

Requirements and recommendations for human-centred human-AI collaboration design in manufacturing domain

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Research Article

Keywords: Human-Centred-AI, Human-AI Collaboration, Human-centred design, Collaboration design, Manufacturing, Expert Interviews, Design Requirements, Design Framework

Posted Date: August 25th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10201793/v1>

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Additional Declarations: No competing interests reported.

Abstract

The increasing artificial intelligence (AI) introduction to manufacturing domain and various forms of human-AI collaborations are transforming everyday manufacturing work towards more digital. While human-AI collaboration in manufacturing offers significant potential benefits, like improving productivity and worker safety, designing effective and human-centred collaborations remains challenging due to the complexity of manufacturing domain and the lack of comprehensive and domain-specific design guidance. This challenge is particularly relevant in the context of Industry 5.0, which emphasises human-centricity, worker well-being, resilience, and sustainable technological development. In our study, we shift the design focus from AI systems to human-AI collaboration as the primary design challenge. Hence, in this study, we aim to identify design requirements and synthesise them for human-centred design guidance for human-AI collaboration in manufacturing. Building on a previously proposed conceptual design framework, our study extends the understanding of human-AI collaboration through additional literature and expert interviews. Our study results reveal eight design dimensions to consider: (i) *pre-design considerations*, (ii) *collaboration task*, (iii) *collaboration team*, (iv) *skills and skill development*, (v) *AI agent characteristics*, (vi) *interaction and communication*, (vii) *collaboration infrastructure*, and (viii) *organisational responsibilities*. Together these dimensions provide a socio-technical perspective to the collaboration design. The contribution of this study is a refined design framework and related design guidelines that support the design of human-centred human-AI collaboration in manufacturing, aligned with the principles of Human-Centred AI (HCAI) and Industry 5.0 and promoting human-centricity, worker well-being, resilience, and effective human-AI teamwork.

1. Introduction

Manufacturing is going through a digital transformation as industrial companies are increasingly introducing intelligent technologies such as artificial intelligence (AI) and data-driven systems to their processes in order to improve productivity, efficiency, flexibility, and decision-making [33]. These developments have been promoted globally under initiatives such as Industry 4.0 in Europe, Smart Manufacturing in the United States, and Smart Factory in Asia, all aiming to enhance manufacturing performance through digitalisation and advanced technologies [20, 24, 16]. While these initiatives have improved technological innovation and delivered significant operational benefits, they have also been criticised for their strong emphasis on automation, efficiency, and technological progress [16]. In response to the critiques and concerns, new human-centred visions for manufacturing have emerged. In particular, the European Industry 5.0 initiative and the broader Human-Centric Smart Manufacturing perspective seek to balance technological advancement with human well-being, sustainability, and resilience [34, 7]. These approaches position humans at the centre of manufacturing system development and emphasise technological development that acknowledges and supports workers' capabilities, safety, well-being, and meaningful participation in work [7]. For manufacturing blue-collar floor-worker, digitalisation means increasingly collaborating with diverse AI-powered solutions, as various AI technologies enable machines to assist in work tasks, perform certain task independently, and to learn continuously [24]. This significantly transforms everyday work tasks, leading to a shift from

manual operations to towards collaborative interactions with AI [28]. In the manufacturing domain, human-AI collaboration offers various benefits and includes diverse objectives [14]. However, As intelligent technologies become part of everyday manufacturing work, concerns have emerged regarding their effects on blue-collar workers' roles and well-being [28]. Despite widespread introduction of human-AI collaborations in manufacturing companies around the world, little consideration exists regarding the designing collaboration in a way that supports human worker's physical and mental well-being. Several research and instructions address the technological and operational collaboration possibilities, however, operator's well-being is not in focus in these. The shift from manual practises to human-AI collaboration has a big effect on blue-collar workers' work task and environments, and that way to their well-being [31]. Digitalisation is essential for maintaining industrial competitiveness, yet human workers remain the biggest asset for the manufacturing companies [34]. Therefore, appropriate human-centred design of the collaboration is the key to truly effective and successful collaboration and supporting the workers' well-being.

Human-centred AI (HCAI) is a design approach that puts the end-users and their needs in the centre of the development, while acknowledging AI-related factors [12]. Several instructions for human-AI interaction design or teamwork exists but these can be very general or concentrating on certain topic (e.g. collaborative problem solving) or certain domain (e.g. banking). Manufacturing as a domain brings context-related factors and constraints that should be addressed and acknowledged in the design. Hence domain specific design instructions are needed, acknowledging not only the needs of the blue-collar manufacturing workers, but also the contextual requirements. Therefore, in this study, we aim to identify design requirements for human-AI collaboration in manufacturing and synthesise them into design guidance. We build on a conceptual framework from our previous scoping review, and we extend the understanding with additional literature and expert insights. That way we produce a refined design framework and a set of design recommendations to inform and support human-centred human-AI collaboration design for manufacturing domain. We approach this study aim with following two RQs:

RQ1: *What are the key design requirements for effective human-AI collaboration in manufacturing?*

RQ2: *How can these requirements be translated into design guidance?*

Our study findings address the gap in current knowledge in emerging topic of how to design human-AI collaboration in manufacturing, in a way that supports human-centricity and operators' well-being, while acknowledging the factors and constraints rising from the manufacturing domain.

2. Background and previous work

This chapter presents the background for the study and relevant related literature.

2.1 Industry 5.0 and human-centric manufacturing

Industry 5.0 emerged as a response to critiques of Industry 4.0, which primarily focused on automation, efficiency, and digitalisation [16]. In contrast, Industry 5.0 places human-centricity, sustainability, and resilience at the centre of industrial development [7]. Rather than focusing solely on technological advancement, Industry 5.0 seeks to ensure that new technologies contribute to worker well-being, meaningful work, and sustainable industrial transformation [20]. Aligned with the goals of Industry 5.0 is Human-Centred Artificial Intelligence (HCAI). Building upon the principles of human-centred design (HCD), HCAI is a design philosophy and development approach that emphasises the design, development, and deployment of AI systems aligning with human needs, values, capabilities, and well-being [12]. Instead of technical performance focus, HCAI considers social, ethical, organisational, and contextual factors, aiming to ensure that AI systems remain understandable, trustworthy, beneficial, and supportive of human agency. Important part of HCAI is human control and autonomy, human understanding of AI, and responsible and accountable introduction and utilisation of AI [12]. In this study, we adopt the Industry 5.0 goals and HCAI approach by focusing on the human-centred design of human-AI collaboration that supports both organisational objectives and worker well-being.

2.2 Human-AI collaboration in manufacturing

Integrating AI and related digital technologies into manufacturing processes creates new opportunities to enhance both operational performance and human work. Traditionally, intelligent systems have primarily functioned as tools that support human workers in performing their tasks. However, advances in AI are increasingly shifting manufacturing from human-computer interaction towards human-AI collaboration, where AI actively participate in joint activities, share responsibilities, and contribute to task execution alongside human workers [14]. Depending on the application, AI may provide recommendations, support decision-making, perform tasks autonomously, or collaborate directly with workers [28]. These developments enable a wide range of applications in manufacturing. For example, robotics and automation can reduce physically demanding, repetitive, or hazardous tasks, thereby improving ergonomics, occupational health, and worker safety [28]. Augmented and virtual reality (AR/VR) technologies can provide real-time guidance, training, and remote assistance, while Internet of Things (IoT) technologies and digital twins support monitoring, predictive maintenance, and process optimisation [33]. In addition, natural language processing (NLP) interfaces can facilitate more intuitive communication between workers and intelligent systems, enabling new forms of interaction and collaboration in smart manufacturing environments [1]. This has a significant implication on the nature of work. This requires forming and adapting a social perspective to be able to help the workforce to incorporate into the modern manufacturing workforce in socially sustainable way [28]. This includes assisting ageing, disabled and apprentice operators by using advanced digital and industrial enabling technologies [24]. Additionally, by reducing physical strain, supporting safer working conditions, enhancing productivity and quality, and assisting workers in demanding tasks, AI-enabled technologies can help maintain worker well-being [14]. However, these new forms of collaboration also introduce an important design challenge: how to create human-AI collaborations that achieve organisational objectives while supporting worker well-being and addressing the manufacturing-specific characteristics, constraints, and requirements.

2.3 Human-AI collaboration and teaming design

Literature presents a few different research direction related to the human-AI collaboration design. First, human-AI interaction and enabling UI design has received attention in recent literature. For example, Amershi et al. (2020) present 18 guidelines to support human-AI interaction design. These guidelines provide instruction to the design of the human-AI interaction especially through UI (user interface) design, but they are not domain specific. In addition, the social, contextual, and organisation considerations are missing from this seminal work. Xu et al. (2025) reviewed literature in order to provide comprehensive collection of design principles, guidelines, and standards. However, these instructions concentrate strongly on AI system design [35]. In [9] Fragiadakis et al. (2024) propose a framework to systematically evaluate human-AI collaboration and the collaborative team. Another research direction is human-AI teaming. For example, in [15] Hagemann et al. (2023) provide perspectives to human-AI teaming for work environments. They also discuss about the teaming challenges and propose ways to overcome these. In [31] Song et al. present design consideration for human-AI collaboration. They present human-AI collaboration framework with consideration especially on the roles of the collaborators as well as the design of the AI system. This study is informatic covering both humans and AI but heavily concentrates on AI system design for the collaboration. Domain specific information for human-AI teaming can be found for certain tasks like decision-making (e.g. [1]) or creative task (e.g. [18]). In addition, domain specific teaming and collaboration instruction can be found, like for education [1] and healthcare [22]. Also, AI-related factors and their design in collaboration have been the focus in several papers. For example, in [1] Ehsan et al (2020) provide instruction to human-centred design of explainability. They provide storytelling perspective to increase the understandability of the AI explanations. Transparency has an important role when interacting with AI. In their work, Schmitd et al. (2020) provide guidance in designing transparent AI systems and interactions [27]. Rising research direction is in human intent understanding and modelling to support the human-Ai interaction. For example, in [12] Fung et al. (2026) discuss about the importance of human intent understanding in collaboration and propose ways to enable it.

For manufacturing domain, Alonso et al (2021) present a review of multimodal interaction methods between human workers and manufacturing machines and robots. They work cover different manufacturing suitable interaction methods like intelligent interaction support technologies like NLP, VR (virtual reality), and XR (extended reality) and as well as audio, visual, haptic or gestural interaction possibilities, to achieve a more natural human-machine interaction in manufacturing work tasks [1]. In our previous study, we conducted a scoping literature review on key concepts for human-AI collaboration design in manufacturing [14]. Our work presents six key concepts related to human-AI collaboration and conceptual framework for design: (i) *Collaboration goal* that refers to the objectives set for the collaborative actions performed by humans and AI, (ii) *Collaboration team* that consists of two or more human and machine actors working together toward shared goals, (iii) *Skills* refer to the individual perceptual, cognitive, emotional, and motoric skills that all agents possess and can also be acquired and developed through collaboration, training, and learning, (iv) *Collaboration task* are formed with activities

that collaboration team conduct to meet the collaboration goals, (v) collaboration tasks and interactions between the agents are carried out via *Collaboration system* that should promote agent communication, understanding, and learning, as well as situational awareness. (vi) *Communication* between the collaborating agents coordinate team behaviours, conveys essential procedural information, and provides feedback. Important part of communication is understanding that is gained especially through AI transparency and explainability.[14] In this study, we are building on this review and these key concepts.

2.4 Research gap

Despite the growing human-AI collaboration introduction in manufacturing, little attention has been paid to how such collaborations should be designed to support workers' well-being, capabilities, and long-term engagement. However, the effectiveness of human-AI collaboration depends not only on technological performance but also on the ability and willingness of workers to engage with, understand, and utilise AI in their daily work [31]. Poorly designed collaborations may reduce worker acceptance, increase workload, undermine well-being, and ultimately lead to the abandonment of otherwise promising solutions [16]. In addition, manufacturing introduces domain-specific characteristics and constraints that distinguish it from many other human-AI collaboration contexts. Safety-critical operations, dynamic production environments, physical and cognitive work tasks, large-scale machinery, and rapidly changing operational conditions create requirements that generic human-AI design guidance may not address. Hence, there is a need for empirically grounded and context-specific design guidance that supports the development of human-centred human-AI collaboration in manufacturing. Research is especially needed to identify design requirements that acknowledge both the workers needs and the manufacturing domain realities. We aim to addresses this gap by synthesising insights from literature and practitioner expertise to develop a human-centred design framework and guidance for human-AI collaboration in manufacturing.

3. Research methodology

In this study, we build on a scoping review human-AI collaboration design in manufacturing presented in our previous paper [14]. The scoping review adopted an exploratory perspective, and it provided the initial theoretical foundation and served as the first data source for this study by semi-systematically identifying existing knowledge and key concepts for human-AI collaboration. In this study, we bild on that conceptual foundation and we further analyse and extend these findings together with additional literature and expert interview data to derive human-centred design requirements and develop practical design guidance for human-AI collaboration in manufacturing.

Source	Role in the synthesis
Scoping review	Theoretical foundation and framework (6 concepts)
Extended literature review	Adds practical insights and current design requirements and recommendations
Expert interviews	Adds expert perspectives and insights
Synthesis	Combine all three to derive structured requirements and recommendations

3.1 Data collection

Literature: to complement the findings from the scoping review, we searched for additional literature. As our review goal was to collect design requirements, we turned to pragmatic literature review because this allowed for identifying diverse insights, requirements, and design recommendations from a wide range of sources beyond the manufacturing domain [14]. In pragmatic literature review approach, the literature review is pragmatic and problem-driven: what matters is what helps solve the problem, not comprehensive coverage. A pragmatic literature review is suitable when the field is dynamic, interdisciplinary, and design-oriented, and for studies with an aim to gather useful insights without strictly following systematic review protocols [14]. The additional literature included both academic publications and industrial reports and they worked as supplementation for the original review data. Academic sources were selected to complement manufacturing-specific findings with broader insights from human-AI interaction and collaboration research. Industrial reports were included to provide manufacturing perspectives on AI adoption, implementation challenges, workforce implications and practical needs,, and industrial concerns. The supplementary literature review was not intended to be exhaustive and therefore may not capture all relevant studies.

For the academic studies, we utilised Google Scholar, as it covers all the major databases. Academic studies we searched with keywords *“human-AI interaction design; human-AI collaboration design; human-AI team design; and human-AI*”*. With this search we were aiming to find studies presenting design instructions, requirements, and recommendations. We selected relevant publications based on their contribution to human-AI interaction or collaboration design, human-centred AI design, and related design considerations. We utilised the six key concepts form the scoping review as a lens, and our expertise in HCI and HCAI in order to decide the relevancy of the included additional literature. Our review process prioritised relevance and applicability over comprehensiveness [14]. As this was pragmatic review, our inclusion and exclusion criteria were loose and we did not have rigid protocols: those that seem most relevant, insightful, or authoritative for our study purpose, prioritising usefulness over strict comprehensiveness. We added total 10 academic papers to our study corpus. For the industrial reports, we utilised Google search. We utilised following keywords: *AI report; human-AI collaboration; AI in manufacturing; and Industrial AI*. We found several reports and based on their content

we selected one providing relevant content to our study. We added nine industrial reports to our study corpus. Comprehensive list of all the literature included to our study corpus in in Appendix X.

Expert interviews

Process: To extend and compliment the literature review, we conducted nine expert interviews with participants working in manufacturing-related roles. Expert interviews are a qualitative study method that offers a valuable tool to guide theory advancement [2]. They are a great tool to explore how the experts see the phenomena and the current situation, and what kind of recommendations they can give based on their expertise. Our semi-structured interviews focused on the topic of human-AI collaboration within the context of manufacturing. We had eight pre-prepared questions related to the scope of our study: (i) experiences with AI-supported work, (ii) perceived challenges in human-AI collaboration, (iii) needs and expectations for AI design. We sent the questions to the participants beforehand, so that they got an opportunity to familiarise themselves with the questions before the interview. In addition, we clearly communicated the objective of the interview and our study. Interviews were held in the language preferable for the participant (Finnish or English). All interviews were conducted remotely through Microsoft Teams. The interviews lasted approximately 53 minutes (shortest was 29 minutes and the longest lasted 1 hour and 27 minutes). All Interviews were recorded and transcribed for analysis purposes, resulting in approximately 53 000 words of textual data.

Participants: To get a comprehensive view on the topic, we were aiming to have experts from three different categories: designers, academics, and manufacturing company representatives. However, we were not able to recruit anyone from manufacturing companies to participate. Hence, we recruited designers and researchers who are familiar with manufacturing as a domain. We had nine expert participants. All participants had experience on humans collaborating with AI powered solutions. All participants work in Finland. Table 1 provides more detailed information of the participants. We had one pilot interview, and based on that, we added more information to the information about the study purposes and word definitions. In addition, we did some modification to the phrasing of the question. However, these changes were minor (and not related to the content) that we included the results of the pilot interview to our study. See the participant information in Table 1.

Table 1
expert interview participant information

Reference	AI-experience	Position
P1	Robotics	Designer / researcher
P2	Robotics	Designer / researcher
P3	AI in general	Researcher
P4	AI in general	Software developer
P5	Voice-based AI solutions	Researcher
P6	AI in general	Researcher
P7	AI in general	Researcher
P8	AI in general	Designer / researcher
P9	AI in general	Researcher

3.4 Data analysis

We combined all the data - the insights from the scoping review, additional literature, and expert interviews - and we conducted thematic analysis to identify design dimensions, requirements, and guidelines for human-AI collaboration in manufacturing. We analysed the combined data using hybrid deductive-inductive thematic analysis in order to collect design requirements. This method is useful in studies that seek to extend existing theoretical understanding while remaining open to new insights emerging from the data [1]. The six concepts from the scoping review [14] served as our initial analytical lens (*deductive*). However, we remained open to new themes emerging from the new data (*inductive*). Some concepts were added, merged, renamed, or redefined to better represent the observed design considerations. To strengthen the validity of the findings, we utilised data triangulation method suggested by Patton [20]. We combined evidence from the previous scoping review, supplementary literature, industrial reports, and expert interviews. The utilisation of multiple data sources enabled the identification and verification of recurring themes and design considerations across both academic and practitioner perspectives [20]. We recognised eight reoccurring themes that we call ‘*design dimensions*’ (*concepts* in the scoping review) and we extracted total 87 design requirements from the data that we incorporated into the refined framework. The full list of the design requirements, their source, and their involvement to design guidelines and considerations is in *Appendix 2*.

4. Findings: Design requirements for human-AI collaboration in manufacturing

This chapter presents eight design dimensions and related requirements resulting from our thematic data analysis. As recommended in literature, each section begins with an introductory discussion of design dimension relating to the general functional area. This discussion combines findings from

literature and expert interviews. That discussion provides perspective for the requirements and guidelines that follow in the next chapter [26].

Design dimension (previous 'concept')	Definition
1. Pre-design considerations	what should be understood and prepared before designing a human-AI collaboration?
2. Task configuration	what work is being done and how?
3. Collaboration team	who collaborates?
4. Skills and skill development	what can collaborators do and how do they develop?
5. AI characteristics	what characteristics should the AI collaborator possess?
6. Interaction and communication	how do collaborators exchange information?
7. Collaboration infrastructure	what enables the collaboration?
8. Organisational responsibilities	what organisational conditions support the collaboration?

4.1 Pre-design considerations

Pre-design considerations refer to the considerations that should be done before the design.

4.1.1 Collaboration goals and context

Literature strongly suggest that the purpose and context of the collaboration should be clearly defined before designing human-AI collaboration systems. In literature, the collaboration goal refers to the intended outcome of the collaboration and may focus on process-related objectives, such as improving productivity or efficiency, or on team-related objectives, such as enhancing the capabilities and learning of the collaborators (L13, L15, L20, L30). The selected goal influences design decisions, including task allocation, interaction design, performance expectations, and evaluation criteria (L30). From a human-centred perspective, the expected benefits for workers should be considered when defining collaboration goals (L11). Both literature and interview findings emphasise the importance of establishing realistic expectations and clear success criteria for the collaboration. Appropriate evaluation metrics should be aligned with the intended objectives and may include both technical outcomes, such as performance or efficiency, and human-centred outcomes, such as worker well-being and user experience (L13, L30). Interview participants also stressed that the collaboration should be designed to support the actual work task and problem being addressed, rather than introducing AI for its own sake (P1). The findings also highlight the importance of understanding the deployment context before design activities begin, because the collaboration is shaped by the manufacturing environment possibilities and constraints (L22). Factors such as noise, dust, physical workspace characteristics, and operational requirements

may influence technology choices, interaction methods, displays, and alarm mechanisms (L11, L13, L16). Interview participants also noted that understanding the problem, key tasks, and operational environment helps create a shared understanding among stakeholders and guides coming design decisions (P8).

4.1.2 Understand and prioritise worker needs and co-design

Both the literature and expert interviews emphasise that human-AI collaboration design should adopt a human-centred approach, prioritising the needs, capabilities, rights, and well-being of the workers affected by the collaboration (L16, L22, L25). Rather than focusing solely on technological capabilities, the design process should consider the broader socio-technical work system, including work organisation, task characteristics, contextual factors, and the implications of AI adoption for workers (L16). The findings highlight the importance of understanding the manufacturing context, users, and work practices before design activities begin. Literature advocates involving users and stakeholders throughout the design process through participatory and co-design approaches (L7, L16, L22), allowing workers to contribute their expertise, express their needs and concerns, and influence decisions that directly affect their work. Experts strongly agreed with the literature. Participants repeatedly emphasised that manufacturing workers possess valuable experiential knowledge of everyday work and should therefore actively contribute to collaboration design (P4, P5, P6). Experts further highlighted the importance of understanding workers' current tools, work practices, challenges, expertise, and familiarity with AI technologies before proposing design solutions (P5, P6). Both the literature and interviews also emphasise that human-centred design should continue throughout the development process rather than being limited to an initial requirements-gathering phase. Participants stressed the importance of beginning with user research to understand the problem, users, and context of use, followed by iterative prototyping, evaluation, and refinement based on continuous user feedback (P6, P8). In addition, experts underlined the importance of multidisciplinary collaboration during the collaboration design and development. Human-AI collaboration design requires expertise from multiple domains, including design, engineering, AI development, manufacturing operations, and end-user work practices (P1).

4.1.3 Organisational readiness and maturity

Both literature and interview findings highlight the importance of understanding an organisation's current state before designing and implementing human-AI collaboration solutions. Participants emphasised that information about existing processes, previous experiences with AI and digital technologies, organisational capabilities, and implementation practices provides valuable input for design activities (P1). In particular, readiness or maturity assessments were viewed as useful tools for evaluating the readiness of both the organisation and workforce for human-AI collaboration initiatives. Participants also noted that successful implementation depends not only on technological capabilities but also on organisational openness and support for AI adoption (P1). Assessing organisational maturity can therefore help identify strengths, limitations, and potential barriers before implementation, enabling solutions to be tailored to the specific context and capabilities of the organisation.

4.1.4 Ethical and responsible AI considerations

Literature highlights the importance of considering ethical issues and human values before the design. The literature emphasises that ethical considerations should be treated as design requirements rather than secondary concerns (L6, L22). Human-AI collaboration should therefore be designed in a way that aligns with organisational values, societal expectations, and relevant regulations. The experts emphasised the importance of maintaining a human-centred perspective in AI adoption. Several participants argued that AI should primarily augment human capabilities rather than replace human workers (P2, P3, P7). Participants also raised concerns regarding biased systems, worker surveillance, privacy implications of data collection technologies, and the long-term societal consequences of AI adoption (P2, P4, P8).

4.2 Task configuration

Human-centred task design is about allocating activities, responsibilities, and authority between humans and AI collaborators in a way that supports human well-being, meaningful work, safety, productivity, and effective collaboration. Literature emphasises that effective human-AI collaboration depends on clearly structured tasks and coordinated activities. Collaboration tasks in manufacturing consist of manual or non-manual actions that usually are connected. They can range from single operations to sequential processes (L14, L30, L34). These tasks require explicit definition of responsibilities, visibility of task progress, and shared understanding of how collaborating agents' individual contributions relate to the overall collaboration goal (L20, L21). Literature emphasises the importance of task allocation. Tasks should be distributed according to the capabilities, knowledge, and skills of the collaborators, ensuring that each activity is performed by the actor best suited for it (L11, L15, L16, L34). AI collaborators are particularly suited for tasks requiring speed, scalability, repeatability, data processing, and analytical reasoning, while humans contribute contextual expertise, creativity, social intelligence, flexibility, and the ability to manage unexpected situations (L1, L2, L16, L18, L20). Human-centred task allocation seeks to improve worker safety, ergonomics, and well-being by assigning repetitive, hazardous, physically demanding, or cognitively intensive activities to AI collaborator whenever appropriate (L2, L4, L11, L16, L20, L22). At the same time, human participation should remain meaningful and active, preserving human agency, oversight, and decision-making authority (L2, L16, L19, L33). The literature highlights the risk that poorly designed task allocation can reduce cognitive engagement and transform human work into passive monitoring, potentially leading to skill degradation and reduced job meaningfulness (L16, L15). In addition, literature emphasises the importance of clearly defining roles, responsibilities, and contributions within collaborative tasks (L11, L16, L21, L30, L33). Individual activities should have clearly identified executors, responsibilities should align with collaborators' capabilities, and the overall task structure should be documented and communicated transparently to all participants (L21, L18). In dynamic manufacturing environments, task allocation and responsibilities may need to evolve over time as situations, technologies, and operational requirements change (L15, L11, L13).

The interviewed experts strongly support these literature observations. Participants described collaboration tasks as shared activities in which humans and AI pursue the same overall objective while taking responsibility for different roles and subtasks (P1). Experts emphasised that collaboration should utilise complementary strengths, with AI contributing broad computational capabilities and humans contributing specialised expertise and contextual understanding (P2). The interviews also highlighted different collaboration arrangements, including situations where AI supports human work and situations where humans support AI by contributing domain knowledge and task-specific expertise (P2).

4.3 Collaboration team

In literature, human-AI collaboration in manufacturing is conceptualised as a collaboration team consisting of one or more human and AI actors working together towards a shared goal (L9, L10, L15, L18, L16, L30, 34). Depending on the manufacturing context, AI collaborators may take the form of virtual assistants, chatbots, intelligent software agents, or AI-enabled robotics (L17, L18, L23, L26). While the team and its structure may vary across contexts (L26, L28, L33, L34), the underlying principle remains the same: human and AI collaborators contribute different capabilities towards achieving a common objective.

Experts strongly supported the importance of complementary strengths. Experts described human-AI collaboration as a partnership in which humans contribute specialised domain expertise while AI contributes computational capabilities and broad knowledge resources (P2). Several participants emphasised that humans should maintain responsibility for defining goals, evaluating outcomes, and leading the collaboration, while AI supports human work by performing repetitive or otherwise burdensome activities (P5, P8). This aligns with the literature's emphasis on maintaining meaningful human involvement in collaborative work. The interviews also revealed different hierarchy perceptions. While some participants viewed AI primarily as an advanced tool supporting human work (P7), others argued that effective collaboration requires treating AI as an equal teammate whose contributions are respected and incorporated into the collaboration process (P5). Despite these differing views, experts generally agreed that collaboration should be based on cooperation rather than competition, and that AI should enhance the human role (P2, P5, P8). In addition, they emphasised the mutual support.

4.4 Skills and skill development

Literature identifies skills and skill development as fundamental enablers of successful human-AI collaboration in manufacturing. As manufacturing technologies, AI technologies and solutions, and work processes continue to evolve, both human and AI collaborators require new competencies and continuous development to participate effectively in collaborative work (L1, L16, L17, L19, L21, L15, L16). Literature emphasise that collaboration introduces not only task-specific skill requirements, but also additional competencies related to working with AI. Effective collaboration depends on the capabilities, knowledge, and expertise of both human and AI collaborators, and the skills of the collaborators should align with the requirements of both the task and the collaboration itself (L5, L20, L30, L43). In particular, human workers require sufficient expertise to operate AI-supported systems, interpret AI outputs, assess

AI capabilities and limitations, and participate in collaborative decision-making processes (L1, L21, L40). Additionally, literature stresses that task demands should remain compatible with human capacities and skill levels to support performance, trust, and worker well-being (L7, L11, L21, L19, L16). Poorly designed task may place excessive cognitive demands on workers, requiring them to manage complex technologies or intervene in unexpected situations without adequate preparation (L16). Therefore, in literature skill development is identified as critical requirement for successful human-AI collaboration (L15, L21, L19, L1, L4, L35, L23). As technologies and work environments evolve, continuous upskilling, reskilling, and learning are necessary to address emerging skill needs and maintain workforce competence (L15, L39).

Experts strongly support these literature observations. Participants repeatedly emphasised that workers must understand how AI operates, what they are capable of doing, and where their limitations lie in order to collaborate effectively with them (P5, P6, P8). Several experts highlighted that AI-generated outputs should not be accepted uncritically; instead, workers need sufficient domain expertise and AI-related competencies to evaluate the validity and usefulness of AI recommendations within the specific work context (P5, P8). Participants also stressed the importance of practical guidance and training that helps workers understand how to use AI solutions appropriately, how to benefit from them, and how to avoid misuse (P5, P6).

Important finding from both the literature and interview indicates that skill development should be a continuous and bidirectional process. Human collaborators require ongoing training and support to adapt to evolving technologies, while AI collaborator benefits from human feedback, guidance, and expertise to improve their performance over time (L4, L12, L15, L19, L12, L8, P2). The interviews additionally highlighted concerns regarding overreliance on AI and the potential loss of human expertise if workers become passive recipients of AI recommendations rather than active participants in the collaboration (P7).

4.5 AI agent characteristics

Literature suggests that successful human-AI collaboration depends strongly on the AI collaborator characteristics and behaviours. AI collaborator should possess qualities that support effective collaboration, reliance, safety, and human oversight in complex manufacturing tasks and environments.

Transparency emerged as one of the most important AI characteristics. Existing studies emphasise that transparent AI should clearly communicate their capabilities, limitations, reasoning processes, actions, and current state to human collaborators (L13, L20, L33). Literature suggests that AI collaborator should be able to communicate limitations, uncertainty, and inability to perform tasks when necessary, enabling humans to make informed decisions regarding reliance on AI support (L14, L30, L33). Transparency is particularly important in manufacturing environments where AI is often perceived as black boxes and where incorrect decisions may have safety, operational, or financial consequences. By making uncertainty, confidence levels, and performance limitations visible, transparent AI support trust, situational awareness, and appropriate human oversight (L30, L33). Closely related to transparency is

explainability. Literature argues that AI should provide understandable explanations regarding how decisions are made, why recommendations are generated, and how outcomes are produced (L2, L21, L30, L33, L34). Explanations should be tailored to users' expertise, situational demands, and information needs, helping workers develop accurate mental models of the AI collaborator, and enabling them to detect, anticipate, and correct potential errors (L21, L33). In addition, important for successful collaboration is that AI collaborator should be capable of understanding human teammates, including their intentions, goals, actions, and situational needs, to support efficient and failure-free collaboration (L4, L7, L13). Effective collaboration also requires AI collaborator to maintain awareness of human collaborators' status and intentions and to coordinate actions in ways that support rather than burden human workers (L33). A recurring theme across the literature is adaptability. AI collaborator should adjust their behaviour to changing tasks, environments, and human needs when needed. This includes adapting to individual workers' capabilities, preferences, and working styles, as well as modifying collaboration strategies as situations evolve (L34).

Experts strongly agreed with these literature observations. Several participants identified workers' limited AI understanding as one of the major challenges for successful collaboration (P6, P7, P8). Experts emphasised that AI should clearly communicate what they can and cannot do, what kinds of outputs users can expect, and on what basis recommendations or decisions have been made (P6, P8). Participants also stressed that transparency must be understandable and appropriately balanced, providing sufficient information to support decision-making without overwhelming workers (P7). Additionally, interviewees highlighted the importance of interactive explainability, where users can request rationales or additional information regarding AI-generated recommendations (P6).

4.6 Interaction and communication

In literature, interaction and communication emerged as fundamental elements of human-centred human-AI collaboration in manufacturing. Literature emphasise that successful collaboration depends on effective bidirectional communication between human and AI collaborators (L7, L19, L13, L15, L33). While communication focuses on the exchange of information between collaborators, interaction encompasses the broader processes through which humans and AI coordinate activities, exchange feedback, build shared understanding, and work towards common goals. Communication should support not only information exchange but also the development of common ground between collaborators, enabling them to coordinate activities efficiently and respond appropriately to changing circumstances. Literature identifies two primary purposes of communication within human-AI collaboration. First, communication supports task execution by conveying operational information such as instructions, warnings, recommendations, status updates, and task-relevant knowledge (L3, L12, L19, L13). Second, communication enables reciprocal feedback and coordination between collaborators, helping humans and AI align actions, monitor progress, and adjust their behaviour as collaboration unfolds (L13, L20, L21). Through these processes, communication contributes to trust, cooperation, and the development of mutually beneficial working relationships (L3, L12, L19).

A recurring theme across the literature is the importance of mutual understanding. Effective collaboration requires both human and AI collaborators to maintain sufficient awareness of the task, environment, collaboration process, and each other's actions and intentions (L7, L12, L18). Human-AI communication is therefore dynamic and context-dependent, shaped by the specific situation, task demands, and operational environment (L12, L14, L13, L20, L34). Literature also emphasises the importance of multimodal and adaptive interaction. Human-AI communication can be verbal communication, or non-verbal gestures, body movements, visual cues, augmented reality interfaces, behavioural signals, and other direct or indirect forms of interaction (L5, L13, L40, L38). The suitability of different communication strategies depends on contextual factors such as task characteristics, environmental conditions, user preferences, cognitive workload, and operational constraints (L15, L19, L35, L37). Therefore, communication should be adapted to human collaborator's needs, capabilities, and readiness, ensuring that information is delivered in an understandable manner and at an appropriate time (L15, L30, L33, L34).

Experts' views align with these literature findings. Participants emphasised the importance of mutual understanding between the collaborators. Experts highlighted that AI collaborator should better understand human intentions, environmental conditions, and task situations in order to provide appropriate support and reduce collaboration effort (P5). Participants also noted that monitoring AI can create additional cognitive burden for workers, particularly when system behaviour is unclear or unexpected. In such situations, AI should actively communicate what has happened, why a problem has occurred, and how the issue might be resolved (P5). This type of proactive communication was viewed as essential for effective cooperation and team performance. One expert introduced a novel topic in the collaboration communication – the social aspect of the AI collaborator.

4.7 Collaboration infrastructure

Literature emphasise that collaboration infrastructure serves as the coordinating mechanism that connects collaboration goals, tasks, collaborators, and the manufacturing environment. Rather than collaboration occurring directly between human and AI collaborators alone, most interactions, information exchanges, and collaborative activities are mediated through an infrastructure that connects human operators, AI solutions, production equipment, and the surrounding manufacturing environment (L9). Effective infrastructure provides relevant and timely information regarding the collaboration process, task status, system state, and environmental conditions, enabling human and AI collaborators to coordinate their activities and make informed decisions (L1, L6, L11, L14, L18, L15, L19, L33). As manufacturing environments are dynamic and continuously changing, collaboration infrastructures must support adaptability, resilience, and continuous evolution alongside changing tasks, technologies, and user needs (L1, L11, L15, L16, L17, L2, L6, L14, L22). Literature commonly conceptualises these infrastructures as cyber-physical and socio-technical systems that integrate digital and physical processes to support collaborative work (L6, L11, L13, L16, L17, L19, L22).

Situational awareness emerged as a central function of collaboration infrastructure. The literature highlights that effective collaboration depends on providing collaborators with access to relevant

information about tasks, roles, system status, environmental conditions, and collaboration progress (L15, L16, L33, L34). Shared displays, dashboards, visualisations, confidence indicators, alarms, and other information-sharing mechanisms support the development of situational awareness and enable human operators to maintain oversight of AI-supported operations (L33). Since humans ultimately remain responsible for collaboration outcomes, they require sufficient awareness of what the AI is doing, why actions are being taken, and when intervention may be necessary (L19, L22, L33).

In addition, literature stresses the importance of designing information infrastructures that balance information availability with cognitive demands. Manufacturing workers often operate in information-rich environments where critical information can easily become lost among competing signals. Therefore, collaboration infrastructure should present relevant information in accessible, understandable, and salient forms while minimising information overload (L19, L33). Multimodal interfaces, shared displays, context-aware interaction mechanisms, and ergonomic interface designs can support effective information management and decision-making in dynamic production environments (L2, L11, L19).

Experts added to the literature findings by emphasising the importance of information and data as a foundational component of collaboration infrastructure. Participants repeatedly identified data quality, data availability, data integration, and data security as critical prerequisites for successful human-AI collaboration (P2, P4). Experts stressed that AI can only perform as effectively as the data on which they are trained and operated, and poor-quality or unavailable data can significantly undermine collaboration performance regardless of the quality of the system design (P2). Participants also highlighted challenges related to integrating data from multiple sources, ensuring data security, and addressing privacy concerns associated with worker monitoring technologies and sensor-based data collection (P4).

4.8 Organisational considerations and responsibilities

Literature emphasises that successful human-AI collaboration depends not only on system and interaction design, but also on organisational readiness and support. In manufacturing contexts, organisations play a critical role in enabling collaboration by providing appropriate resources, training, and governance structures (L15, L23). A central theme is the importance of continuous workforce development. Rapid technological change and increasing use of AI create significant skill gaps in manufacturing, which can hinder adoption and effective use of new technologies (L15). Insufficient training may lead to human errors, incorrect decision-making, and reduced ability to detect abnormal system behaviour (L19). Therefore, organisations must provide ongoing training and reskilling opportunities to ensure that workers can effectively collaborate with AI (L15, L23). Training should not be limited to initial onboarding but must be continuous and adaptive, reflecting evolving technologies, tasks, and work environments. This includes both formal training and work-based learning opportunities integrated into everyday operations. In addition, training should support understanding of AI behaviour, including its capabilities, limitations, and expected performance, which is particularly important for building appropriate expectations and decision-making practices (L33). Literature also emphasises that organisations must consider human-centric factors, including safety, worker well-being, and meaningful

work. Human-AI collaboration should be designed and implemented in ways that support workers' physical and cognitive capacities, as well as their long-term professional development (L15). In addition, organisations are responsible for defining roles, responsibilities, and accountability in AI-supported work processes. As humans are typically accountable for outcomes in manufacturing environments, clear governance structures are required to ensure safe and reliable AI operation (L14, L33).

5. Discussion

We reviewed literature and conducted expert interviews in order to collect design requirements for human-centred collaboration design in manufacturing domain. Our study findings strongly suggest that successful human-AI collaboration in manufacturing cannot be understood solely as an interaction or UI design problem. Therefore, we state that effective collaboration design requires socio-technical approach combining human, technological, task-related, and organisational factors. We like to mention that unlike in the current human-AI interaction literature, in our work, the design target is not AI design, but the collaboration, where AI is one actor participating in the collaboration. In addition, the design target is not the design of the AI system or its UI, but instead this design instruction includes the "collaboration infrastructure" that enables and supports the collaboration. Hence, this infra is not the AI system, but AI is part of this bigger manufacturing infrastructure that enables and supports the collaboration. In addition, our work stresses the importance of the deploying organisation, and their responsibilities in facilitating the collaboration and AI adoption in general. This is different perspective than the prevailing view in recent human-AI collaboration and interaction literature. We combined data from different sources and thematically analysed it in order to collect design requirements. Our thematic analysis revealed eight design dimensions to acknowledge in comprehensive and context-relevant collaboration design. Across the design dimensions, four higher level human-centred design principles emerged from both literature and interviews:

Principle 1. *Augmentation rather than automation*

Reoccurring theme across the findings is that AI should augment rather than replace human capabilities. Rather than viewing AI as a substitute for human workers, the framework conceptualises AI as a collaborative actor whose role is to complement human expertise, compensate for limitations, and support workers in achieving their goals. These findings strongly aligns with the notions from previous collaboration literature and supports the aims of HCAI and Industry 5.0.

Principle 2. *Meaningful human involvement*

Both the literature and interview findings stressed the importance of maintaining meaningful human involvement, control, and oversight. Although AI may increasingly take part on conducting manufacturing work tasks, collaboration should preserve workers' expertise, autonomy, engagement, and well-being while ensuring that humans remain active participants in the collaborative process. Reducing the human role to passive monitoring of AI activities may make work less meaningful and engaging while limiting opportunities to apply and develop skills. Over time, this may contribute to the loss of important human

expertise and competencies as workers become increasingly dependent on AI-generated recommendations and decisions. Hence, maintaining meaningful human involvement is important for ensuring oversight and accountability, and for supporting worker motivation, competence, skill development, and long-term well-being.

Principle 3. Understandable collaboration

Our findings contribute to current discussions on transparency, explainability, and trust in human–AI collaboration. Existing literature often treats explainability as a one-way process in which AI provides explanations to human users. However, our interview findings suggest a more interactive perspective. Participants emphasised not only the importance of receiving explanations but also the ability to actively request additional information and clarifications when needed. We therefore argue that explainability should be viewed as an interactive communication process rather than a one-way information provision mechanism. While AI should proactively communicate its actions, limitations, and uncertainties, human collaborators should also be able to seek additional explanations when deeper understanding is required. This perspective is particularly relevant in manufacturing environments where misunderstandings may have safety, quality, or productivity implications. Related to this, our findings challenge the common assumption that collaborative AI should always behave predictably. As AI systems increasingly learn and adapt, complete predictability may not always be achievable or desirable. Instead, workers primarily require sufficient understanding of AI behaviour to make informed decisions regarding trust, reliance, and intervention. Consequently, we argue that transparency, explainability, and communication mechanisms should focus on supporting understanding rather than predictability.

Principle 4. Manufacturing-specific teaming

Our findings stress important manufacturing-specific perspective for human-AI teaming. Much of the existing teaming literature emphasises adaptive teams as a key characteristic for effective collaboration. However, we found that in manufacturing environments human and AI collaborators are brought together because there is a task, process, or production goal that needs to be achieved. Hence, changes in collaboration are primarily driven by changing task requirements, production goals, and operational conditions rather than changes within the team itself. Therefore, we argue that collaboration designers should focus on creating adaptive task configurations that allow work allocation, roles and responsibilities to evolve while continuing to utilise the complementary strengths of both human and AI collaborators.

6. A human-centred design framework and related design guidelines

Our study findings strongly show that successful human-AI collaboration design cannot be understood solely as an interaction design problem. Instead, effective collaboration requires consideration of factors before design, during collaboration design, and after deployment through organisational support. Hence, our refined design framework consists of three-level design considerations:

6.1 Refined design framework and proposed guidelines

In this study, we built upon the conceptual framework proposed by Hartikainen et al. [6], which identified six key concepts relevant to human-AI collaboration design in manufacturing: collaboration goal, collaboration team, collaboration task, skills, collaboration system, and communication. While the original framework provided a useful conceptual foundation, the additional literature and expert interviews enabled us to develop a more detailed and design-oriented understanding of these concepts.

Our findings largely confirmed the original concepts but also revealed the need for refinement. First, we repositioned collaboration goal as an a-priori design consideration, as our findings suggest that the purpose, scope, and expected outcomes of the collaboration should be defined before collaboration design begins. Second, we refined collaboration system into collaboration infrastructure to reflect a broader socio-technical perspective that encompasses information flows, situational awareness support, interfaces, sensors, and coordination mechanisms. Third, we expanded communication into interaction and communication to better capture the reciprocal, adaptive, and collaborative nature of human-AI teamwork. In addition, we identified three new design dimension that were not explicitly represented in the original framework. We introduced *AI characteristics* as a distinct design dimension to capture the importance of transparency, explainability, adaptability, and proactivity in collaborative AI behaviour. We also added *organisational responsibilities* to capture the role of workforce development, governance, data management, and human-centred implementation. Finally, we introduced *pre-design considerations* to emphasise the importance of understanding collaboration goals, organisational readiness, stakeholder needs, contextual requirements, and ethical implications before design activities begin. These refinements resulted in a socio-technical framework and related design guidelines: The proposed refined framework adopts a socio-technical perspective where human, technological, task-related, and organisational considerations intersect across all design dimensions. Rather than treating these elements separately, the framework integrates them throughout the design process. Through this structure, we conceptualise human-AI collaboration as a collaborative team consisting of human and AI actors working towards a shared goal through task configuration and interaction, enabled by a socio-technical infrastructure and embedded within an organisational context. See the design framework in Fig. 1.

Our analysis identified a large number of detailed design requirements (total 87) across the different design dimensions. To improve their practical applicability, we synthesised these requirements into a smaller set of higher-level design activities and guidelines. This abstraction enabled us to balance comprehensiveness with usability, reducing complexity while preserving the underlying design insights. The resulting 19 guidelines and related activities provide actionable direction to designers and manufacturing companies while remaining applicable across different manufacturing contexts and technologies. See the guidelines and related design considerations in *Appendix 3*.

PRE-DESIGN ACTIVITIES

Pre-design activities shape the design process itself by ensuring that collaboration goals, contextual constraints, stakeholder needs, organisational readiness, and ethical implications are understood before design decisions are made.

Pre-design activity1: Define the collaboration goal, expected benefits, and evaluation metrics

Clarify why the collaboration is needed and what outcomes it should achieve. / Goals influence task design, team requirements, interaction design, performance expectations, and evaluation criteria.

Pre-design activity2: Understand the manufacturing context and select fitting technologies and interaction methods

Ensure the collaboration design fits the operational environment.

Pre-design activity3: Assess organisational readiness

Understand whether the organisation, workforce, technologies, and processes are prepared for the intended collaboration.

Pre-design activity4: Involve users and stakeholders in design

Ensure the collaboration reflects real work needs and worker perspectives.

Pre-design activity5: Use HCD approach throughout the collaboration design and deployment

Support feasible and effective human-AI solutions.

Pre-design activity6: Address ethics and human values in the design

Ethical concerns and human values should be treated as design requirements, and they should be considered before collaboration implementation to ensure responsible and human-centred collaboration.

COLLABORATION DESIGN GUIDELINES

Collaboration design guidelines guide the design of the collaboration itself through six design dimensions: (i) task configuration, (ii) collaboration team, (iii) skills and skill development, (iv) AI characteristics, (v) interaction and communication, (vi) collaboration infrastructure.

Guideline1: Clearly define and communicate collaborative task structures and collaborators' roles and responsibilities in it

Successful collaboration requires collaborators to understand what needs to be done, who is responsible for each activity, and how individual contributions support shared goals.

Guideline2: Allocate work according to task requirements and collaborator capabilities

Appropriate task allocation allows AI to support human work while improving performance, safety, ergonomics, and well-being.

Guideline3: Maintain meaningful human involvement and agency

Human-centred collaboration requires workers to remain active contributors rather than passive observers. Meaningful involvement supports engagement, skill retention, accountability, trust, and worker well-being.

Guideline4: Design for adaptive task allocation

Manufacturing environments are dynamic, requiring task configurations to evolve in response to changing conditions, technologies, collaborators, and operational requirements. // Manufacturing environments, tasks, technologies, and collaborators continuously change

Guideline5: Build collaboration teams by matching task requirements with complementary human and AI capabilities

Skills demand should be derived from the task requirement, and the team should be assembled to match those requirements. Human-AI teams perform best when collaborators contribute according to their individual strengths and limitations.

Guideline6: Support cooperative and mutually beneficial teaming

Effective collaboration depends on collaboration being perceived as a cooperative partnership rather than a competitive or purely supervisory relationship.

Guideline7: Ensure collaborators possess the skills required for the task

Effective collaboration depends on human and AI collaborators possessing sufficient knowledge, expertise, and capabilities to perform their assigned responsibilities.

Guideline8: Support AI collaboration literacy

Human collaborators require specific AI-related skills to collaborate effectively with AI beyond those needed to perform the task itself.

Guideline9: Design collaboration to preserve and develop human expertise

Human-AI collaboration should preserve and strengthen human collaborators skills and expertise.

Guideline10: Design AI collaborators that are understandable to human collaborators

Human collaborators must be able to understand AI behaviour, reasoning, capabilities, limitations, and uncertainty sufficiently to support effective collaboration, informed decision-making, and appropriate reliance.

Guideline11: Design adaptive AI collaborators

Human-centred and effective collaboration requires AI to adjust its behaviour to changing tasks, environments, operational conditions, and human collaborators.

Guideline12: Design proactive AI collaborators

AI should actively contribute to collaboration by identifying relevant information, emerging issues, and support opportunities rather than only responding to explicit requests.

Guideline13: Design communication to support coordination and collaboration

Human-AI collaboration depends on effective information exchange that enables collaborators to coordinate activities, monitor progress, exchange feedback, and work towards shared goals.

Guideline14: Support mutual understanding between collaborators

Successful collaboration requires human and AI collaborators to develop sufficient understanding of the task, environment, collaboration process, and each other's intentions and actions.

Guideline15: Design adaptive and multimodal communication

Communication needs vary according to tasks, environments, user characteristics, and operational constraints. Effective collaboration requires flexible communication mechanisms that adapts to user and contextual needs.

Guideline16: Design information delivery to be timely, context-aware, and actionable

The value of information depends not only on its content but also on when and how it is delivered. Timely and proactive communication can improve coordination, reduce workload, and support decision-making.

Guideline17: Design infrastructure that enables coordinated and informed collaboration

Human-AI collaboration depends on infrastructure that connects collaborators, tasks, systems, and the manufacturing environment, enabling coordinated action and decision-making.

Guideline18: Support situational awareness and human oversight

Effective collaboration requires collaborators, particularly human workers, to maintain awareness of tasks, system states, environmental conditions, and AI activities.

Guideline19: Design multimodal and adaptive information infrastructures

Human-AI collaboration relies on the information availability, quality, security, and accessibility.

ORGANISATIONAL RESPONSIBILITIES

Organisational responsibilities structures, practices, and policies that enable, constrain, and shape human-AI collaboration in manufacturing environments. Organisational support plays a critical role in creating the conditions that enable effective, safe, and sustainable human-AI collaboration.

Organisational responsibility 1: Support workforce development for human-AI collaboration

Organisations should ensure that workers possess the competencies required to collaborate effectively with AI technologies and adapt to evolving manufacturing environments.

Organisational responsibility2: Establish data governance and management practices

Human-AI collaboration relies on trustworthy, accessible, and well-managed data. Organisations are responsible for ensuring that AI systems have access to suitable data while protecting workers' rights and privacy.

Organisational responsibility3: Define governance, accountability, and responsible AI practices

Organisations should establish clear governance structures that define responsibilities, accountability, and acceptable AI use within manufacturing operations.

Organisational responsibility4: Promote human-centred organisational values

Organisations should ensure that AI adoption aligns with human-centred values and supports worker well-being, safety, and meaningful work.

7. Limitations and future study

This study has several limitations that provide opportunities for future research. First, although we synthesised evidence from a previous scoping review, supplementary literature, industrial reports, and expert interviews, the review was intended to provide a focused design-oriented synthesis rather than an exhaustive review of all literature related to human-AI collaboration. Future work could extend the framework by incorporating additional evidence from emerging research. Second, although the expert interviews included specialists in AI, human-centred design, and manufacturing, we were not able to recruit representatives from manufacturing companies directly responsible for designing and deploying human-AI collaborations. Including practitioners from manufacturing organisations could provide valuable insights into organisational needs, implementation challenges, and practical design requirements. Third, the proposed framework and design guidelines have not yet been validated in real-world manufacturing settings. Future work should evaluate their usefulness through expert evaluation and application in industrial case studies to assess their practical applicability and refine the framework further. Finally, one expert highlighted an emerging research topic that is currently underexplored in manufacturing: the role of AI collaborators' social characteristics in shaping collaboration. As AI solutions become increasingly interactive and agentic, understanding how social traits influence trust, communication, and collaboration represents an interesting direction for future research.

8. Conclusion

We investigated how human-centred human-AI collaboration in manufacturing can be supported through design. By synthesising evidence from a previous scoping review, supplementary literature, industrial reports, and expert interviews, we identified the key design requirements for human-AI collaboration and translated them into practical design guidance. The study resulted in a refined socio-technical framework for human-centred human-AI collaboration in manufacturing. The framework comprises six collaboration design dimensions, supported by pre-design considerations and organisational responsibilities, providing a holistic perspective on collaboration design that extends beyond the design of AI systems alone. Based on the identified design requirements, we further developed eighteen design guidelines and related design considerations that provide actionable support for designing effective, safe, and human-centred human-AI collaboration in manufacturing. We contribute to both research and practice by shifting the design focus from AI systems towards the design of human-AI collaboration as a socio-technical whole. Rather than viewing AI solely as a technological system, our framework conceptualises AI as a collaborative actor operating alongside human collaborators within a broader organisational and technological environment. We hope that the proposed framework and guidelines support researchers and practitioners in designing human-AI collaborations that align with the principles of Human-Centred AI and Industry 5.0 while promoting effective collaboration, worker well-being, and sustainable manufacturing.

Declarations

Funding declaration

This research was funded by Business Finland under grant 2451/31/2022

Ethical approval and accordance

Our study followed and was in accordance with the rules and policies of the Tampere University Ethics committee. Accordingly to those rules and policies, our study does not require an ethical review as it includes informed consent and does not involve any of the following: underage subjects, exposure to strong stimuli, potential long-term mental distress, or intervention with the physical integrity of participants. Our study was considered as low-risk and, hence, was ineligible to even apply for a review. The study participants were provided with a consent form that included a link to a detailed ethics disclaimer explaining the integrity and data management principles.

Consent to participate

All the study participants were provided with study informed consent -form before the study. The form included information about the study and its purposed. Participation was voluntary, and participants were informed of their right to withdraw from the study. Additionally, all the participants were provided detailed information what data we were collecting in the study, and about how the collected data was

being handled, saved, and deleted. All the study participants gave their consent to participate to the study before the study.

Consent to publish

Not applicable.

The datasets generated and analysed during this study are not publicly available due the protection of the anonymity of the participants, according to the Informed consent -form of this study.

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Figures

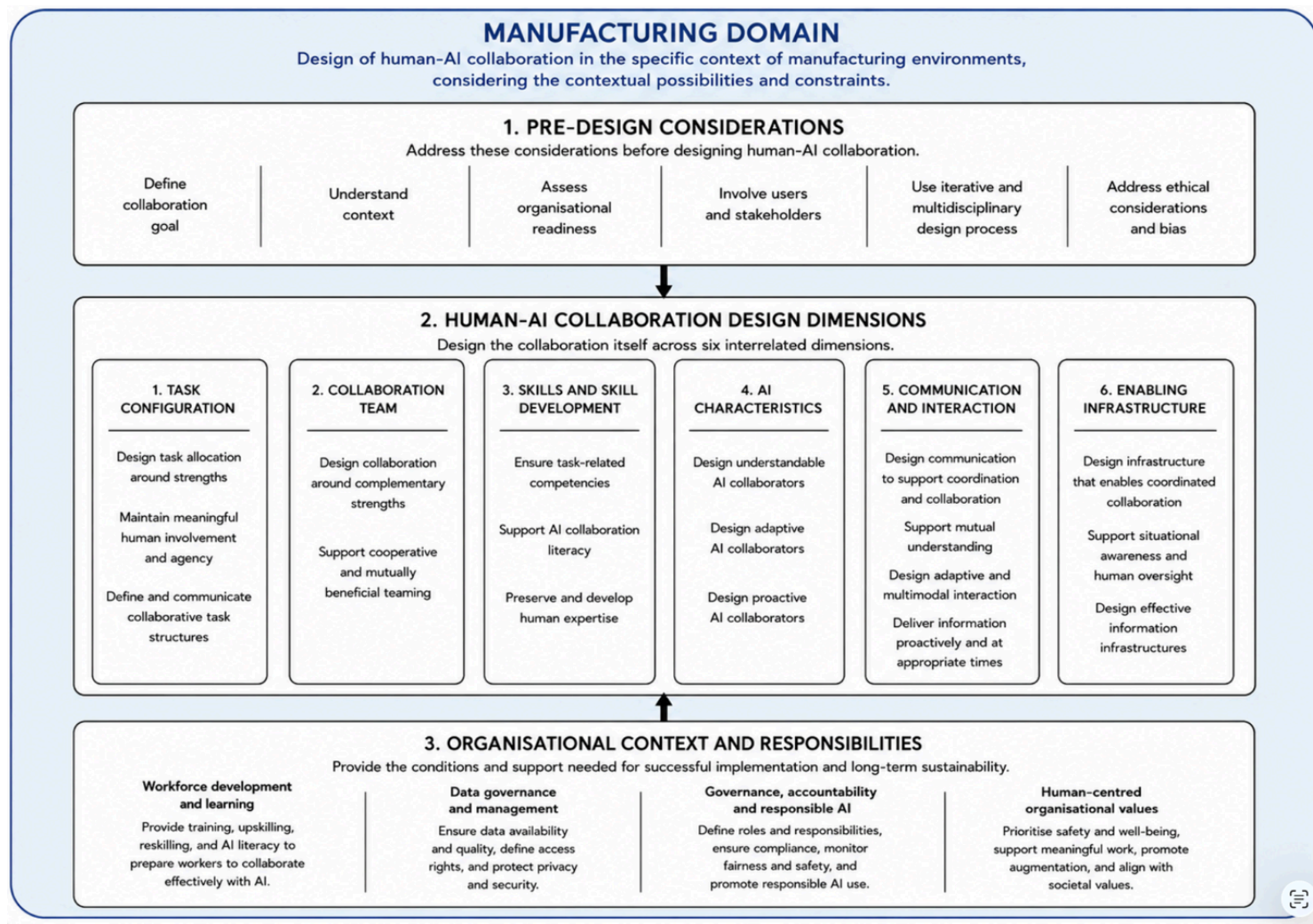


Figure 1

AI-created visualisation of the design framework for human-AI collaboration design for manufacturing

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