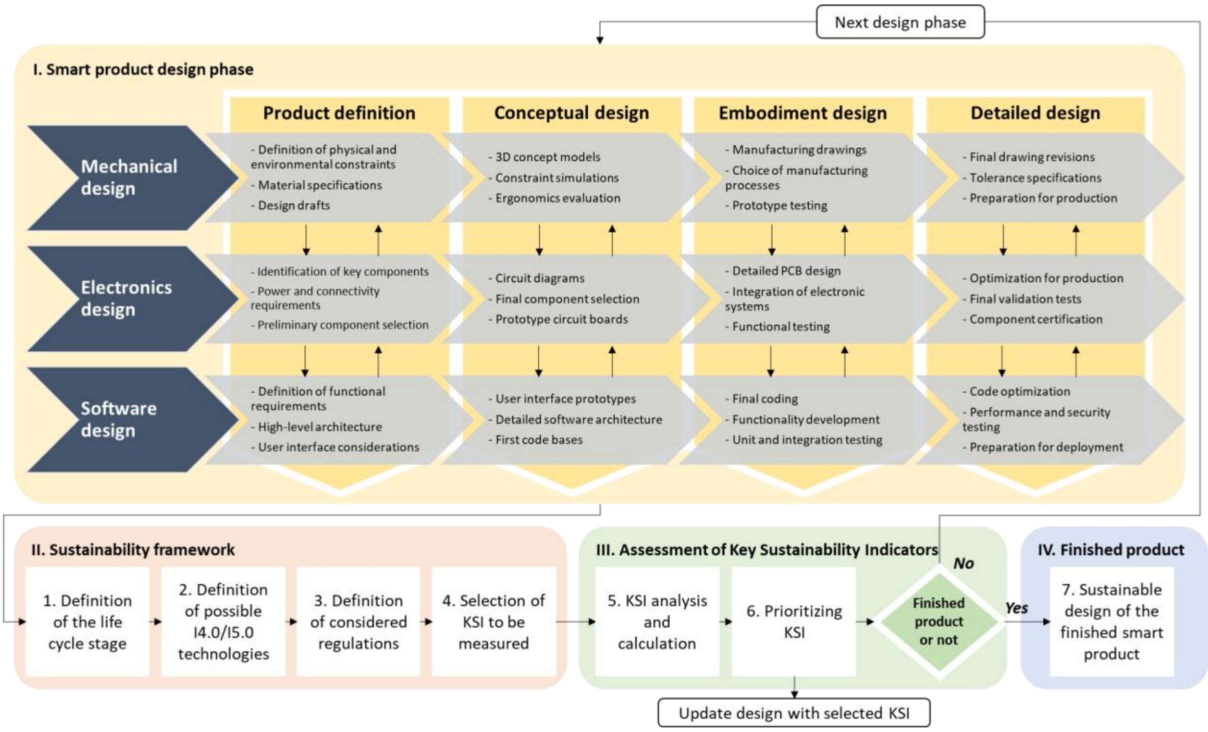

Figure 2. Framework for designing sustainable smart product within Industry 4.0/5.0

In line with the framework presented above. The Table 2 represents the latter's decision stages, where it correlates design phases, life cycle stages, Industry 4.0/5.0 technologies and sustainability indicators, while specifying relevant standards and regulations. For each phase and stage intersection, it identifies the adequate technologies to use and the corresponding KSI, justifying their selection to ensure the smooth integration of sustainability throughout product development. We present here an iteration of our framework for the "Conceptual design" phase, more specifically for the "Use" stage. The Internet of Things (IoT) and the Digital Twin (DT) are used to refine the "Benefits and Losses" and "Use and Energy Efficiency" sustainability indicators. The IoT plays a key role in real-time monitoring of energy efficiency, while the DT provides a platform for testing and improving user interaction with the product in a simulated environment. This approach is aligned with ENERGY STAR (a program known as a label that reduces energy consumption) and EPEAT (Electronic Product Environmental Assessment Tool is an eco-label that enables the consumer to assess the effect of a computer product on the environment), reflecting an ambition to reduce the energy footprint and increase added value for the user, in line with sustainability objectives. These advanced technologies support a design that not only complies with the most demanding energy standards, but also promotes intuitive and efficient user interaction, in line with industry best practice and market expectations.

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Table 2. Relationship between design stages, lifecycle stages, 4.0/5.0 technologies, regulations and Key Sustainability Indicators for the sustainable development of smart products

Design stages	Lifecycle stages	4.0/5.0 Technologies	Regulations & standards	Key Sustainability Indicators	References
Product definition	Raw Material	AI, IoT	ISO 14001, ISO 26000	Material Use and Efficiency, Suitability	Wee *et al.*, 2015; Stock and Seliger, 2016, Kamble *et al.*, 2018; Liu *et al.*, 2018
	Production	CPS, AM	ISO 9001, ISO/TS 16949	Reliability, Maintainability	Liu *et al.*, 2018
	Use	IoT, DT	ENERGY STAR, EPEAT	Energy Use and Efficiency, Usability, Interactive customization, The ability to provide services	Zhang *et al.*, 2012; Valencia *et al.*, 2015; Wee *et al.*, 2015; Stock and Seliger, 2016; Kamble *et al.*, 2018
	Transport	CT, BDA	Euro 6, Clean Air Act	Direct/Indirect Costs, Portability	Song and Moon, 2017; Liu *et al.*, 2018; Nascimento *et al.*, 2019
	End Of Life	VR/AR, Automation	WEEE, RoHS	Product EOL, Product EOL Management	Song and Moon, 2017; Frank *et al.*, 2019; Nascimento *et al.*, 2019; Rajput and Singh, 2019
Conceptual design	Raw Material	AI, IoT	ISO 14001, ISO 26000	Initial Investment, Material Use and Efficiency	Wee *et al.*, 2015; Stock and Seliger, 2016; Kamble *et al.*, 2018
	Production	CPS, AM	ISO 9001, ISO/TS 16949	Direct/Indirect Costs, Reliability, Maintainability	Kim *et al.*, 2013; Song and Moon, 2017; Liu *et al.*, 2018; Nascimento *et al.*, 2019
	Use	IoT, DT	ENERGY STAR, EPEAT	Benefit and Losses, Energy Use and Efficiency, Usability	Wee *et al.*, 2015; Stock and Seliger, 2016; Kamble *et al.*, 2018; Tao *et al.*, 2018; Liu *et al.*, 2018
	Transport	CT, BDA	Euro 6, Clean Air Act	Total Cost for Smart Product, Portability, Community Feeling	Dreyer *et al.*, 2006; Valencia *et al.*, 2015; Liu *et al.*, 2018;
	End Of Life	VR/AR, Automation	WEEE, RoHS	Product EOL Management, Waste and Emissions, Security	Kim *et al.*, 2013; Song and Moon, 2017; Frank *et al.*, 2019; Nascimento *et al.*, 2019; Rajput and Singh, 2019
Embodiment design	Raw Material	AI, IoT	ISO 14001, ISO 26000	Compatibility, Suitability	Liu *et al.*, 2018
	Production	CPS, AM	ISO 9001, ISO/TS 16949	Reliability, Maintainability, Functional Performance	MacArthur and Waughray, 2016; Liu *et al.*, 2018; Frank *et al.*, 2019;
	Use	IoT, DT	ENERGY STAR, EPEAT	Usability, Community Feeling, Ease to Use, Digital controlling and smartness	Kim *et al.*, 2013; Valencia *et al.*, 2015; Liu *et al.*, 2018
	Transport	CT, BDA	Euro 6, Clean Air Act	Portability, Total Cost for Smart Product	Dreyer *et al.*, 2006; Liu *et al.*, 2018
	End Of Life	VR/AR, Automation	WEEE, RoHS	Product EOL, Waste and Emissions, Safety and Health Impact	Kim *et al.*, 2013; Frank *et al.*, 2019; Rajput and Singh, 2019
Detailed design	Raw Material	AI, BDA	ISO 14001, ISO 27001, GRPD	Material Use and Efficiency, Security	Wee *et al.*, 2015; Stock and Seliger, 2016; Kamble *et al.*, 2018; Liu *et al.*, 2018
	Production	CPS, AM	ISO 9001, ISO/TS 16949	Direct/Indirect Costs, Maintainability, Product Quality and Durability	Wang *et al.*, 2016; Song and Moon, 2017; Liu *et al.*, 2018; Frank *et al.*, 2019; Nascimento *et al.*, 2019
	Use	IoT, CPS	ENERGY STAR, EPEAT	Energy Use and Efficiency, Functional Performance, Ease to Use	Kim *et al.*, 2013; Wee *et al.*, 2015; MacArthur and Waughray, 2016; Stock and Seliger, 2016; Kamble *et al.*, 2018; Frank *et al.*, 2019
	Transport	CT, IoT	Euro 6, Clean Air Act	Total Cost for Smart Product, Portability	Dreyer *et al.*, 2006; Liu *et al.*, 2018
	End Of Life	Automation, AI	WEEE, RoHS	Waste and Emissions, Product EOL Management	Kim *et al.*, 2013; Song and Moon, 2017; Frank *et al.*, 2019; Nascimento *et al.*, 2019; Rajput and Singh, 2019

5. Conclusions and future work

Systematic literature analysis enables us to identify SI in Industry 4.0/5.0 for the development of smart products. A categorization of SI according to design stages has been proposed to identify relevant indicators (KSI) at each design stage and to find out the impacts on 4.0/5.0 technologies and major stages of the product life cycle. To summarize this work, it's necessary to understand that, in view of the literature analyses, there is no framework proposing SI as a function of the design phase. SI are impacted by the choice of life-cycle stage and 4.0/5.0 technology involving long and complex decisions, where the company's objective is to reduce the time-to-market of smart products, respecting product quality and sustainable over time, while being adapted to the market. The framework in question helps the designer to make decisions to adapt or even redesign the product. An interesting approach is also to propose a decision matrix to help the designer select the appropriate indicators to prioritize them in the design phases. It would be interesting to integrate these indicators into an information system (e.g. PLM) to automate the search for and use of relevant measures in design with existing computer-aided design (CAD) tools. The aim would be to proactively combine the use of indicators with Life Cycle Assessment (LCA) tools and CAD tools, to identify the appropriate design context and disseminate the relevant measurements, or even disseminate them through the DTH.

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