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Human in the loop: revolutionizing industry 5.0 with design thinking and systems thinking

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Abstract

This study delves into Industry 5.0's Human Centric Manufacturing and Systems (HCM and HCS), emphasizing worker welfare and sustainability. Industry 5.0 advocates a human-centric approach, built upon three foundational pillars safety, inclusivity, and empowerment. The paper highlights the successful integration of Design and Systems Thinking in HCM and proposes a workshop at MADE COMPETENCE CENTRE proving the effectiveness in raising awareness and promoting Human-Centric principles throughout the system life cycle and in achieving Human-Centric Systems (HCS).

Keywords: *systems thinking, human centric manufacturing, human centric systems, design thinking, human-centred design*

1. Introduction

Advancements in technology have ushered in novel perspectives on the transformation of industrial production and manufacturing, one of which is the concept of Industry 5.0 (Dautaj and Rossi, 2022). Industry 5.0 primarily prioritizes worker welfare during the manufacturing process, advocating for a human-centric system. This approach harmonizes human and technological coexistence, ensuring production remains within the ecological limits of our planet. The ultimate objective of Industry 5.0 extends beyond economic growth and employment generation, encompassing broader social objectives and sustainable development, with the aim of nurturing an intelligent yet environmentally conscious society and a sustainable and prosperous industrial community (Leng et al., 2022; Dautaj et al., 2023).
To advance the objective of a Human-Centric Manufacturing (HCM) system, the workforce must master the skills developed during the Industry 4.0 era (Acerbi et al., 2022). Furthermore, companies must prioritize worker welfare, with safety, empowerment, and inclusivity serving as the main pillars of this approach (Dautaj et al., 2023; Kumar et al., 2021) . Implementing these pillars is crucial to achieving the goals of Industry 5.0 and fostering a harmonious relationship between humans and machines. To enable their implementation to fullest achievements, it is necessary to create awareness among industry and to educate practitioners, both existing (through re-skill or up-skill), and upcoming, as the newest generation of workers (through academia), around the concepts of safety, inclusivity, and empowerment as for the HCM's dictate. Then, the challenge for both industry and university, is to understand how HCM concepts can be embedded in manufacturing systems since the design phase, meaning how to design manufacturing systems able to incorporate human-centricity from the outset and throughout all the life cycle stages. This leads to the double challenge of embracing the HCM concepts in a comprehensive way, understanding how safety, inclusivity, and empowerment enfold in manufacturing systems (from concept to dismission through realization) and how human-centric systems could be

designed from scratch. The authors are engaged in contributing to this emerging opportunity by finding proper approaches to create awareness and promoting HCM principles to be included in the design phase, and to extend those principles throughout all life cycle stages through the concept of Human Centric Systems (HCS). In literature and practice, effective approaches to systemic consideration and human (user) centric design are System Thinking (ST) and Design Thinking (DT), a combination seems effective to meet the proposed objectives. Indeed, DT & ST approaches align the system more closely with human needs and reflects societal needs and desires. This evolution is reflected in the increasingly specialized technological tools and methods used in planning design and manufacturing processes. Design, as a reflection of societal needs and desires, has evolved alongside technological advancements, shifting from discipline centric outputs to include technical, productive, manufacturing and economic systems, as well as human-centered values. The changing landscape of manufacturing, influenced by tools, processes, and bureaucratic regulations, has redefined the role of design in today's reality. In parallel, ST, rooted in Systems Science, views a system as a whole comprising of interacting elements. The research question that will be addressed is related to the possibility of the implementation of a collaboration between the use of DT and ST to synergically enhance the HCM and HCS perspective. Our methodology, a novel integration of DT and ST, is applied in a workshop setting, demonstrating its unique contribution to HCM practices as well as HCS considerations. The workshop serves as an experiential framework where participants explore and apply DT and ST principles, showcasing their synergistic benefits and validating the enhancement of the human-centric view. The study emphasizes the importance of human-centric values in design and manufacturing, with the workshop enabling practitioners to integrate these concepts into their processes for more values-driven outcomes.
Summarising, this paper aims to propose a combined approach to educate and demonstrate the applicability of DT and ST in promoting the concept of HCM and broadly HCS, as a central theme in Industry 5.0, and providing a method for operationalize HCM principles in design phase as well as conceive HCM as "systems", with their life cycle implications (i.e., HCS). To validate this objective, a pilot workshop with practitioners and academics, was conducted at MADE Competence Centre (in Milan) where participants were tasked with a challenge to use principles of DT and ST to create human-centric systems throughout the lifecycle stages.
This paper reports results and contribution from that workshop and puts the basis for a more generalizable approach. Section 2 of this paper examines the state of the art of HCM and posits some insights on ST and DT. Section 3 presents the research objectives and methodologies showcasing the developed framework integrating DT and ST and HCS. While section 4 outlines the workshop piloting and data collection, Section 5 and section 6 presents the workshop results and discussions respectively. Section 7 concludes by addressing findings, limitations, and future research proposals.

2. State of the art (HCM, DT & ST)

This chapter provides an overview of the current status of HCM, DT and ST.

2.1. Current status of Human-Centric Manufacturing (HCM)

The concept of Industry 5.0, integrates social, environmental, and societal considerations, building on Industry 4.0 paradigm. It aims to establish a "new normal" that promotes a more sustainable and ecologically conscious industry, thereby enhancing competitiveness (Rada, 2015). Industry 5.0, calls for a paradigm shift towards a person-centric approach, where collaboration between humans and machines yields social and environmental benefits (Li *et al.*, 2023). According to (Kumar *et al.*, 2021), businesses need to focus on the well-being of their employees in a variety of ways, with safety, empowerment, and inclusivity serving as the three key pillars. Literature is now in the process of formalizing the main elements constituting a HCM system, few models exist and propose, the following main dimensions (Dautaj *et al.*, 2023; Lu *et al.*, 2022):

- **Safety:** Employees perceive safety in three dimensions (emotional, professional, and physical safety). Emotional safety involves feeling valued and part of a team; professional safety is about job security, ensuring that one's position is not at risk; physical safety includes an ergonomic and healthy work environment with proper tools and furnishings.

- **Inclusivity:** In the context of HCM, inclusivity is understood in two ways. Personal inclusivity means accepting inherent characteristics (age, gender, etc.) that don't affect job performance; work related inclusivity acknowledges diverse skills among employees, crucial when roles expand or new team members join.
- **Empowerment:** Individual and structural empowerment are the two perceived dimensions. Individual empowerment is feeling confident in one's abilities and decisions, driven by recognising one's impact in the organization; structural organisation involves strategies fostering power-sharing, decision making, and resource control.

These are in this research considered as the three main pillars of HCM system.

2.2. Design thinking

DT has its roots in humanistic, technological, and operational innovation. It challenges traditional roles in design and engineering by offering a solution-focused, and human-centered methodology. From the 1980s to the early 2000s, writers, designers and thinkers including (Buchanan, 1992; Nigel, 2001), (Peter G. Rowe, 1991), (Norman, 2013), and (Camacho, 2016) expanded the discourse by infusing scientific methods with Humanistic-Centered Values (HCV) in design, ensuring safety, health, well-being, and considering the limits and roles of individuals in manufacturing. DT is iterative, emphasizing interdisciplinary and team-based processes, encouraging a shift from product-focused to user-experience-focused design. The primary purpose of DT is that it aims to inspire innovative, human-centered solutions to complex challenges in various domains, including manufacturing, strategic planning, and organizational relations. Moreover, DT addresses the need for a paradigm shift and responds to the growing demand for innovative, human-centered solutions in various disciplines and economies. The benefits of DT include fostering innovation and creativity, especially in businesses seeking human-centered solutions. It extends beyond traditional efficiency and quality improvement approaches to consider HCV. In the early 1990s DT applications and methods were used and promoted by the design company IDEO, which in turn helped to inspire design firms, companies, and institutions to utilize human-centered approaches to solve problems and develop strategies through interdisciplinary, team-based processes. The DT movement resonated throughout the world, especially in businesses, disciplines, and economies that sought innovative, human-centered solutions to complex design challenges, strategic planning, and organizational relations in businesses. DT, while innovative, can be subjective, lacking clear, objective criteria for evaluating solutions. Its iterative and interdisciplinary nature may be resource-intensive, which might pose challenges Additionally, the application of DT may face limitations in addressing certain complex and ambiguous problems, requiring complementary approaches and innovative solutions.

2.3. Systems thinking

This paper draws on (Bertalanffy, 1950) the concept of a system and aligns with INCOSE and ISO/IEC/IEEE 15288 (Sillitto *et al.*, 2019; Walden *et al.*, 2023) definitions. ST includes several key characteristics and involves a comprehensive examination of the properties and behaviour of system elements, both individually and in relation to each other. The introduction of the concepts of system, boundary, and environment establishes demarcation lines between the system and its surroundings. Additionally, systems can manifest as physical entities (products) or conceptual abstractions, emphasizing the importance of understanding the meaning expressed by the system.

The primary purpose of ST is to understand and navigate the complexity inherent in a system. For systems engineers and practitioners, the goal is to successfully engineer a system that interacts with operational environments, achieving intended purposes while satisfying beneficiaries and adhering to applicable constraints (Sillitto *et al.*, 2019). ST encourages a holistic examination of the system, considering not only its internal elements but also its interactions with the external environment (humans included). ST addresses various needs crucial for system understanding and development. It establishes what the system is comprised of and identifies at least one beneficiary for the system. Furthermore, it addresses the dynamic nature of stakeholder needs, emphasizing the importance of monitoring and maintaining alignment across the system life cycle. Additionally, ST contributes to handling the

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complexity of systems by examining their elements, relationships, and purposes. ST offers several benefits for decision-making and engineering processes. It facilitates holistic decision-making by considering the entire system and its interactions (Arnold and Wade, 2015). As such, engineered systems may include people, products, services, information, processes, and/or natural elements. For engineers, it contributes to the successful engineering of systems, ensuring they meet intended purposes and provide benefits. The adaptive approach of ST, focusing on human knowledge and desires, enhances planning, execution, and the acceptance of outcomes. While ST provides valuable insights into broad systematic relationships, it is not without limitations. A significant amount of "trial and error" occurs during development, potentially indicating challenges in accurately predicting system behaviour. Stakeholder needs may fluctuate across the system life cycle, posing a challenge in maintaining alignment. The text also implies that certain approximations may be hidden behind measures of production efficiency, suggesting potential limitations in transparency. Additionally, ensuring sustainability and circularity in systems, especially concerning disposal and waste management, may present challenges requiring a systemic perspective.

3. Research objectives and methodology

In this paper, our objective is to advance HCM by proposing an innovative approach that integrates DT and ST within the context of Industry 5.0 and towards the formalization of the HCS concept. The primary goal is to enhance awareness and facilitate the design of HCM systems. To achieve this, we delineate a comprehensive framework that encompasses both DT and ST principles. In particular, we describe a structured workshop, developed through a systematic approach. The workshop unfolds through distinct steps and culminates in a practical pilot conducted at the MADE Competence Centre in Milan. This iterative process is crucial for implementing HCM principles during the design phase and treating HCM as dynamic systems with life cycle implications. The conducted pilot workshop, involving both practitioners and academics, serves as a validation point for our proposed approach, showcasing its applicability in real-world scenarios and laying the groundwork for a more universally applicable methodology. The research methodology consists of an initial framework development based in literature, followed by the design of a workshop, both described in the following.

3.1. Integration of DT and ST for HCM and HCS framework

DT in human-centric manufacturing prioritizes users by understanding their needs and limitations. This approach identifies and designs suitable assistance functions for manufacturing systems, ensuring user-friendly, efficient, and accepted solutions. Involving users in the design process results in systems with positive user experiences, connectivity, and resilience. Ultimately, DT enhances productivity and satisfaction in HCM (Pokorni et al., 2020). DT and HCM are compatible, both prioritizing user needs. DT, used within the framework of human-centricity, guides ideation and prototyping, ensuring user-centered solutions tailored to work system challenges. Combining these approaches enables businesses to create innovative solutions that improve system performance and enhance the well-being and satisfaction of workers (Kadir and Broberg, 2021). According to (Mühlemeyer, 2020), ST and DT share a common ground beyond methodological convergence. Both approaches begin with a conceptualization of systems and conclude with a call to action, whether through design or creative inquiry. The mutual concern lies in the principles of action and the implied principles within different theoretical and practical concepts of systems and design. Amidst evolving technology and changing societal expectations, there is an opportunity to explicitly articulate design and systems principles. Engaging in a new conversation about these issues allows us to delve into the reasons behind design judgments, using DT to address complex ethical conflicts and overcome wicked problems.
The core idea revolves around exploiting and exploring DT and ST within the context of HCM. (Figure 1) elucidates this concept showcasing the synergistic interaction and relationship between DT and ST. Certainly. DT and ST work collaboratively to ensure that human-centric principles are seamlessly integrated into various phases of a system's lifecycle, thereby developing Human-Centric Systems (HCS). This collaborative approach extends beyond the manufacturing phase, encompassing the entirety of the lifecycle, thereby emphasizing the holistic incorporation of human-centricity in the design, implementation, and maintenance of systems.

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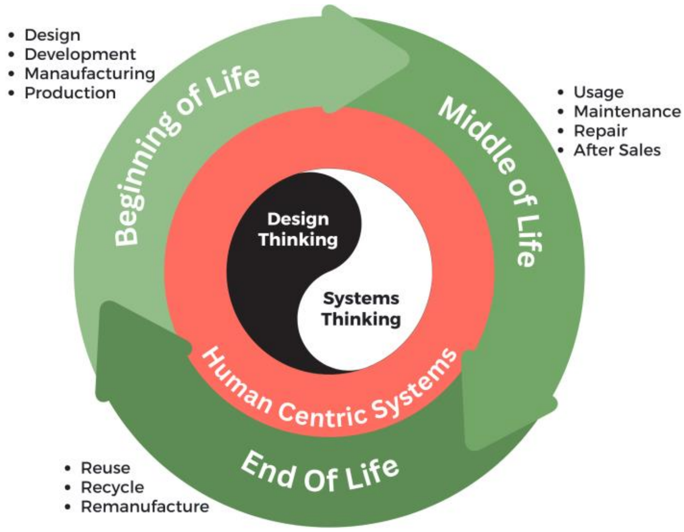

Figure 1. Integration framework of DT, ST and HCS

In the dynamic interplay of manufacturing approaches, DT is vital in HCM, enhancing user experiences and system resilience. Combining DT with HCM generates powerful results, fostering innovation and improving overall system performance and worker satisfaction. Additionally, the synergy between DT and ST emphasizes a shared concern for principles of action. This interconnected approach, amplifies the strengths of each method, offering a potent strategy for addressing complex challenges, ethical conflicts, and evolving technological landscapes in manufacturing and design.

3.2. Human in the loop workshop development

The article addresses the aforementioned research problem by developing a systematic approach to the workshop based on a didactical-technological approach (Tisch *et al.*, 2016). This approach enables the systematic design of the conceptual levels 'Learning Objectives' (macro), 'teaching module' (meso), and 'learning situation' (micro).

a) **Macro Level ('Learning Objectives'):**

The macro-level perspective places emphasis on the overarching goals of a HCM system. It highlights the critical need to raise industry awareness and educate practitioners on seamlessly integrating HCM principles into manufacturing systems. At this level, the complexities involve grasping the full extent to which HCM concepts can be intricately utilized into manufacturing processes. The workshop methodology navigates through the dual challenge of wholeheartedly embracing HCM principles, advocating for a transformative shift towards a more human-centric paradigm in the manufacturing landscape.

b) **Meso Level ('Teaching Module'):**

At the meso level, the strategies and approaches needed to promote HCM principles at the design phase are highlighted. The developed workshop suggests that a combination of ST and DT proves effective in achieving this goal. The meso level involves the use of specialized technological tools and methods in planning design and manufacturing processes, emphasizing the importance of systemic consideration and human-centric design in the manufacturing context.

c) **Micro Level ('Learning Situation'):**

The micro level is evident in the research paper's discussion of a workshop conducted with practitioners and academics. In this workshop, participants are tasked with a challenge to utilize principles of DT and ST to create human-centric systems. Section 5 of the paper presents and discusses the results of the workshop, showcasing concrete outcomes that underscore the efficacy of merging DT and ST in HCM at the micro level. The workshop serves as a practical application of the combined approach, demonstrating its impact on the design and development of HCM systems.

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The pilot workshop with the theme of Human-in-the-loop was conducted in Milan with 24 participants from academia (engineering students) and industry (a mix of roles and sectors) organized into four teams of six individuals each. Each team consisted of one engineering student and five employees, with one team member specializing in 'Systems Design.' The composition of the workshop included 25% students and 75% employees. Notably, 25% of the attendees were practitioners in design.

The circular life cycle framework (Figure 1) is taken as a reference here, and the methodology has been introduced by the authors, levering on their yearly expertise on DT, ST and Industry 4.0 topics and elaborating on the definition, peculiarities and applicability of both DT and ST in the emerging context of HCM. The system life cycle encompasses the stages and processes needed to ideate, conceptualise, design and develop, produce, install, operate, maintain and retire the engineered system at the end of its life; with humans involved in all those phases. In particular, the manufacturing stage was underlined in connection with Industry 4.0 and 5.0 as the more discussed for more and more challenging environment where human and technology visibly come together. But as it has been already mentioned and as ST advocates, production is only tangible effect of what has been developed earlier in the design phase, where DT can definitely play a crucial role. The purpose is to facilitate a shift in mindset, by learning through doing.

Basically, the authors have developed a method (stated above), leveraging on literature and experts' expertise (authors themselves) that incorporates DT + ST and they dispense it through a workshop to educate and create awareness around HCM in a systemic view. The purpose of the activity was to facilitate a shift in mindset through experiential learning. The method can also be deployed in real technical offices where, without time constrains as it happens for workshops. Through more in-depth analyses, data collections and analytics, and testing and prototyping, it might serve the scope to become a real guide for deploying HCM systems.

4. Human in the loop: piloting and data collection

The workshop, developed as described in the previous paragraph, has been piloted at MADE (Competence Center of Industry 4.0 in Milan), with the purpose of validating it, so to make a repeatable format. The workshop has taken the name of Human-in-the-Loop, to recall the role of the Human through the system life cycle phases and to emphasises his presence through it and since the beginning. The activity aimed at transferring knowledge to participants on how DT and ST can support the development of a HCM system. The core directive guiding the workshop revolves around the following inquiry: "When presented with an electric bicycle, what 'concerns' should be taken into account to emphasize the human-in-the-loop at various stages of the system life cycle (such as production, usage, etc.) through the utilization of Design Thinking and/or Systems Thinking?" This pivotal question forms the cornerstone for the hands-on challenge briefing. Participants are charged with delving into specific considerations pertaining to the human-in-the-loop dynamics within the electric bicycle's life cycle. As the workshop unfolds, encompassing interactive components like hands-on visits and demos, its aim is to furnish participants with additional context and creative inspiration, fostering a well-rounded approach to addressing the challenge. The selection of the e-bike is motivated by the fact that it is a quite universally known product, that recalls for human-centricity in many aspects of its life cycle: both in terms of usability (considering its final user, i.e., who rides the e-bike) and in terms of manufacturability (considering its production and assembly process, i.e., who produce/assemble the e-bike components). The product can be modified as needed (e.g., the e-bike can be replaced with other systems to be designed/improved), even though consistency and replicability would play a role in data analysis after the workshop will be repeated, allowing for comparison and more robust findings.

Participants to the workshop are split into teams of 4-6 people each, paying attention to distribute evenly the expertise through the teams, in case of diverse competences and skills in the audience. Possessing diverse sensibilities and probably competences regarding the e-bike's functionality, participants are tasked with identifying and addressing appropriate 'concerns' essential for highlighting the human-in-the-loop across various stages of the system's lifecycle, encompassing production, usage, etc. The challenge runs for roughly 2.5 hours. Before tackling the challenge, participants are introduced to foundational works in systems thinking by notable figures such as (von Bertalanffy, 1950), (Weinberg, 2001), (Meadows, 2008), (Senge and Sterman, 1992), and (Ing, 2013). Key features of a generic system

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are outlined, emphasizing elements like interaction, boundary, environment, life cycle, purpose, beneficiary, and benefits. The discussion on needs includes distinguishing between declared and latent needs, with a focus on stakeholder considerations. The 'user' as a key stakeholder is leveraged, covering various aspects from end-users to regulatory bodies, according to DT, whose steps are shared. This introduction is indeed quite basic and short, straight to the point and lasts about 1 hour. Post-challenge, participants voice key learnings, including a heightened awareness of the ubiquity of systems, the criticality of human-centricity, the importance of addressing user needs early in system design, and a better understanding of systems thinking. This final discussion lasts roughly 1. 5 hours, and might vary based on numbers of teams attending.

5. Workshop results

The findings revealed that participants, regardless of their technical understanding of e-bike mechanics, successfully applied ST and DT principles along with the concept of HCM. This resulted in valuable suggestions for enhancing the human-centric nature of e-bikes. Participants adeptly incorporated ergonomic considerations and design-for-X concepts across different phases of the system life cycle. The ideas generated were not only human-centric but also sustainable, aligning with the boundaries of the system. The results also provided useful insight into the human-in-the-loop across the entire life cycle and working environment. The following overview comprises of the outcomes put forth by each team member in a concise manner.

Team 1: The second team took a holistic view of the e-bike system, emphasising improvements across industrial processes, involving both users and operators in production and maintenance. Their suggestions spanned the entire life cycle (Figure 2a), incorporating indoor training cycles, equipment accessories, sensors for wheel pressure, and an app for bike maintenance. The use of cobots in assembly processes aimed to empower operators, enhance efficiency, and ensure the inclusivity of the entire assembly process.

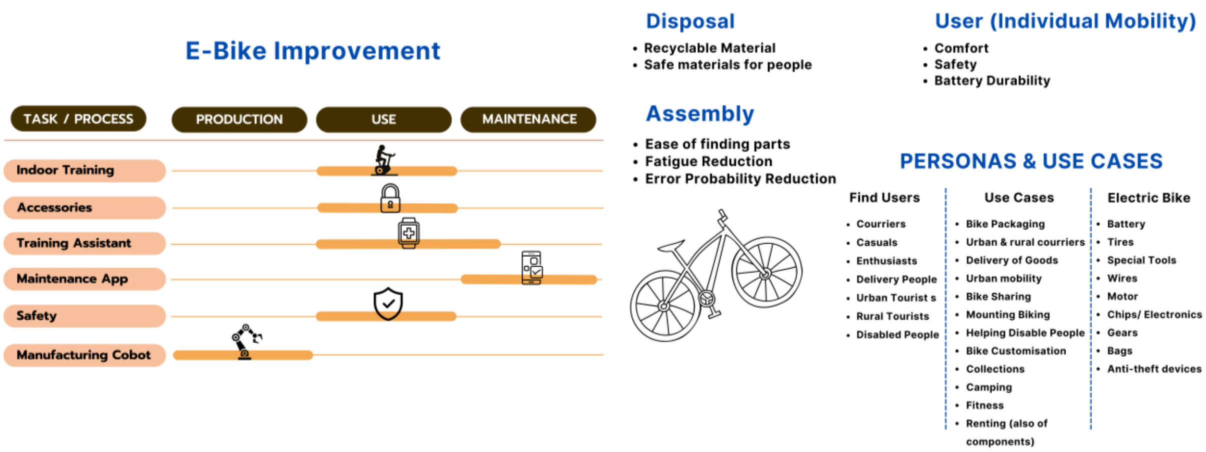

Figure 2. a) Process improvements across the lifecycle of an e-bike b) Enhancing the use and assembly of bicycles

Team 2: The first team approached the challenge by thoroughly investigating the bicycle system, identifying key stakeholders from production to maintenance. Their innovative idea centered on enhancing the use and assembly of bicycles (Figure 2b), with focus on user needs and prioritises such as comfort, safety, and battery durability as well as the fact that considering the end-of-life phases right at the beginning would be beneficial in the design of the e-bike. Notably, they suggested integrating nature into the design and employing technology for health maintenance through ergonomic handles.

Team 3: The third team, concentrated on designing a human-centric bicycle, establishing criteria for human-centricity throughout the lifecycle of the electric bike. They delved into use cases such as commuting, foldable bicycles, and bike packing, emphasizing inclusivity for various user groups.

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Additionally, they proposed an ethic business strategy, considering the impact of raw materials on people, and highlighting the importance of reconditioning, reselling, reusing and recycling (Figure 3a).

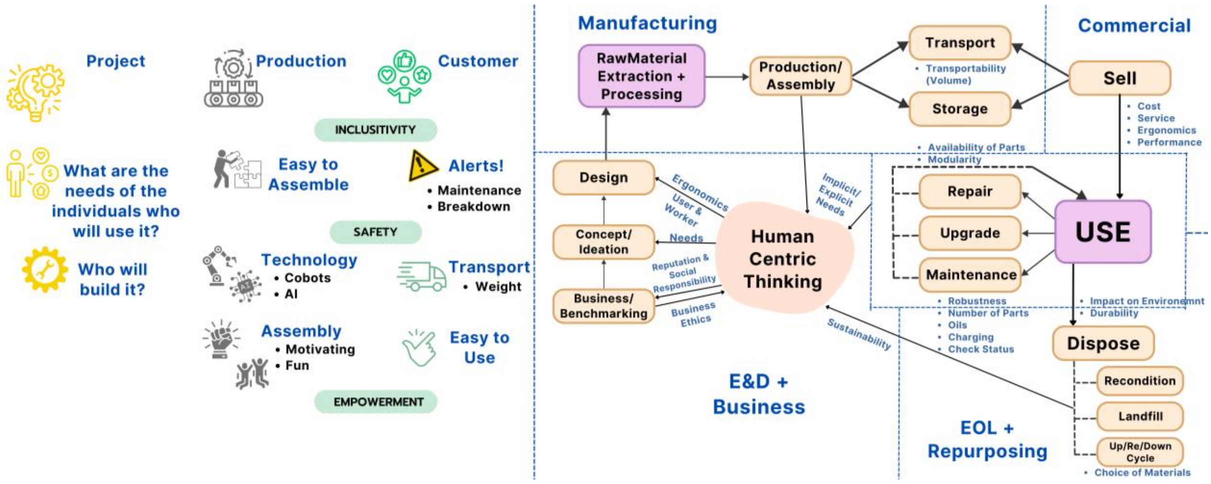

Figure 3. a) Human centricity aspects for an e-bike b) Integrating human-centric thinking and product lifecycle in the design of E-bikes

Team 4: The fourth team approached the challenge by focussing on manufacturing aspects of the e-bike system. As seen in (Figure 3b), they introduced the use of cobots for producibility, aiming to enhance the assembly process and increase satisfaction for human workers. They also addressed the knowledge gap among users regarding e-bikes compared to traditional bikes, proposing a first aid kit for e-bikes and advocating for inclusive customer representation in product development.

6. Discussion

All teams recognised the importance of human centric approach in designing and manufacturing electric bicycle systems. Their ideas ranged from incorporating nature and technology for user well-being to employing cobots for efficient production, addressing safety, inclusivity, empowerment, and emphasizing ethical business strategies. These insights contributed to the broader discourse on how DT and ST can revolutionise systems, placing human needs and experiences at the forefront of the design and development process.

Moreover, the workshop provided concrete outcomes that underscore the efficacy of merging DT and ST, particularly in the context of HCM. The participants, regardless of their technical backgrounds, demonstrated a successful application of ST and DT principles, resulting in valuable suggestions for enhancing the human-centric nature of the e-bike, in a few hours activity.

To quantitatively assess the impact, several metrics and key observations were identified. Throughout the workshop, various metrics were employed to measure the effectiveness of merging DT and ST. In terms of Diversity of Solutions, the number of unique solutions generated by participants was measured, revealing a rich array of ideas despite differing technical backgrounds. This highlighted the inclusivity of the approach. Another metric, Alignment with Sustainability Goals, assessed the percentage of ideas aligning with sustainable practices. The observation here was that a significant portion of generated ideas not only addressed human-centricity but also demonstrated a strong alignment with sustainable principles, facilitated by ST principles, under a life cycle and systemic viewpoint. Additionally, the integration of ergonomic considerations was tracked through the metric of the number of suggestions incorporating ergonomic factors. The observation indicated that participants adeptly integrated ergonomic principles, emphasizing a user-centered approach to design. The timely identification of needs was measured by the ratio of declared to latent needs identified during the challenge, showcasing the workshop's effectiveness in uncovering implicit requirements early in the system life cycle, demonstrating participants' awareness of various user categories and human factors. Finally, Post-Workshop Learnings were assessed through participant feedback on key insights, revealing an enhanced

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awareness of DT and ST frameworks, human-centric design, and the importance of addressing user needs early in the design process.

7. Conclusion

In the ever-evolving landscape of industrial production, the emergence of Industry 5.0 underscores a fundamental shift towards prioritising workers' health, welfare, and fostering human-centered systems. Industry 5.0 goes beyond economic and ergonomic objectives, aiming to create a socially responsible and environmentally conscious society. Industry 5.0 builds upon the foundations of Industry 4.0, emphasizing a paradigm shift where people take centre stage, collaboration between humans and machines is paramount, and social and environmental benefits are prioritised. HCM focuses on the well-being of workers through the pillars of safety, inclusivity, and empowerment. In such a view, a holistic perspective is crucial. as well as recognising the interconnections of various elements in the manufacturing process. To achieve the goals of I5.0 and HCM, and to cope with emerging challenges of educating and fostering HCM systems creation for smooth human technology coexistence, this paper introduced the Human-in-the-loop methodology: a workshop that leverage on DT and ST as a combined approach to design HCM systems. Through the workshop, participants demonstrated the successful application of DT and ST principles, demonstrate the understanding of HCM pillars of Inclusivity, Safety and Empowerment, proposing innovative ideas for an electric bicycle that not only prioritises human needs but also align with sustainability goals. The participants, regardless of their technical backgrounds, demonstrated a successful application of ST and DT principles for HCM and developing HCS.

A limitation is the reliance on qualitative assessments. More empirical evidence, potentially incorporating quantitative metrics, is needed to robustly support the observed effectiveness of HCM practices. Future research should focus on developing quantifiable metrics for measuring human-centricity. This approach aligns with the objective of advancing the measurement of HCM, ensuring a more evidence-based and measurable impact assessment on product design and manufacturing processes. As we navigate the intricate intersections of DT and ST, and human-centric manufacturing, the importance of a "human circularity" approach becomes evident. Across the system life cycle, humans play a pivotal role, driving engineering efficiency, quality, and priorities.

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