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A human-centric methodology for the co-evolution of operators' skills, digital tools and user interfaces to support the Operator 4.0

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ABSTRACT

The concept of Operator 4.0 has been recently defined to evolve the modern industrial scenarios by defining a knowledge sharing process from/to operators and industrial systems, creating personalized skills, and introducing digital tools towards socially sustainable factories. In this context, dynamic and adaptive user interfaces can make humans part of the intelligent factory system, supporting human work contextually and providing specific contents when needed, preserving the human wellbeing. This paper defines a human-centric methodology for the symbiotic co-evolution of operators' skills, assistive digital tools and user interfaces, developed within the Horizon Europe project titled "DaCapo - Digital assets and tools for Circular value chains and manufacturing products". The project focuses on defining a new set of human-centric digital tools and services for the manufacturing industry capable of boosting the application of circular economy (CE) throughout the manufacturing value chains. The proposed methodology can link the specific needs of an industrial case to the definition of the most proper assistive digital tools and functionalities to drive the design of adaptive, proactive user interfaces for the Operator 4.0. The method has been applied and validated on one of the project use cases, involving a manufacturing company operating in warehousing and logistics.

1. Introduction

In the constantly evolving landscape of Industry 4.0 (I4.0) [1], operators face new challenges, reflecting the profound transformations brought about by the integration of advanced technologies, such as Augmented Reality (AR), Internet of Things (IoT) and Big Data, and the new challenges brought by Artificial Intelligence (AI). The introduction of these key-enabling technologies [2] has drastically changed the way of work and raised challenges in terms of compatibility and the overall integration into existing systems. Moreover, the advent of novel sophisticated technologies has not only increased the number of on-board machinery sensors but has also exponentially expanded the volume of data to be visualized and monitored [3]. Consequently, the functionalities of machines and systems themselves have grown, leading to an increased complexity in human-machine interaction. This aspect led to a heightened cognitive workload for modern operators [4], who are called to manage and interpret vast amounts of information in real-time and make strategic decisions rapidly [5]. In this scenario, Human-Machine Interfaces (HMI) has a crucial role for the effective implementation of I4.0 principles, underlining the critical importance of HMI design to enhance the overall user experience (UX) [6,7]. For these purposes, design methodologies able to address the above-mentioned challenges are welcome, promoting themes such as human-centric design, resilience, and sustainability included in the so-called Industry 5.0 (I5.0) trend [8]. The introduction of I5.0 shifts focus away from solely prioritizing digitalization and AI-driven technologies to emphasize social fairness, sustainability, and the enduring contribution to humanity within the limits of our planet [9]. In fact, compared to automation, humans bring irreplaceable and unique qualities to modern smart manufacturing systems, such as creativity, dexterity, cognition, and decision-making abilities. Human workers can form versatile partnerships with machines and technologies, resulting in higher productivity than either manual work or automation alone in various manufacturing tasks, including inspections, diagnosis, assembly, maintenance, and logistics [10]. Responding to this demand, the proposed ideal symbiotic work system integrates H—CPS and adaptive automation, aiming to foster a socially sustainable manufacturing workforce, identified as Operator 4.0 (O4.0) [11] and Operator 5.0 (O5.0) [12]. Thus, O4.0 and

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O5.0 represent the current revolutions in operator-oriented paradigms [13].

Alongside these concepts, a Circular Economy (CE) is an eco-friendly model that emphasizes resource recycling, aiming to minimize extraction, maximize utilization, and reduce emissions. However, modern companies face significant challenges in efficiently dismantling large volumes of waste products and in the sustainable use of materials and energy during the manufacturing process [14]. In this context, CE principles play a pivotal role in defining the modern operator competencies and skills, necessary to promote a closed-loop approach to resource management [15]. Digital tools can validly support this process: they facilitate the monitoring and optimization of material flows, enabling operators to implement circular strategies and improve their knowledge on specific topics [16,17]. However, the state of the art in CE research highlighted that current research trends are based on the analysis of sustainability issues or lifecycle assessment. Rare studies have been found including human factors in the CE landscape, mostly focused on competence creation and training, and not oriented to system design [18,19].

At the same time, the concept of Adaptive Automation (AA) modifies the allocation and interaction of functions between humans and machines, unlike traditional static systems where the Level Of Automation (LOA) remains constant. In AA, tasks dynamically shift between humans and machines based on system conditions, performance, and human attributes, adjusting the LOA to suit contextual needs. This dynamic allocation requires careful system design. While AA is well-established in fields like aeronautics, automotive, and aviation, its application in manufacturing is still limited, though research and test cases are emerging [20]. A key design element of AA systems are certainly Adaptive HMIs, that can be used to validly support operators' activities in an efficient and low intrusive way, as demonstrated by recent literature [21]. Adaptive HMIs are advanced user interfaces that are specifically developed to continuously adapt and optimize their display and functionality according to the specific needs, preferences, and executed tasks [22]. By incorporating real-time data from sensors and production systems, these interfaces can dynamically personalize the interface for operators. In an industrial setting, these HMIs are AI-driven to elevate the quality of the human-machine interaction [23]. This adaptability greatly improves the overall usability, efficiency, and safety for operators by providing them with timely and relevant information and tools tailored to the ever-changing demands of the production environment [24].

The research aims to introduce the analysis of human factors and human-machine interaction in designing complex systems within the realm of CE. This area has been relatively under-studied, highlighting a gap in the existing body of knowledge. Therefore, this study aims to bridge the emerging gap resulting from the lack of integration of human factors within the design process related to sustainability and design for CE. The main objective is the definition and application of a methodological design framework able to integrate all aspects related to sustainability, digitalization, and their application in industrial contexts and manufacturing, focusing of human interaction with industrial systems.

The research uses advanced digital tools, like adaptive HMIs, to promote the human-machine knowledge sharing and evolution towards the realization of socially sustainable factories. However, the main challenge is how to select the best technologies according to the human-system interaction requirements, as well as the most suitable HMI functionalities and adaptivity behaviours based in the user and CE requirements. For this purpose, a human-centric methodology is defined to provide design guidelines and successfully select the most proper digital tools supporting the Operator 4.0, placing humans at the center of the digitalization processes, and not starting from the technology capabilities as implemented in literature so far. Indeed, a human-centric approach ensures that the ethical considerations of sustainable practices and circular economy principles are upheld, aligning technological advancements with societal values [25]. Moreover, enhancing the operators' skills through dedicated training programs and adaptive interfaces will foster a seamless integration of technology, making the transition to I5.0 more intuitive and valuable [26]. As a result, operators and organizations alike enhance their resilience, adapting swiftly to dynamic changes, and maintaining a consistently high level of efficiency in pursuit of objectives.

The paper is structured as follow: in Section 2 is presented the literature background about the use of digital tools in the context of CE and the matrix-based methodology, in Section 3 are shown the equation and calculations for the methodology application, in Section 4 is described the DaCapo use case in logistics and in Section 5 are reported the main results followed by a critical discussion.

2. Material and methods

2.1. System design in the context of the circular economy

The concept of CE has radically transformed traditional linear production models into regenerative systems, ensuring that resources are continually reused and revitalized, thereby minimizing the ecological footprint of industrial processes. The integration of circular economy principles into the design process represents a fundamental change in sustainable resource management and environmental protection. Additionally, it allows the achievement of sustainable development goals and promotes a more resilient and resource-efficient economy.

The current state of the art in sustainability largely revolves around the concepts of circular economy, understood as life cycle assessment (LCA), primarily focusing on environmental considerations [27,28]. However, a critical aspect often overlooked is the integration of human factors into sustainability frameworks [29]. While CE and LCA methodologies are largely adopted for evaluating environmental impacts and resource efficiency, they often neglect the intricate interaction between human behavior, social needs, and the built environment [30]. Sustainable design must transcend the environmental focus and incorporate a holistic approach that considers social, cultural, and economic dimensions alongside environmental aspects [31]. By integrating human factors into sustainability-oriented design, designers can better address issues such as user behavior, accessibility, equity, and cultural relevance, ensuring that solutions are not only environmentally friendly but also socially just and inclusive [32]. This broader perspective is essential for advancing sustainable development agendas and creating truly resilient and equitable societies. Therefore, the integration of human factors is crucial to complement and enrich existing sustainability paradigms, facilitating the transition towards more holistic and impactful design solutions. The advent of Human-Cyber-Physical System (HCPS) is central to human-centric manufacturing and has become integral to sustainability efforts in smart factories. HCPS enhances human capabilities with automation and boosts manufacturing system intelligence through human decision-making, enabling flexible human-robot collaboration in manufacturing [33].

From the literature analysis, it emerged that no one has succeeded in this endeavor. Pinzone et al. [34] have proposed general guidelines for CPS-enabled services that consider human factors within the design process and recognized the key-role the of technologies in the context of I4.0 and sustainable design. With a similar goal, Villani et al. proposed an approach for the design of adaptive human-centered HMIs for industrial machines and robots, based on the measurement of user's capabilities and exploiting the potential of adaptive HMIs, but focusing mainly on the creation of an inclusive and flexible working scenario environment [32]. The aim of this paper is therefore to integrate all these factors, to fill the identified gaps and present a design methodology capable of providing designers with a digital tool assisting them in the design process of novel HMIs in the CE context.

2.2. The use of digital tools in the context of circular economy: the DaCapo project

In the contemporary industrial landscape, the convergence of sustainability, CE principles, and digitalization has become imperative for fostering a resilient and eco-friendly future. In product design, including digital products, it is essential to consider aspects related to sustainability, such as reuse, recycling, and recovery [35]. The primary focus is on environmental sustainability and the correlation between interactive technologies and responsible resource utilization. This encompasses examining how interactive technologies can be employed to promote more sustainable behaviors and evaluating environmental sustainability as a whole [36].

From the analysis of the current literature, the emergence of a symbiotic co-evolution of the operators' skills, digital tools, and user interfaces is demanding for supporting the everyday work of modern operators, who largely interact with different systems where interaction is characterized by high complexity and strategic decision making. However, even though a large variety of digital tools and novel technologies is available on the market (e.g., smartphones, tablets, smart glasses, smart bracelets/watches) [36], their selection is not easy due to difficulties in understanding the impact on human work [37]. Qasim et al. underline the change in perception of user interfaces introduced by hand-held devices that deep impact the operator expectations and experience with industrial HMIs [38].

As a consequence, a tool capable of guiding designers and companies in selecting the most suitable technologies and designing the main HMI features has become apparent. The identified emerging gap is the lack of a methodology that assists designers in specifically identifying the most suitable technology for each situation and corporate context.

In this direction, the Horizon Europe DaCapo project (G.A. 101091780) [39] focuses in defining a new set of digital tools for the manufacturing industry capable of boosting the application of CE principles at different phases throughout the manufacturing value chains, enhancing the circularity of industrial processes and products [40]. These tools and services, focused on the introduction of new digital assets, AI-based systems and the application of process and product digital twins, can substantially improve the sustainability and efficiency of imported and critical raw materials in manufacturing. The project aims to address the technical challenges that CE adoption imposes on manufacturing value chains and overcome market barriers, such as the workforce skill shortage regarding the adoption of new advanced digital tools and services, and the lack of awareness, trustworthiness and risk-aversion of end users to new digital technologies adoption.

The backbone of the DaCapo project is the development of an agile methodological approach supporting the decision-making accounting business models, material flows, relevant indicators, and data-sharing circular strategies. In particular, one of the main objectives of the DaCapo project is the definition and development of a methodology for the symbiotic co-evolution of digital tools, operators' skills and multi-level user interfaces to support circular economy in manufacturing value chains, based on the concept of the human-automation symbiosis [41].

The project DaCapo demonstrates its commercial and replicability potential on high-impact applications in critical European manufacturing sectors: aeronautics, consumer electronics, and warehousing (logistics, including construction). This research considers one of the project use cases, including a large company that delivers cutting-edge solutions for logistics of manufacturing facilities in pulp and paper, metal, and tire industries.

2.3. The research approach and methodology

By following a UX design approach, the paper defines a new methodology for the co-evolution of digital tools, operators' skills and interfaces and designs proactive, adaptive Human-Machine Interfaces (HMIs) for the project use cases. The UX design approach consists of including user experience analysis in every design stage, from the user research to the design and the prototyping of the solution, until the evaluation with users [42].

The proposed methodology, developed in the framework of the DaCapo project, was applied to a specific DaCapo use case concerning automatic warehouse management and maintenance. The proposed method is based on a set of correlation matrices that moves from the Sustainability and Circular Economy objectives and the users' skills necessary to achieve them to define the best digital tool functionalities and HMI typologies to support users in different industrial scenarios.

This methodology draws inspiration from the House of Quality according to Quality Function Deployment (QFD) approach [43]. The House of Quality is a matrix-based instrument that plays a vital role in the QFD process by establishing a clear connection between customer requirements and engineering characteristics. This enables effective communication and collaboration across different teams and departments. Similarly, the aim of the developed methodology is to support the definition of the most proper digital tools (HMIs and interaction devices) supporting humans in the project use case and the identification of the necessary skills to be trained to define ad-hoc training programs accordingly.

At the beginning, the specific use case must be investigated by several UX techniques aiming at defining the design requirements, namely questionnaires and focus groups. Questionnaires are administered to inquire about the specific users involved in the use case, the tasks assigned to them and the context of interaction. Focus groups [44] are useful to gain deeper insights into the processes involved, findings from which will be expounded upon in subsequent phases. They involve the main expert of the company for the considered use case, with different background and vision, to fully describe the interaction process. Focus groups can be carried out physically or remotely. After that, a description of the target user and the context of interaction are defined respectively by personas [45] and scenarios [46]. Adding subjective evaluation at the start of the methodology emphasizes its flexibility, designed to fit various case studies and application domains. This method allows for gathering feedback and requirements from staff within the organization, ensuring a detailed understanding of their specific needs and preferences. By actively seeking input from those involved in the operational context, the methodology aims to create a collaborative environment for developing customized solutions that meet the needs of end users and align with organizational goals. At this point, the proposed methodology can be adopted to elicit the digital tools' design requirements. Such methodology is composed by three main steps, using a set of five matrices:

1. Definition of the Digital Tools Functionalities (DTFs): it consists of the selection of the most proper functions of the HMI to train and upskill (or reskill) the workforce in an industrial context. To achieve this result, two different matrices are used, namely M1a and M1b. The former correlates the Sustainability and Circular Economy objectives (S&CE objs) given by a specific company with the required User Skills (USs) considered as the target, the latter correlates these USs with a list of most common functionalities to include in digital user interfaces;
2. Definition of the HMI typologies (HMITs): it consists of the selection of the most proper types of digital HMI using two matrices, namely M2a and M2b. M2a relates the Interaction Requirements (IRs) of the specific considered scenario with the most common modes of interaction called Digital Tools Interaction Modes (DTIMs), while M2b correlates the DTIMs with a list of HMI typologies (HMITs) in order to understand which fits the initial requirements.
3. Definition of the HMI adaptive behaviours (HMIABs): it consists of the identification of the most proper adaptive behaviours starting from the availability of the various type of data in the specific context (ATDs) and a list of common adaptive behaviours.

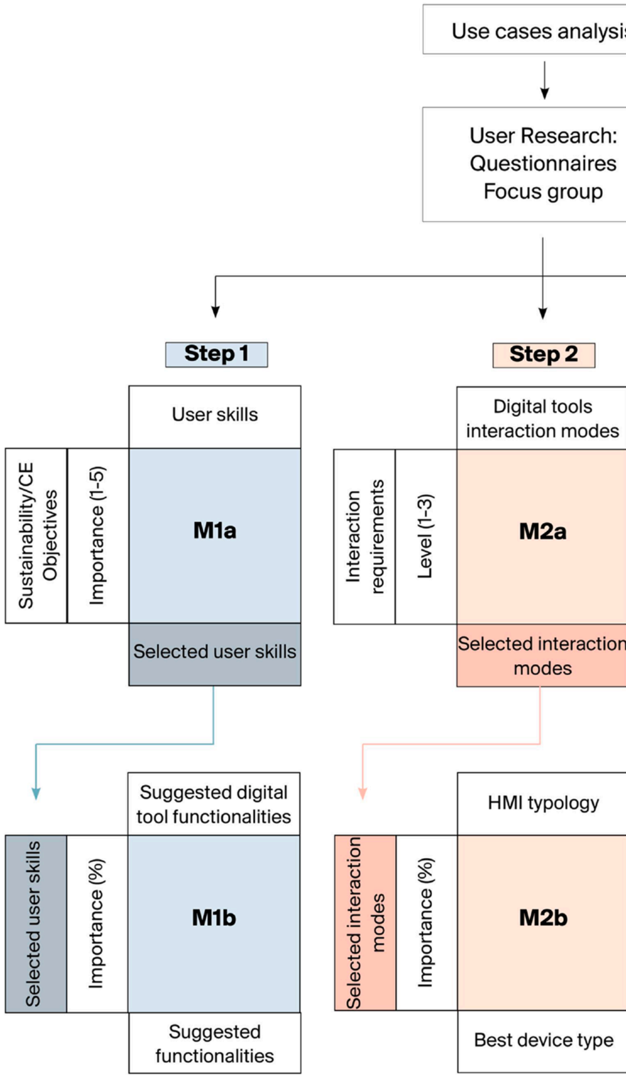

Fig. 1. Overview of the DaCapo human-centric methodology.

Table 1
Sustainability and Circular Economy (S&CE) objectives and related importance (I).

Category	Sustainability and Circular Economy objectives	Importance (I)
Design	Conscious (Circular / Eco / Sustainable) product and process design Product and process sustainability performance optimization (e.g., deployment) Preview product / process (design phase review) Increase machine/process awareness for action adjustment	1–5
Quality	Support during task execution (Manufacturing phase, e.g., assembly) Materials and resources tracking in order to be modified and updated during the lock-up period time Predictive maintenance Product quality assessment (post-production) Component analysis (post-production, post-use…)	1–5
User	Decision making post component analysis (post-use…) Upskilling / reskilling Safety conditions improvement Improvement of the workers' consciousness of sustainable activities	1–5

A visual overview of the methodology is represented in Fig. 1, while the steps are explained in more detail in the next paragraphs.

2.3.1. Definition of the Digital Tools Functionalities

The first step of the methodology starts from the weighting S&CE objs for the specific use case, from a list of objectives collected in literature. These are intended as a list of practices and principles that companies should follow in order to achieve more sustainable processes and products.

The selection of the S&CE objs started with an initial research phase, involving a comprehensive analysis of the current state of sustainability and circularity objectives documented in existing literature [35,47]. Following the identification of all objectives present in the literature, a panel of subject matter experts conducted a meticulous evaluation, ultimately discerning 13 objectives. This decision-making process considered outcomes that closely resonate with the issues examined in the reference case studies. The subsequent analysis facilitated the construction of a framework encompassing sustainability objectives. This framework is designed to empower individual companies to enhance the implementation of S&CE principles within their processes and/or products. The objectives considered in this study are described in Table 1.

These S&CE objs are subsequently correlated with the requisite User Skills (USs). USs are derived from an extensive literature review

Table 2
Digital Tools Functionalities (DTFs).

Category	Digital Tools Functionalities
Content organization	Step by step guide Ontime suggestions Shortcuts
Content specification	Product information (DPP, technical characteristics, and features) Resource route and plan (cost, timing…) Process information (process control, tools, resources) Remote support by an operator / AI 3D model / DT visualization
User-related data	Content adaptivity Human parameters monitoring Work management / status Specific training procedures (different simulation scenarios)

performed by Pinzone et al. [15,19,48] forming a comprehensive framework that aligns the identified S&CE objs with the necessary competencies for their achievements. To achieve this, matrix M1a was established with S&CE obj as rows and USs as columns.

At this stage, a correlation value between each S&CE obj and the various USs is required. The correlation between S&CE objs and USs was discussed during a focus group among experts involved in the project. For each S&CE obj and US, a correlation value was given: 0 means no correlation, 1 for low correlation, 3 for medium correlation and 9 for strong correlation. Once a correlation score is given for each S&CE obj and US, the M1a correlation matrix is complete.

Then, an Importance Value (IV) is needed from companies to understand the level of importance of each S&CE obj in the considered use case, according to a 1 to 5 Likert scale (1=low importance, 5=high importance). These IVs are discussed during a focus group with the companies involved in the project. Through the use of the equations explained in the next chapter, each US was given with a relative importance in percentage. As result, M1a matrix serves to understand which USs are more important in the relative use case scenario to achieve the defined S&CE objs.

The obtained results from M1a are reported in matrix M1b, that correlates the USs with the Digital Tool Functionalities (DTFs). Digital tools encompass a wide range of software and applications designed to perform specific functions to enhance user experiences across various domains. The DTFs can vary significantly based on their intended purpose, but there are common functionalities often found in digital tools that could be used in industrial context. The identification of Digital Tool Functionalities (DTFs) was initiated taking inspiration from Jemal et al. [35]. After this, focus groups were conducted with representatives from the examined case studies, facilitating the tailored selection of DTFs for contextual use. This method enabled the assessment of functionalities deemed pertinent and specific to the analyzed companies. The considered list of functionalities is described in Table 2.

Similarly to matrix M1a, the obtained results from M1b matrix are the relative importance of each DTFs compared to the others for the specific scenario. The DTFs that have the highest scores are the most suitable for the demonstrator in the considered case study. So, the overall result of the first step is the definition of the most proper tools to train and upskill (or reskill) the workforce in an industrial context.

2.3.2. Definition of the HMI typologies

The second step of the methodology uses matrix M2a and matrix M2b to link the Interaction Requirements (IRs) of the specific use case with a list of Digital Tools Interaction Modes (DTIMs). IRs are considered the main characteristics about communication, workspace, and user equipment. Communication takes into account: quantity, complexity, variability and frequency of communication sent and received by the operator, and communication during concurrent task and the use of shared tools. Workspace category considers the characteristics of the work environment, such as dimensions, variability, presence of noise and dust. User equipment considers the use of safety glasses or helmet, gloves, and ear protection. These features are reported in Table 3 and they compose the rows of M2a matrix.

Table 3
Interaction requirements (IRs).

Category	Interaction requirements	Importance (I)
Communication	Quantity of communication sent Complexity of communication sent Variability of communication sent Frequency of communication sent Quantity of communication received Complexity of communication received Variability of communication received Frequency of communication received Communication during concurrent tasks Shared tool	low, medium, high never, sometimes, always
Workspace	Dimension of operational area Variability of the task execution area Dimension of the task execution area Presence of noise Presence of dust	never/small, medium, big
User	Use of safety glasses and/or safety helmet Use of safety gloves Use of ear/helmet protection	never, sometimes, always

Table 4
Digital Tools Interaction Modes (DTIMs).

Category	Digital Tools Interaction Modes
Interaction	Touch Gesture Voice Gaze control
Feedback	Sound/Voice Visual Haptic
Use	Fixed Mobile

Such IRs are correlated with the Digital Tools Interaction Modes (DTIMs) in matrix M2a, using IRs as rows and DTIMs as columns. DTIMs are divided into three main categories: interaction, feedback and use. Interaction means the various typology of possible interactions, so Touch, Gesture, Voice and Gaze control. Feedback considers the different types of feedback that could be used, so Sound/Voice, Visual and Haptic. Use means how the digital tool is used, so if it is Fixed or Mobile. DTIMs are summed up in Table 4.

The correlation between IRs and DTIMs was discussed during a focus group of experts involved in the project, similarly to M1a. For each IR and DTIM, a correlation value was given in the same manner as previous step. Once a correlation score is given, the M2a correlation matrix is complete. Then, for each IR a level is defined (from 1 to 3 according to

Table 5
HMI typologies (HMITs).

Category	HMI typologies
Fixed	Monitor Fixed speaker Fixed camera
Hand-held	Tablet Smartphone
Wearable	Smartwatch Glasses Hand/Wrist wearable devices Mobile speaker

Table 6
Availability of the different types of data (ATDs).

Category	Availability of the different types of data	Importance (I)
Environment	Crowding	Yes / No
	Noise	
	Workspace layout	
	Temperature	
	Pollution	
	Light	
Machines	Equipment set-up	
	Process lifecycle	
	Product geometry	
	Product data	
	Performance	
	Production cost	
	Machine status	
	Quality inspection plan	
	Maintenance plan	
	Production parameters	
Humans	Posture	
	Anthropometry	
	Sweating	
	Eye tracking	
	ID recognition	
	Physiological parameters (to indicate stress condition)	
	Position and movements	
	Facial expressions	
HMIs	Type of interaction	
	Type of device	
	HMI layout	
	Navigation path	
	Visualized pages	
	Interaction time	
	No. of clicks	
	Tone of voice	

Table 7
HMI Adaptive Behaviours (HMIABs).

Category	HMI Adaptive Behaviours
Physical Adaptation	Inclination
	Orientation
Visual Adaptation	Zoom
	Text quantity reduction
	Change of colour
	Information selection
	Content subdivision in steps
	Contents re-organisation
	Light condition
	Customised HMI layout
	Customised HMI's information architecture
	Content quantity regulation
Vocal/Sound Adaptation	Volume regulation
	Voice speed regulation
	Voice tonality
Functional Adaptation	Warning message
	Suggestions
	Lock

1=low/never/small, 2=medium/sometimes/partially, 3=high/big/always) discussing it with the same focus group with the companies involved in the case study. Through the use of the equations explained in the next chapter, a relative importance in percentage was given for each DTIM. As result, M2a matrix serves to understand which DTIMs are more important in the relative use case scenario.

The second phase of this step is voted to correlate the selected DTIMs with the different HMI typologies (HMITs) using matrix M2b. HMITs are the different devices that could be used as interface, exploiting the framework proposed by Jacko [22], summed in Table 5. The output of matrix M2b is the definition of the best HMITs that could be used in the specific use case scenario. As a result of Step 2, from matrices M2a and M2b it could be possible to define the best HMIs proactive design and development.

2.3.3. *Definition of the HMI adaptive behaviours*

The last step consists of the definition of the most suitable HMI Adaptive behaviours (HMIABs) for the specific use case, starting from the availability of the different types of data (ATDs). Such data could be collected in the context of I4.0, considering the adoption of different types of sensors. Such data can support the creation of HMI adaptive behaviors because they can be used to trigger specific actions or modify the HMI aspects or contents in an intelligent way.

The various types of data are divided into four main categories (i.e., environmental, machine, human, HMIs) and retrieved to a previous work recently published in literature [41]. The ATDs selected for this study are summed up in Table 6.

At the same time, the methodology defines a set of HMI adaptive behaviors (HMIABs) related to four main categories (i.e., physical, visual, vocal/sound, functional). These HMIABs were extracted from literature by previous research works [49,50], as summed up in Table 7. The correlation between ADTs and HMIABs is described by proper correlation values in matrix M3.

M3 uses ATDs as rows and HMIABs as columns. For each ATD and HMIAB, a correlation value was given as in the previous steps. Once a correlation score is given, the M3 correlation matrix is complete. Then, for each ATD is given a 1 or a 0 depending on the availability of this type of data, discussing it in a focus group with the companies involved in the case study. Through the use of the equations explained in the next chapter, for each HMIAB was given a relative importance in percentage. As result, M3 matrix serves to understand which HMIABs are more important in the relative use case scenario.

3. Theory and calculation

This section describes the calculation behind the proposed methodology. Considering a generic matrix *Mx*, for each entry in rows (i) an Importance (I) is defined, based on the judgement provided by the companies involved in the project. Company employees have been involved using focus groups using remote meetings. Values can vary among the matrices: from 1 to 5 according to the importance of the S&CE objectives in matrix M1a, from 1 to 3 in matrix M2a according to the level of IRs, and binary (0 or 1) in matrix M3 according to the ATDs. Each I_i is compared to the others using a Relative Importance (RI_i), expressed by Eq. (1):

$$RI_i = \frac{I_i}{\sum_1^m I} * 100 \tag{1}$$

with m as the number of the matrix rows and i as the number of the row from 1 to m. The concept of *Importance* includes a variety of aspects, such as the frequency and the consistency of the referred entity. It is conceivable that certain rows may exhibit very similar RI values, however, this circumstance does not pose a significant issue.

For each matrix, the evaluation of the strength of the relationship between rows and columns, discussed during the focus group according to a 0-1-3–9 scale, results in a $m\ x\ n$ matrix called *Correlation Matrix* (*CMx*). Each *CMx* created and composed as following (Eq. (2)):

$$CMx = [CMx_{11}, \ldots, CMx_{mn}] \tag{2}$$

with m is the number of the matrix rows and n as the number of the matrix columns. Correlation values are defined by experts in HMI design and UX design. These values serve as input for the calculation of the *Column Importance* (*CI*), calculated for each column j as (Eq. (3)):

$$CI\ j = RI_1 * CMx_{1j} + \ldots + RI_i * CMx_{ij} + \ldots + RI_m * CMx_{mn} \tag{3}$$

with j as the number of the generic column from 1 to n. Then the results

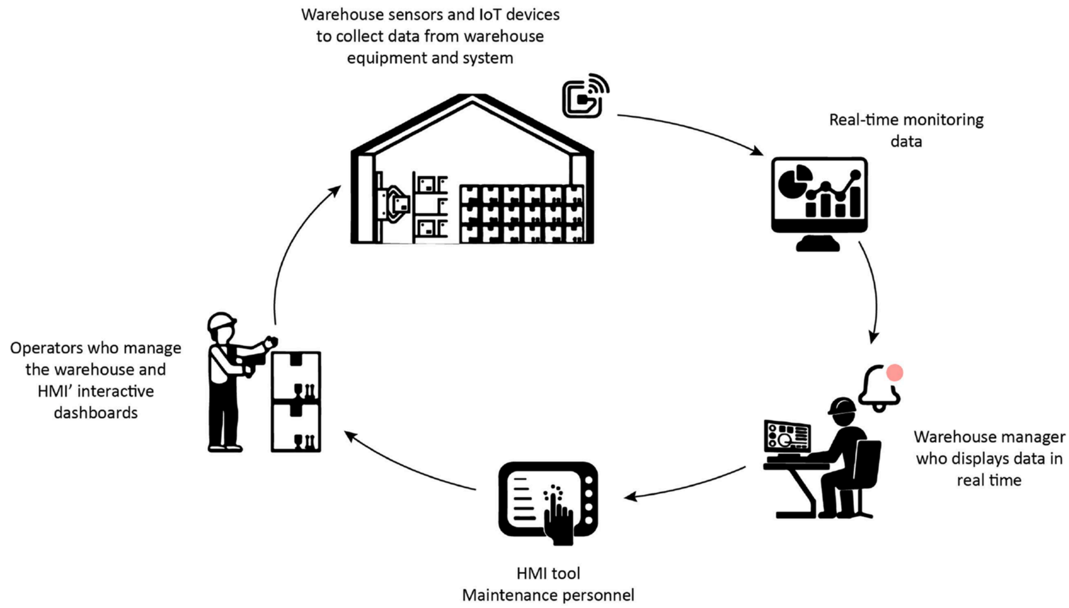

Fig. 2. Visual representation of the considered use case.

of the generic matrix are calculated using the *Column Relative Importance* (*CRI*), expressed in percentage as in Eq. (4):

$$CRI\ j = \frac{CI\ j}{\sum_1^n CI} * 100 \tag{4}$$

The *CRIs* with the highest scores are the most suitable for the case study considered. The calculated *CRIs* are reported in the following matrix according to the overview presented in Fig. 1. For instance, *CRIs* from matrix *Mxa* are used in matrix *Mxb* as input for the secondary calculation process.

The proposed correlation is linear based on the theory of QFD [43] and several empirical results collected on different application fields [51,52]. It is a simplified model, but it has been found pretty good to map the correlations among different entities related to product or service design, as demonstrated by previous studies.

4. DaCapo use case in logistics

The selected use case has been developed in collaboration with Pesmel, a global leader with over 40 years of experience in optimizing material flows and logistics for diverse manufacturing facilities, specialized in customer-centric design and active lifecycle service, with a focus on tailored solutions. With over 400 material flow technology deliveries on five continents, Pesmel has subsidiaries in North America, Europe, and Asia, supported by a wide network of representatives globally [53].

In the use case, the focal point is the management of data for warehouse operations and associated maintenance tasks, leveraging real-time data sourced from warehouse devices. The primary objectives encompass the identification of anomalies, represented by alarms, to

Table 8
Results from focus group as input for matrix M1a.

Sustainability and Circular Economy objectives	Importance Value (1÷5)
Conscious (Circular / Eco / Sustainable) product and process design	2
Product and process sustainability performance optimization	4
Preview product / process (design phase review)	3
Increase machine/process awareness for action adjustment	5
Support during task execution (Manufacturing phase, e.g., assembly)	1
Materials and resources tracking in order to be modified and updated	1
Predictive maintenance	3
Product quality assessment (post-production)	4
Component analysis (post-production, post-use…)	1
Decision making post component analysis (post-use…)	1
Upskilling / reskilling	5
Safety conditions improvement	5
Improvement of the workers' consciousness of sustainable activities	4

Table 9
Results from focus group as input for matrix M1b.

Category	Interaction requirements and related levels	Level (1÷3)
Communication	Quantity of communication sent: (low, medium, high)	2
	Complexity of communication sent: (low, medium, high)	1
	Variability of communication sent: (low, medium, high)	3
	Frequency of communication sent: (low, medium, high)	3
	Quantity of communication received: (low, medium, high)	2
	Complexity of communication received: (low, medium, high)	3
	Variability of communication received: (low, medium, high)	3
	Frequency of communication received: (low, medium, high)	3
	Communication during concurrent tasks (never, sometimes, always)	2
	Shared tool (never, sometimes, always)	2
Workspace	Dimension of operational area: (small, medium, big)	3
	Variability of the task execution area: (never, partially, always)	2
	Dimension of the task execution area: (small, medium, big)	3
	Presence of noise: (never, sometimes, always)	3
	Presence of dust: (never, sometimes, always)	2
User	Use of safety glasses and/or safety helmet: (never, sometimes, always)	3
	Use of safety gloves: (never, sometimes, always)	2
	Use of ear/helmet protection: (never, sometimes, always)	3

Table 10
Results from focus group as input for matrix M3.

Category	Availability of the different types of data	Availability (Y/N)
Environment	Crowding	0
	Noise	1
	Workspace layout	1
	Temperature	1
	Pollution	0
	Light	1
Machines	Equipment set-up	1
	Process lifecycle	1
	Product geometry	1
	Product data	1
	Performance	1
	Production cost	1
	Machine status	1
	Quality inspection plan	1
	Maintenance plan	1
	Production parameters	1
Humans	Posture	0
	Anthropometry	0
	Sweating	1
	Eye tracking	1
	ID recognition	1
	Physiological parameters	1
	Position and movements	0
	Facial expressions	1
HMIs	Type of interaction	1
	Type of device	1
	HMI layout	1
	Navigation path	1
	Visualized pages	1
	Interaction time	1
	No. of clicks	1
	Tone of voice	0

Table 11
Results from matrix M1b: suggested digital tool functionalities (DTFs) for the PESMEL use case.

Suggested digital tool functionalities (DTFs)	Relative Importance (%)
Integration of process information (process control, tools,	15,91 %
resources)	13,47 %
Integration of product information (DPP, technical	12,63 %
characteristics, features)	10.10 %
Implementation of step-by-step guides	9.90 %
Resource route and plan (cost, timing…)	9.03 %
Specific training procedures (different simulation scenarios)	8.58 %
3D model / DT visualization	6.49 %
Ontime suggestions	4.81 %
Remote support by an operator / AI	4.70 %
Human parameters monitoring	2.33 %
Work management / status	2.05 %
Content adaptivity	
Shortcuts	

discern irregularities or deviations from standard operations, indicative of potential issues or equipment malfunctions. To enhance decision-making, HMI tools are required for displaying warehouse and device status, alongside visualizations of alarms and trends (Fig. 2). The insights derived from these visualizations empower warehouse operators, the central figures in this context, and warehouse maintenance personnel, offering a comprehensive understanding of potential issues. The proposed approach is designed to address these challenges and augment decision-making processes based on data visualization.

Findings from the focus groups with the company users and experts are detailed in Tables 5–7 below. Consistent with the established methodology, these scores served as inputs for subsequent stages,

Table 12
Results from matrix M2b: suggested HMIs typologies (HMITs) for the PESMEL use case.

HMIs typologies (HMITs)	Relative Importance (%)
Smartwatch	17,94 %
Glasses (AR)	14,95 %
Monitor	10,96 %
Tablet	10,96 %
Smartphone	10,96 %
Hand/Wrist wearable devices	9.97 %
Mobile speaker	9.30 %
Fixed speaker	8.97 %
Fixed camera	5.98 %

Table 13
Results from matrix M3: suggested HMI Adaptive Behaviours (HMIABs) for the PESMEL use case.

HMI Adaptive Behaviors (HMIABs)	Relative Importance (%)
Customised HMI's information architecture	10,05 %
Suggestions	9,37 %
Monitor Inclination	8,35 %
Customized HMI layout	7,67 %
Information selection	6.81 %
Voice tonality	5.62 %
Orientation	5.28 %
Contents re-organization	5.28 %
Text quantity reduction	5.11 %
Voice speed regulation	5.11 %
Change of color	4.77 %
Warning message	4.60 %
Content quantity regulation	4.43 %
Zoom	4.09 %
Volume regulation	3.92 %
Content subdivision in steps	3.75 %
Light condition	3.24 %
Lock	2.56 %

yielding the results delineated in Section 3 through the provided calculations. As shown in Table 8. Results from focus group as input for matrix M1a., the most important S&CE objs are *Increase machine/process awareness for action adjustment, Upskilling / reskilling* and *Safety conditions improvement,* that collected the maximum importance value. These objectives reflect the needs to control in real-time the automatic warehouse systems and the requirements to have operators that are continuously trained to take the best actions during the faulting situations. Other objectives that collected higher scores (4 out of 5) are *Product and process sustainability performance optimization, Product quality assessment (post-production)* and *Improvement of the workers' consciousness of sustainable activities.*

Considering IRs and their related levels (Table 9), from the focus group emerged an high level of variability and frequency of communication received and sent by the operator, while the complexity of the information is high only for the received communications. In the scenario considered, the dimensions of the operational and task execution area are crucial due to the big spaces in which operators move in warehouse. The presence of noise is another key factor to consider. As user equipment, operators always wear safety glasses and safety helmets, while gloves are used only sometimes (Tables 9, 10).

Results from focus group as input for matrix M1b.highlights the availability of the different types of data (ATDs). In the case study considered, the type of data concerning the machines is available, and includes information regarding the machine set-up, product and process features, performances parameters and machine status information. In the same manner, the HMIs data such as design interaction and layout

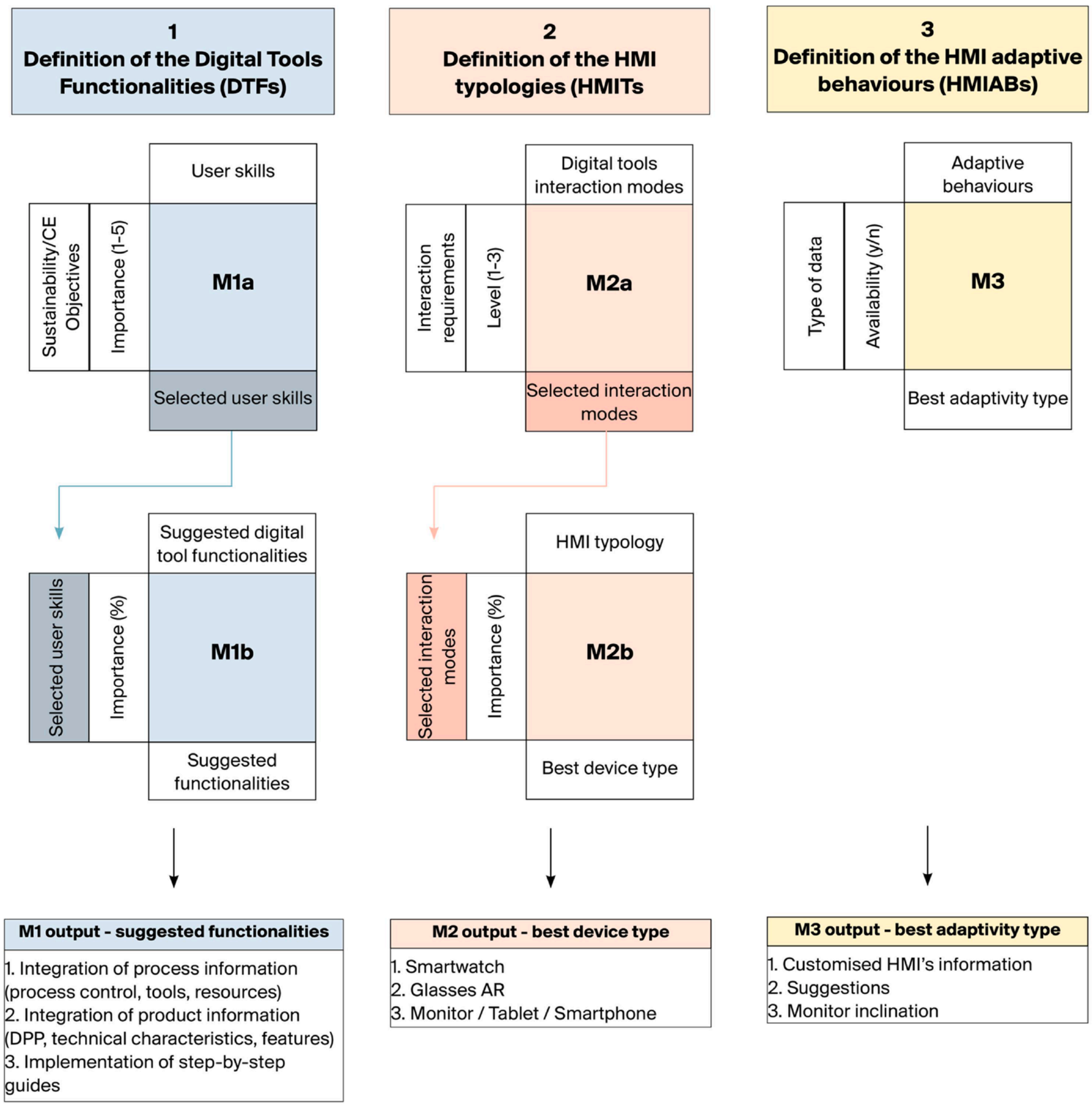

Fig. 3. Design guidelines as result of methodology application to PESMEL use case.

are all available excepts for the *Tone of voice*. For environmental and human data category there are some types of data that are missing for the specific use case.

5. Results

This section presents the primary outcomes derived from the application of the methodology in the considered use case. Starting from the selection of the most proper DTFs, Table 11 reported the relative importance of the suggested findings. From the relative importance percentage, it seems crucial the integration regard the product and process information, such as process overview, technical information, features, and the implementation of a guide to support the operator through the use of specific instruction step-by-step. Important information also refers to the material and resource flow, the training indifferent scenarios and the visualization of the 3D model, followed by the on-time suggestions.

Concerning the HMITs, Table 12 shows the calculated relative importance. The methodology identifies as the most important two HMITs that are wearable by the operator: the first is a *smartwatch* type, followed by *glasses* for augmented reality applications. Next, with the same relative importance, we find three devices with similar characteristics (e.g., monitor, tablet and smartphone).

Table 13 sum up the results concerning the best HMIABs, features to be included in the design of the interface. The customization of the information architecture collected the higher result, followed by the inclusion of suggestions and the physical adaptation of HMIs using device inclination. Nevertheless, the personalization of HMI layout is important, as the selection of the information to be visualized during the process.

The outcomes of the M1b, M2b and M3 matrix allow us to define the main basis to start the following HMI design. Fig. 3 sums up the top three results according to the presented methodology. This contribution was important for designers and engineers working at the CE innovation project in PESMEL to inspire future design solutions to be adopted in order to promote CE practices within the company.

Drawing insights from the obtained results, the design methodology successfully detected significant challenges arising from the absence of real-time data and the monitoring of anomalies, crucial points of the process considered in the case study. A principal recommendation emerging from this analysis is the incorporation of enhanced process-related information to augment decision-making capabilities. Concurrently, the inclusion of product-related information (e.g., DPP) proves advantageous for operators and maintenance technicians, facilitating the reuse and maintenance of specific components. Additionally, the integration of *step-by-step guides* is deemed beneficial to support operators across routine and maintenance processes, empowering them to solve faults and anomalies with less time and effort.

Addressing HMI typologies, the adoption of the design methodology proposes the deployment of *smartwatches* for operators to monitor real-time data within various sections of the warehouse, receiving prompt notifications about anomalies. Alternatively, Augmented Reality (AR) glasses offer a platform for visualizing sustainability-related parameters, aiding in strategic decision-making. The use of these wearable devices is particularly effective for the considered case study, allowing the operator to have access to data during the work shift in different areas of the warehouse. Alternatively, the use of monitors, tablets, and/or smartphones is recommended to show operators a comprehensive view of process progress, allowing interventions on different strategic parameters.

Considering adaptivity types, the identification of *Customized HMI's information architecture* emerged as the optimal adaptivity type, highlighting the importance of designing HMIs with interface flexibility to display diverse data types catering to varied operator needs. To optimize decision-making processes, it is essential to introduce adaptabilities that encompass personalized *suggestions* tailored to the various profiles and varying levels of knowledge and experience of the operators involved. Finally, the methodology underscores the necessity for physical adaptation using different device *inclination*. Moreover, *customized HMI layouts* enable each operator to visualize personalized data and detect anomalies according to his specific needs.

6. Conclusions

In this research work, the authors defined a human-centric methodology to support the design of modern industrial systems, based on the symbiotic co-evolution of digital tools, operators' skills, and multilevel user interfaces to support circular economy in manufacturing value chains. Such a method has been developed within the Horizon Europe project titled DaCapo. The aim is having an easy-to-use design tool, highly usable also by designers and engineers who are not familiar with human factors and user experience design, to guide companies in the successful integration of Sustainability and CE principles through the use of digital tools and adaptive HMIs, supporting the smart operator throughout the context of modern industry.

The proposed methodology is structured in a set of correlation matrices, helping designers and engineers in the definition of the HMI functionalities and features, starting from a guided analysis of the user needs and requirements. In the same way, the presented methodology can move from specific Sustainability and CE objectives and user skills of an industrial case to the definition of the most proper assistive digital tools and functionalities to drive the design of adaptive and proactive user interfaces for the modern operator working in Industry 4.0/5.0 context.

The method was applied and validated on the DaCapo project use case involving manufacturing companies operating in warehousing and logistics. From the user research phase, interviews and focus groups with companies highlighted that operators' need to have an HMI able to visualize and monitor different data in real-time and take timely decisions. The methodology supported the collection of inputs from the companies in terms of sustainability and CE objectives and the description of the main peculiarities of the processes to suggest the best HMIs functionalities, devices, and adaptive behaviours. The application of the different phases of the methodology suggested to implement product/process information and a step-by-step guide as main functionalities. As HMI typology, the matrices focused on smartwatch and AR glasses to implement adaptivity behaviours, such as customised HMI information architecture, suggestions and customized HMI layout. Following the results from calculations, companies could significantly improve the decision-making capacity of operators, offering personalized HMIs functionalities to facilitate real-time data monitoring, tailored to the considered case study.

As future research directions, the application of the presented methodology could be extended to other case studies of the same project, as well as to different projects, concerning other types of processes and manufacturing sectors to further investigate the flexibility of the proposed approach.

CRediT authorship contribution statement

Grandi Fabio: Conceptualization, Data curation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Contini Giuditta:** Conceptualization, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Peruzzini Margherita:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Roberto Raffaeli:** Conceptualization, Data curation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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.

Data availability

The data that has been used is confidential.

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Appendix A

This section contained the methodologies matrices fill in for the use case presented in the paper (Tables 1A–5A).

Table 1A
Matrix M1a for the PESMEL use case.

				Problem Solving (operator)	Creative thinking (operator)	Critical thinking (operator)	Entrepreneurial skills	Multidisciplinary Team Work (operator)	Lifelong learning (operator)	Flexibility and adaptability (operator)	Technology confidence (operator)					Fundamentals of sustainable development and the circular economy (designer)
M1 a	SUSTAINABILITY/CE OBJECTIVES	Importance (1-5)	Relative importance	Ability to understand and analyse a problem to be solved, identify difficulties and positive aspects, define objectives, identify all possible solutions, determine the best strategy, put it into practice and evaluate the results.	Ability to innovate by thinking outside the box, looking out of the ordinary, being able to see situations, objects and problems from another point of view, giving space to one's imagination and making original connections and proposing	Ability to analyse information, situations and experiences objectively, distinguishing reality from one's own subjective impressions and prejudices, recognising factors that influence one's own and others' thoughts and behaviour	Ability to act on ideas and opportunities and turn them into values for others.	Ability to coordinate, instruct, negotiate, persuade, service orientation, social perceptiveness of several disciplines to achieve a joint goal	Ability to remain resilient and manage skills development	Ability to adapt to a multitude of tasks, changes of scenarios, jobs, means and technologies by adapting to the work environment whatever the task at hand	Ability to use digital devices (e.g., tablet, smartphone, AR...)	Capability to use, read and interpret 3D digital models	Capability to use management software	Capability to perform production activities supported by AR/VR	Capability to interact with collaborative robots / andavance autonomous machines	Knowledge sustainability and circular economy principles
	Conscious (Circular / Eco / Sustainable) product and process design	**2**	**5.13**	3	3	3	3	3	1	3	3	3	0	9	9	9
	Product and process sustainability performance optimisation (e.g., deployment)	**4**	**10.26**	9	9	3	3	3	0	9	9	9	9	9	9	9
	Preview product / process (design phase review)	**3**	**7.69**	9	3	3	3	9	1	3	3	9	0	9	0	3
	Increase machine/process awareness for action adjustment	**5**	**12.82**	3	3	1	1	3	1	0	3	9	0	3	1	3
	Support during task execution (Manufacturing phase, e.g., assembly)	**1**	**2.56**	1	9	1	1	9	0	1	3	9	1	9	9	3
	Materials and resourses tracking in order to be modified and updated during the lock-up period time	**1**	**2.56**	3	1	0	0	0	3	3	1	3	3	0	0	3
	Predictive mainteanance	**3**	**7.69**	0	0	0	0	0	0	0	3	9	1	3	3	0
	Product quality assessment (post-production)	**4**	**10.26**	1	0	1	1	0	0	9	3	0	9	3	3	0
	Component analysis (post production, post use...)	**1**	**2.56**	1	0	1	1	0	0	3	9	0	3	3	3	3
	Decision making post component analysis (post use...)	**1**	**2.56**	1	3	3	3	1	3	3	9	0	3	3	3	0
	Upskilling / reskilling	**5**	**12.82**	3	3	3	3	3	9	1	3	3	0	9	1	9
	Safety conditions improvement	**5**	**12.82**	1	3	3	3	1	0	3	3	1	0	3	3	3
	Improvement of the workers' consciousness of sustainable activities	**4**	**10.26**	1	3	3	3	9	9	9	1	0	0	3	3	9
			100	302.56	310.26	212.82	212.82	323.08	248.72	392.31	366.67	443.59	217.95	523.08	325.64	469.23
				2.11	2.16	1.48	1.48	2.25	1.73	2.73	2.55	3.09	1.52	3.64	2.27	3.27

System thinking (manager)	Design and management of multiple product-service life cycles (designer)			Design and management of circular operations and production systems (designer)					Design and management of circular value chains (designer)		
Ability to understand how the parts of a dynamic system interact to produce the behaviour of the whole	Ability to apply Design approaches that support sustainability and circular economy - such as Design for Reliability, Design for Multiple Life Cycles (Dissassembly, Remanufacturing, Recycling), Design for Supply Chain, Design for Sustainability	Ability to develop innovative solutions to increase the use of recyclable and compostable materials	Ability to implement co-design practices (participatory design/collaborative design) for the circular economy	Ability to optimise the use of resources in production cycles and environmental management	Ability to design, implement and operate process technologies and industrial production systems in which waste or by-products become new inputs	Ability to design/select, implement and operate "smart" technology systems and innovative processes for Remanufacturing	Ability to evaluate different alternatives and identify the best circular strategy for a given product	Ability to plan and control production in systems characterised by high complexity, uncertainty, heterogeneity in material quality and composition (reverse production planning, reverse MRP, Reprocessing Scheduling)	Ability to design flexible configurations for circular supply chains, manage and operate circular supply chains to maximise environmental, economic and social performance	Ability to create synergies between direct and reverse logistics, plan the transport and handling of recovered products, optimise the use of multi-directional transport networks	Packaging optimisation.
9	9	3	3	3	3	9	9	9	9	9	9
9	3	3	3	9	9	9	9	3	3	9	9
9	3	0	0	9	9	3	9	3	1	9	3
3	1	0	0	3	9	1	1	3	0	1	9
3	3	9	9	1	3	3	3	9	0	9	9
1	1	9	9	9	9	1	3	1	9	9	9
0	1	9	9	1	0	3	3	3	1	1	0
1	3	0	0	3	3	1	3	3	3	9	1
3	0	9	9	3	3	3	3	3	3	9	9
1	1	1	1	3	1	1	9	3	0	1	3
3	3	3	3	3	1	1	3	1	1	3	1
1	3	1	1	0	0	0	1	1	0	1	3
0	9	3	3	3	9	3	9	3	3	3	3
328.21	333.33	269.23	269.23	364.10	469.23	271.79	464.10	289.74	197.44	474.36	446.15
2.29	2.32	1.88	1.88	2.54	3.27	1.89	3.23	2.02	1.38	3.30	3.11

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Table 1A (*continued*)

Assessment of circularity and environmental, social and economic impact (operator)			Development and use of digital solutions as an enabling factor for the circular economy (design team)						
Ability to apply methods for the assessment of ENVIRONMENTAL, ECONOMIC, SOCIAL impacts along the product-service life cycle (e.g. LCA)	Ability to apply methods for assessing "circularity" at product, process, enterprise, value chain level (e.g. Circular Economy Maturity Assessment)	Ability to define interventions to improve circularity and impacts.	Ability to identify, prioritise and exploit the opportunities offered by digital and Industry 4.0 technologies (e.g. additive manufacturing, collaborative robots, etc.)	Ability to select and use solutions for digitising product information, such as digital passports, labels and watermarks for traceability and mapping of resources and hazardous substances (e.g. digital product passport)	Ability to select, implement and use digital platforms for data sharing and integration between multiple actors (Data Spaces)	Ability to select and apply solutions based on Distributed Ledger Technologies (e.g. Circular Chain, Circularise)	Ability to apply modelling and simulation techniques (Digital Twins)	Data management, engineering, analysis and visualisation skills	Ability to select, implement and use artificial intelligence-based applications to support multi-criteria decision-making processes (e.g. design choices, best solution for end-of-life product, etc.)
9	9	9	3	9	9	9	9	9	3
9	9	9	9	3	9	3	9	9	9
3	3	9	9	9	3	3	9	9	1
0	1	3	3	9	9	3	3	9	9
3	1	3	3	3	9	1	9	3	3
9	9	9	9	9	3	3	9	3	3
3	1	1	3	1	9	1	9	9	9
9	9	9	9	9	9	3	9	9	9
3	3	3	3	9	3	9	9	3	3
3	3	9	3	9	3	9	9	9	9
9	9	3	9	3	3	3	9	3	9
9	3	3	9	0	1	0	3	0	3
9	9	9	3	9	3	3	9	3	3
646.15	561.54	576.92	638.46	569.23	566.67	302.56	746.15	600.00	623.08
4.50	3.91	4.02	4.45	3.96	3.95	2.11	5.20	4.18	4.34

Table 2A
Matrix M1b for the PESMEL use case.

M1b			SUGGESTED DIGITAL TOOL FUNCTIONALITIES											
Categories	SELECTED USER SKILLS	Importance (from M1a)	Step by step guide	Remote support by an operator / AI	3D model / DT visualization	Content adaptivity	Ontime suggestions	Product information (DPP, technical characteristics, and features)	Resource route and plan (cost, timing...)	Human parameters monitoring	Process information (process control, tools, resources)	Shortcuts	Work management / status	Specific training procedures (different simulation scenarios)
Problem Solving (operator)	Ability to understand and analyse a problem to be solved, identify difficulties and positive aspects, define objectives, identify all possible solutions, determine the best strategy, put it into practice and evaluate the results.	2.11	9	9	3	0	9	9	9	0	9	0	1	1
Creative thinking (operator)	Ability to innovate by thinking outside the box, looking out of the ordinary, being able to see situations, objects and problems from another point of view, giving space to one's imagination and making original connections and proposing	2.16	0	1	3	3	3	1	0	0	1	0	0	0
Critical thinking (operator)	Ability to analyse information, situations and experiences objectively, distinguishing reality from one's own subjective impressions and prejudices, recognising factors that influence one's own and others' thoughts and behaviour	1.48	0	3	3	3	9	9	3	3	9	0	3	1
Entrepreneurial skills	Ability to act on ideas and opportunities and turn them into values for others.	1.48	0	0	0	0	0	0	0	0	0	0	0	0
Multidisciplinary Team Work (operator)	Ability to coordinate, instruct, negotiate, persuade, service orientation, social perceptiveness of several disciplines to achieve a joint goal	2.25	0	1	0	0	0	1	0	3	3	0	9	9
Lifelong learning (operator)	Ability to remain resilient and manage skills development	1.73	9	0	0	0	0	0	0	0	3	3	3	9
Flexibility and adaptability (operator)	Ability to adapt to a multitude of tasks, changes of scenarios, jobs, means and technologies by adapting to the work environment whatever the task at hand	2.73	9	0	0	0	0	0	0	0	3	3	3	9
Technology confidence (operator)	Ability to use digital devices (e.g., tablet, smartphone, AR...)	2.55	9	1	0	9	9	0	0	0	0	9	0	9
	Capability to use, read and interpret 3D digital models	3.09	9	3	9	3	9	0	0	0	0	0	0	9
	Capability to use management software	1.52	9	3	1	1	9	0	0	0	0	1	3	9
	Capability to perform production activities supported by AR/VR	3.64	9	9	0	9	9	0	0	0	0	0	0	9
	Capability to interact with collaborative robots / andavance autonomous machines	2.27	9	9	1	0	9	0	0	0	0	0	0	9
Fundamentals of sustainable development and the circular economy (designer)	Knowledge sustainability and circular economy principles	3.27	1	1	3	0	1	9		0	9	0	0	1
System thinking (manager)	Ability to understand how the parts of a dynamic system interact to produce the behaviour of the whole	2.29	1	1	9	0	3	9	1	0	9	0	0	0
Design and management of multiple product-service life cycles (designer)	Ability to apply Design approaches that support sustainability and circular economy - such as Design for Reliability, Design for Multiple Life Cycles (Dissassembly, Remanufacturing, Recycling), Design for Supply Chain, Design for Sustainability	2.32	1	0	0	0	1	9	9	1	9	0	0	0
	Ability to develop innovative solutions to increase the use of recyclable and compostable materials	1.88	3	3	3	0	3	9	0	0	3	1	0	1
	Ability to implement co-design practices (participatory design/collaborative design) for the circular economy	1.88	0	0	0	0	0	0	0	0	0	0	0	0
Design and management of circular operations and production systems (designer)	Ability to optimise the use of resources in production cycles and environmental management	2.54	3	0	0	0	1	9	9	1	9	0	0	1

(continued on next page)

Table 2A (*continued*)

	Ability to design, implement and operate process technologies and industrial production systems in which waste or by-products become new inputs	3.27	3	0	0	0	1	0	3	0	9	0	9	3
	Ability to design/select, implement and operate "smart" technology systems and innovative processes for Remanufacturing	1.89	3	0	3	0	3	3	3	0	9	0	9	3
	Ability to evaluate different alternatives and identify the best circular strategy for a given product	3.23	9	1	1	0	1	9	3	0	9	0	3	3
	Ability to plan and control production in systems characterised by high complexity, uncertainty, heterogeneity in material quality and composition (reverse production planning, reverse MRP, Reprocessing Scheduling)	2.02	9	3	3	0	1	1	9	0	9	0	3	3
Design and management of circular value chains (designer)	Ability to design flexible configurations for circular supply chains, manage and operate circular supply chains to maximise environmental, economic and social performance	1.38	3	0	9	0	3	3	1	0	9	0	3	3
	Ability to create synergies between direct and reverse logistics, plan the transport and handling of recovered products, optimise the use of multi-directional transport networks	3.30	1	3	3	0	0	9	9	1	0	1	1	3
	Packaging optimisation.	3.11	1	0	3	0	0	9	3	3	9	0	0	3
Assessment of circularity and environmental, social and economic impact (operator)	Ability to apply methods for the assessment of ENVIRONMENTAL, ECONOMIC, SOCIAL impacts along the product-service life cycle (e.g. LCA)	4.50	9	1	9	0	9	9	9	9	9	0	3	3
	Ability to apply methods for assessing "circularity" at product, process, enterprise, value chain level (e.g. Circular Economy Maturity Assessment)	3.91	3	0	1	0	0	9	9	0	9	0	1	1
	Ability to define interventions to improve circularity and impacts.	4.02	3	3	3	0	3	9	9	3	9	0	0	1
Development and use of digital solutions as an enabling factor for the circular economy (design team)	Ability to identify, prioritise and exploit the opportunities offered by digital and Industry 4.0 technologies (e.g. additive manufacturing, collaborative robots, etc.)	4.45	9	3	9	0	1	3	1	0	3	0	0	3
	Ability to select and use solutions for digitising product information, such as digital passports, labels and watermarks for traceability and mapping of resources and hazardous substances (e.g. digital product passport)	3.96	9	3	3	0	9	9	3	1	9	0	0	3
	Ability to select, implement and use digital platforms for data sharing and integration between multiple actors (Data Spaces)	3.95	1	3	3	1	3	0	0	9	3	0	1	3
	Ability to select and apply solutions based on Distributed Ledger Technologies (e.g. Circular Chain, Circularise)	2.11	3	3	0	0	0	0	0	0	3	0	0	1
	Ability to apply modelling and simulation techniques (Digital Twins)	5.20	3	0	9	0	0	9	0	1	9	3	3	3
	Data management, engineering, analysis and visualisation skills	4.18	0	0	3	0	0	3	9	9	9	0	0	3
	Ability to select, implement and use artificial intelligence-based applications to support multi-criteria decision-making processes (e.g. design choices, best solution for end-of-life product, etc.)	4.34	1	9	1	0	0	1	1	1	1	3	3	3
			441.42	226.81	315.32	81.44	299.93	470.49	352.80	167.89	555.81	71.69	164.37	345.74
			12.63	6.49	9.03	2.33	8.58	13.47	10.10	4.81	15.91	2.05	4.70	9.90

Table 3A
Matrix M2a for the PESMEL use case.

M2a	INTERACTION REQUIREMENTS (level)	Level (1,2,3)	DIGITAL TOOL INTERACTION MODES								
			INTERACTION				FEEDBACK			USE	
			Touch	Gesture	Voice	Gaze control	Sound/Voice	Visual	Haptic	FIxed	Mobile
communication	Quantity of communication sent: (low, medium, high)	2	3	1	3	3	0	0	0	0	0
	Complexity of communication sent: (low, medium, high)	1	1	9	9	9	0	0	0	0	0
	Variability of communication sent: (low, medium, high)	3	9	1	1	1	0	0	0	0	0
	Frequency of communication sent: (low, medium, high)	3	3	1	9	3	0	0	0	0	0
	Quantity of communication received: (low, medium, high)	2	0	0	0	0	3	9	1	0	0
	Complexity of communication received: (low, medium, high)	3	0	0	0	0	1	9	1	0	0
	Variability of communication received: (low, medium, high)	3	0	0	0	0	1	9	1	0	0
	Frequency of communication received: (low, medium, high)	3	0	0	0	0	3	9	1	0	0
	Communication during concurrent tasks (never, sometimes, always)	2	1	9	9	9	9	3	9	0	0
	Shared tool (never, sometimes, always)	2	9	0	3	0	1	9	0	3	3
workspace	Dimension of operational area: (small, medium, big)	3	9	9	1	9	1	9	9	0	0
	Variability of the task execution area: (never, partially, always)	2	0	0	0	0	0	0	0	3	9
	Dimension of the tasks execution area: (small, medium, big)	3	9	9	1	9	1	9	9	1	9
	Presence of noise: (never, sometimes, always)	3	9	9	1	9	1	9	9	0	0
	Presence of dust: (never, sometimes, always)	2	3	3	9	3	9	3	9	0	0
user	Use of safety glasses and/or safety helmet: (never, sometimes, always)	3	9	9	9	1	9	9	9	0	0
	Use of safety gloves: (never, sometimes, always)	2	3	9	9	9	9	9	3	0	0
	Use of ear/helmet protection: (never, sometimes, always)	3	9	9	9	9	1	9	9	0	0
			77	78	73	74	49	105	70	7	21
			13.90	14.08	13.18	13.36	8.84	18.95	12.64	1.26	3.79
			Selected digital tools interaction modes								

Table 4A
Matrix M2b for the PESMEL use case.

M2b	SELECTED DIGITAL TOOL INTERACTION MODES	Relative importance	HMI TYPOLOGIES DEVICE								
			Monitor (GUI)	Tablet (GUI / AR)	Smartphone (GUI / AR)	Smartwatch (GUI)	Glasses (AR)	Mobile speaker	Fixed speaker	Hand/Wrist wearable devices	Fixed camera
Selected interaction modes	Touch (as input)	13.90	9	9	9	9	0	0	0	0	0
	Gesture	14.08	0	0	0	9	9	0	0	9	9
	Voice	13.18	3	3	3	3	3	9	9	0	0
	Gaze control	13.36	0	0	0	0	9	0	0	0	0
	Sound/Voice feedback	8.84	3	3	3	3	3	9	9	0	0
	Visual feedback	18.95	9	9	9	9	9	0	0	0	0
	Haptic feedback	12.64	0	3	3	9	0	0	0	9	0
	Fixed position	1.26	9	3	3	3	3	1	9	3	9
	Mobile use	3.79	0	3	3	9	9	9	0	9	0
			33	33	33	54	45	28	27	30	18
			10.96	10.96	10.96	17.94	14.95	9.30	8.97	9.97	5.98
			BEST DEVICE TYPE								

Table 5A
Matrix M3 for the PESMEL use case.

M3				ADAPTIVE BEHAVIORS																	
		TYPE OF DATA	Availability (Y=1 / N=0)	PHYSICAL ADAPTATION		VISUAL ADAPTATION										VOCAL/SOUND ADAPTATION			FUNCTIONAL ADAPTATION		
				Monitor Inclination	Monitor Orientation	Zoom	Text quantity reduction	Change of color	Informazion selection	Content subdivision in steps	Contents reorganisation	Light condition	Customised HMI layout	Customised HMI's information architecture	Content quantity regulation	Volume regulation	Voice speed regulation	Voice tonality	Warning message	Suggestions	Lock
Environment		Crowding	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Noise	**1**	0	0	0	0	0	0	0	0	0	0	0	0	9	3	0	0	0	0
		Workspace layout	**1**	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Temperature	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Pollution	**0**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Light	**1**	9	9	3	3	3	0	1	1	9	0	0	1	0	0	0	0	0	0
Machines		Equipment set-up	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Process lifecycle	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Product geometry	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Product data	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Performance	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	9	9	3
		Production cost	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Machine status	**1**	0	0	0	0	3	3	0	1	0	0	0	0	0	0	3	9	9	9
		Quality inspection plan	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Maintenance plan	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Production parameters	**1**	0	0	0	0	3	3	0	1	0	0	0	0	0	0	3	9	9	3
Humans		Posture	**0**	9	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Anthropometry	**0**	9	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Sweating	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Eye tracking	**1**	3	3	3	3	3	3	0	3	3	3	3	0	0	0	0	0	3	0
		ID recognition	**1**	9	9	1	3	1	1	9	9	0	9	9	1	1	9	9	0	3	0
		Physiological parameters (to indicate stress condition)	**1**	0	0	3	9	9	9	9	3	1	0	1	9	0	9	9	0	9	0
		Position and movements	**0**	9	9	9	9	3	3	1	1	1	0	0	9	9	3	0	0	0	0
		Facial expressions	**1**	0	0	1	3	3	3	1	3	3	0	1	3	1	3	3	0	9	0
HMIs	general	Type of interaction	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Type of device	**1**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	graphic	HMI layout	**1**	0	0	0	0	0	3	1	9	0	9	9	0	0	0	0	0	0	0
		Navigation path	**1**	0	0	0	0	0	3	0	0	0	3	9	0	0	0	0	0	0	0
		Visualized pages	**1**	0	0	0	0	0	9	0	0	0	3	9	0	0	0	0	0	0	0
		Interaction time	**1**	0	0	0	0	0	0	0	0	1	9	9	1	0	0	0	0	1	0
		Click number	**1**	0	0	0	0	0	0	0	0	1	9	9	1	0	0	0	0	0	0
	voice	Tone of voice	**0**	0	0	0	0	0	0	0	0	0	0	0	1	3	3	3	0	3	0
				49	31	24	30	28	40	22	31	19	45	59	26	23	30	33	27	55	15
				8.35	**5.28**	**4.09**	**5.11**	**4.77**	**6.81**	**3.75**	**5.28**	**3.24**	**7.67**	**10.05**	**4.43**	**3.92**	**5.11**	**5.62**	**4.60**	**9.37**	**2.56**
				Best adaptivity type																	

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