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REVIEW

A review of design frameworks for human-cyber-physical systems moving from industry 4 to 5

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Abstract

Within the Industry 4.0 landscape, humans collaborate with cyber and physical elements to form human-cyber-physical systems (HCPS). These environments are increasingly complex and challenging workspaces due to increasing levels of automation and data availability. An effective system design requires suitable frameworks that consider human activities and needs whilst supporting overall system efficacy. Although several reviews of frameworks for technology were identified, none of these focused on the human in the system (moving towards Industry 5). The critical literature review presented provides a summary of HCPS frameworks, maps the considerations for a human in HCPS, and provides insight for future framework and system development. The challenges, recommendations, and areas for further research are discussed.

KEYWORDS

cyber-physical systems, human factors, Internet of Things, manufacturing processes

1 | INTRODUCTION

The Industry 4.0 (I4.0) paradigm is built from digitalisation, the Industrial Internet of Things (IIoT), smart machines, wearable devices [1], data analytics, machine learning, and artificial intelligence (AI) to create smart factories and connected systems [2]. Despite increasing data analysis capabilities and levels of automation, humans remain the backbone of many creative, dynamic, and manually intensive industrial activities [3, 4]. The vital role of humans within industry as recognised in the emerging paradigm of Industry 5.0 (I5.0), concerns extend beyond efficiency metrics to include worker wellbeing, dignity and sustainable, resilient production [5]. Many complex interactions, decisions, and behaviours need to be captured and modelled to ensure system safety and performance in these contextually sensitive environments. The combination of technological and social elements referred to as Human-Cyber-Physical Systems (HCPS) require new design approaches [6].

Frameworks, standards and architectures are recognised due to their usefulness in supporting effective system design [7]. From an industrial standards perspective, there is an overview of cyber-physically controlled smart systems within a manufacturing context (BS ISO 23704 parts 1, 2, 3), which predominantly focuses on the interface between the cyber control and physical machine components to ensure manufacture in a standardised manner. There is a lack of information around the interface with the operator at all parts of this journey, however it is understood that standards for the process and data transfer underpin these industrial translation building blocks. To ensure full accessibility of an HCPS by a wide range of users, elements of the interface should align with BS ISO 20071 to ensure the digital boundary is effective for information security [4]. Advances in this space are underway within the transport sector with autonomous vehicles, and the medical sector [5, 6]. Both instances focus on the interface of the human and physical system, to ensure decision-making is fast and accurate within time critical and potentially dangerous scenarios. As the industry moves from I4.0–5, more social inclusion is required in regulating standards. This move is reflected in recent UK funding competitions, with the Made

Smarter Network Grant requiring a strong theme of social inclusion in all funding applications [7].

Although many established frameworks in the academic literature (e.g. RAMI 4.0 and IVRA [7]) nominally include people they do not adequately represent their *contributions to* nor *interactions with* the system [8]. Rad et al. reviewed developments in the Social Internet of Things from a technological perspective [9], and Ngoc et al. [10] highlighted a need for unified design frameworks that consider human centred design for HCPS. The Operator 4.0 (Op4) typology was proposed to incorporate humans in I4.0 systems by augmenting various capabilities [11]. However, as a typology rather than a framework it does not consider Human Factors Engineering (HFE) challenges nor the holistic integration of the augmented persons into processes and systems. Several literature reviews were identified from a technology perspective [7, 12, 13], including technologies needed for creating human digital twins [14]; however, no current review of HCPS was identified. A review is required to gain a view of the changing landscape and ensure humans are properly considered.

The research presented in this paper provides a critical overview of HCPS frameworks and from the reviewed research presents a mode showing how humans may be considered to support HCPS design. Three research questions were defined: (RQ1) What are the current frameworks for HCPS design? (RQ2) How are humans considered? and (RQ3) What are the HFE challenges and are these addressed? In Section 2, the method for the literature review is described. In Section 3, the results of the review are presented. In Section 3.1, the framework purpose, components, challenges, and opportunities are summarised. A combined map of the human representations and considerations are presented in Section 3.2. Section 3.3 gives an overview of challenges from an HFE perspective. Open issues and future perspectives are discussed in Section 4. Conclusions are presented in Section 5.

2 | SCOPE

An analysis of the literature was conducted to address RQ1 using terms presented in Yilma et al. (tab. 7, [6]). Web of Science and Science Direct were selected as databases for the review. The date restricted to after 2013, based on the Industrie 4.0 report [15]. A total of 28 frameworks were reviewed. Articles were rejected on full review if the framework was not the main focus, it was inadequately described or illustrated, the domain was not Industry or HCPS or it was less than 6 pages or full text not available.

The key contributions from this study are:

- Presentation of an overarching framework of considerations for HCPS design.
- Identification the key challenges found, namely; comfort, cognitive load, interaction technique, acceptance, perception, practicalities, allocation of function, and change of working practices.
- Exploration the Ethics and privacy of digital twins which remains an open research area.
- Identification of a need for standards and libraries to establish work thresholds, mapping technology to outcomes, to select the best technology for the task or use.

3 | RESULTS AND DISCUSSION

3.1 | RQ1: What are the current HCPS frameworks?

The frameworks were categorised into four emerging themes regarding the focus of the framework: system and work design, social, cognitive and physical augmentations. The approach, components, challenges and opportunities are detailed Table 1. Figure 1 provides an overview and the frameworks are reviewed below.

3.1.1 | System and work design

May et al. [16] proposed a comprehensive list of attributes required to model workers, their factory and context. However, the relevance and relationship to system performance was not explored and appropriateness of the extensive list was unclear. The Lifecycle 4.0 framework by ref. [17] matched activity complexity to interface affordances and provided constant feedback to operators regarding their cognitive and affective performance (i.e. the behavioural and emotional response to interface use). The goal was to develop dependency and to appeal to intrinsic motivators (i.e. using gamification). Their framework assumes the use of Op4 technologies can overcome operational challenges in volatile, uncertain, complex, and ambiguous environments and highlights the need for good interface design. Zhou et al. [18] proposed horizontal, vertical, and life cycle integration of humans contributing to interactive use and the creation of the HCPS considering the human creator. In their framework, the human and the CPS collaborate through cloud-based services in a continually updating loop; however, they do not consider how they identify which tasks are best suited to which system agent, that is, allocation of function. Sony and Naik [19] propose using socio-technical systems theory to optimise overall system performance by designing for human and CPS capabilities. They acknowledge this requires significant further work to establish how well such principles translate to dynamic I4.0 systems and a need for cross domain application in practice rather than theory.

Assessing change

Several frameworks indicated the need to evaluate the effect of change to system design from multiple perspectives, stakeholders, and throughout the lifecycle of system design and use [17, 19, 23, 24, 28]. To address changes caused by technology implementation, Fantini et al. [20] suggested evaluating problem setting, scoping and analysis from the perspectives of human and CPS components. They model the human

TABLE 1 Summary of purpose according to theme.

Theme	Ref	Purpose/*Approach*	Evaluation method: Industry	Lab	Theory
System and work design	[16]	Human centric factory model, detailing all possible data to be modelled. *Interview and case study analysis for development.*	-	-	-
	[17]	Lifecycle engineering for human centred manufacturing combining value chain and design for human factors in I4.0.			X
	[18]	Considering design at hierarchical levels from ecosystems of networked product, production, service and units within HCPS.			X
	[19]	Integration of socio-technical systems theory into I4.0 system design.			X
Assessing change	[20]	To develop guidelines for work design—to provide decision makers with high level of awareness regarding design implications on workforce.			X
	[21]	To guide industrial engineers/designers to consider human, technology and organisation.			X
	[22]	Work design change due to CPS implementation.			X
	[23]	To address HFE at early stage of I4.0 system design with 5 design steps.			X
	[24]	Holistic design for transition into I4.0 systems. *Case study and focus group to assess.*	X	X	
	[25]	Worker centric design and evaluation of Op4 support technology. *Pilot study, questionnaire, workshop to assess.*	X	X	
Social: Sustainability	[26]	To accommodate ageing workers in adaptive manufacturing systems. *Prototype, emulator and theoretical assessment.*		X	X
	[27]	Decision support to address common social problems that is, health and safety. *Virtual model of room with sensors used to assess.*		X	
	[28]	Inclusion of socio and operational perspectives when implementing CPS. *Consultation with academic staff to develop framework.*	X	X	
Social: Ethics and privacy	[29]	A framework for inclusion of ethics during research, design and use, considering locus of decision and technology maturity.			X
	[30]	To design for privacy when utilising data from IoT and human workers using GDPR as a guiding principle. *Workshop assessment and development.*	X	X	
Collaboration and allocation of function	[31]	A semantic problem—problem solver characteristic ontology to develop collaborative problem-solving HCPS.		X	X
	[6]	To develop a domain agnostic cyber physical social meta model for system design.			X
	[32]	Matching best operator to task and provision of a human data model to provide uniform service interfaces upon user request to complex IoT system. *Lab evaluation.*		X	
	[33]	HiLCPS collaboration design. *Simulation and prototype of shared control in autonomous driving scenario for evaluation*.		X	
	[34]	Human—system coevolution and collaboration through understanding of human needs/wellbeing in connection with empathic AI.		X	X
Holons and agents	[35]	The system as collaborative agents that stay connected from physical and control to cyber functionalities.			X
	[36]	Human machine cooperation based on models of know-how (KH) and know-how to cooperate (KHC). *Prototype system.*		X	
Customers and crowdsourcing	[37]	Supporting ubiquitous manufacturing using social internet of things (SIOT). *Prototype system.*		X	
	[38]	People centric IoT framework for crowdsourced manufacturing.			X
Cognitive:	[39]	For training support. Link human activity, smart production, product and machines through AR.		X	
	[40]	For decision support. NSGA2-based human–system interaction with pareto front of optimal scheduling of tasks in CPPS.			X
	[39]	To support human-AI symbiosis, reducing down time, improve agilities and process/product quality.			X

(Continues)

TABLE 1 (Continued)

Theme	Ref	Purpose/*Approach*	Evaluation method		
			Industry	Lab	Theory
Physical:	[41]	Use of IoT and wearables to support system design that supports healthy work-life balance, safety and satisfaction. *Prototype.*		X	

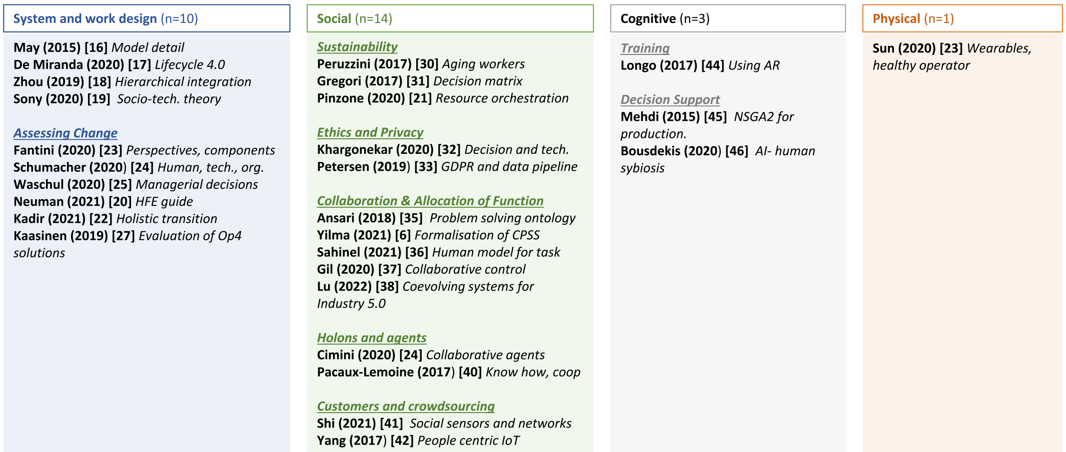

FIGURE 1 Summary of frameworks per theme.

according to skills, abilities and knowledge and do not address HFE. They identified a need for standard libraries of CPS functionality and services from the perspective of supporting human work. In Schumacher [21] information systems architecture is used for modelling human, technology, and organisation. The framework provides high level guidance for continual improvement of production systems by defining the logical structures of components and their interactions, although practical implementation of the framework and guidance to act on the framework results are not provided. Waschul et al. [42] considered the future of work design as a managerial decision, depending on which tasks are selected for automation. The residual tasks are classified as *simplified*, *replaced* or *augmented* and combinations may not be suited to human workers. The framework demonstrated how automation changes the nature of work in terms of complexity and autonomy and stressed the need to consider job design to ensure that resulting human work is suitable, satisfying, and motivational. However, only linear or sequential automation was considered with further work needed to assess simultaneous automation or concurrent tasks. The framework proposed by Neuman in ref. [23] helps system designers assess the effect of technology on stakeholders in a systematic manner. Their matrix provides a template of items to be considered, including aspects of human work that are added or removed considering perspective of perceptual, cognitive, knowledge, physical, and psychosocial demands as well as the resulting effect on the human and combined system performance. The framework does not show how to implement the evaluation nor what to do to address any identified negative effects or how to keep the information timely. They note the limitations of exploring certain HFE elements, specifically psychosocial factors (i.e. social and psychological factors that affect health, wellbeing, and behaviour) which is an open challenge. Kadir and Broberg [24] present relevant metrics for assessing system performance and human well-being across all stakeholders, adapting a software engineering approach (SOFT). They propose that the current state and changes caused by a new system should be assessed in terms of *effectiveness* (meeting system goals), *efficiency* (providing system and workers with more time), *flexibility* (enabling system and workers to do more), *inclusiveness & usability* (ease of use by human), *satisfaction* (of stakeholders through use), and *safety* (reducing risk and uncertainty). The framework built on their previous research [43] which stressed the need to consider effects of new technology on system and work practices from micro (operational level), meso (tactical level), and macro (strategic level) of the business. They note the challenge of assessing the practical application of frameworks in industry as further work alongside a need to develop practical guidance.

Kaasinen et al. [25] proposed a framework to evaluate the effect of technology, considering immediate impacts on usability and safety, leading to outcomes of satisfaction, motivation and system performance, redrawn in Figure 2.

The connection between psychosocial factors and system performance is indicated, however the link between technology and psychosocial factors is unclear. They state, but do not address, a need to consider the ethical implications of Op4 technology deployment and its effects on work and workers over time. They highlighted a need for developing methods to understand motivational effects and preconditions for successful technology deployment. They also acknowledge significant challenges in addressing conflicting and varied viewpoints throughout changes in lifecycle, stakeholders, and system.

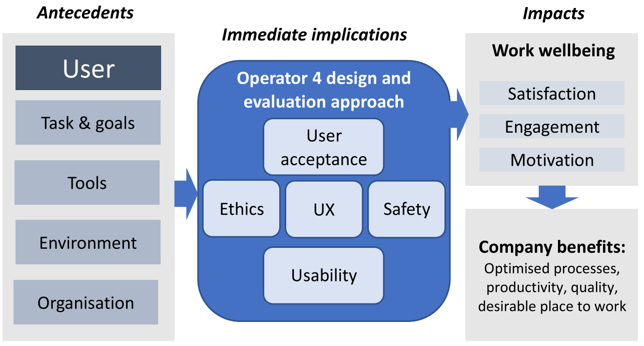

FIGURE 2 Recreation of Kaasinen framework from ref. [25] to design to support Op4 in system change.

3.1.2 | Social augmentation

Frameworks in this theme addressed issues of social augmentation, specifically social sustainability, ethics, privacy, collaboration, holons, and agents and customer or crowdsourcing.

Social sustainability
The term social sustainability includes notions of preserving work-life balance, physical and psychological wellbeing and addressing psychosocial factors (for an overview of topics within social sustainability see ref. [44] tab. 3). The purpose of designing socially sustainable systems is to ensure that they are able to meet the needs of current and future employees in an inclusive manner [28]. To accommodate an ageing workforce, the use of 'virtual commissioning', that is, digital twins, was proposed by ref. [26]. Their approach combined twins with case-based reasoning to physically adapt systems and their information interfaces according to human profile and behaviour. Their framework proposed using digital support technologies to compensate for the loss of 20%–25% capacity of worker groups over 30 (when compared with 30-year-olds). The ergonomic adaptations were designed considering an individual worker interacting with a single machine to accommodate a predicted deterioration in motor and perceptual function; however, individuality, teamworking, and technology acceptance were not considered. To support design of future workspaces for any age, a social decision matrix and four step method were proposed by ref. [27]. Their framework combined virtual and real prototypes to identify potential cognitive, environmental or ergonomic risks, mapping these to appropriate mitigation strategies using sensors and standards. Their approach utilised sensors for detection of risk with human activity recognition, cognitive sensing, temperature, heart rate and 'smart trackers' to develop 'criticalities' for workers. The framework would require extensive knowledge regarding HFE, appropriate standards and mitigation strategies relevant to each activity, user and technology. However, there are no standards available for many of their metrics (e.g. cognitive loads) and they do not address privacy, consent or dignity in the framework. They identify a need for a deep definition of IoT systems and development of recommendations for cognitive and physical working levels to develop appropriate mitigation and detection strategies. The framework proposed in ref. [28] suggests that socially sustainable systems will require three phases of preparation; (i) gathering background information on the system, including assets and processes affected, (ii) identify level of analysis for performance measurement at individual, group, and system level and (iii) identification of performance areas to measure (current and intended). Although their framework guides the assessment of these areas, application would require HFE expertise for analysis and addressing identified issues. Additionally, there was no link identified between technologies and their outcomes nor suitable assessment metrics or performance indicators and are areas requiring further research. The extension of the framework would include consideration of the extended stakeholders such as supply chain, community and through lifecycle.

Ethics and privacy
Ethics and privacy support the sustainability within a wider societal and human context. This requires considering both the locus of decision making and technology maturity [29]. The authors in ref. [29] proposed the use of existing ethical frameworks to be derived from philosophy and established organisations such as research and government bodies. However, the practical implementation of changes to address ethical issues, potential conflicts and semantics are not considered. Future work includes the development of ethical checklists for the whole lifecycle of a product or system design as well as empowerment of workers ability to raise ethical concerns throughout HCPS development and use. Associated with ethics is the appropriate use of data from Op4 technology and wearables, especially considering privacy. A framework is proposed by ref. [30] to consider privacy and adherence to the General Data Protection Regulation (GDPR) [45] throughout the data processing pipeline. The data pipeline is proposed as a stage gate process to instigate privacy checks at each of the points of data collection, use, storage and combination. The framework refers to GDPR as a guideline for supporting privacy; however, the document provides general targets for appropriate use and transparent communication of data collected from data subjects rather than practical, actionable steps required to achieve this.

Collaboration
Collaboration is the joint task completion towards a shared goal by the 'workers' in the system. An ontological approach was proposed by ref. [31] to consider physical, cyber and social interactions as a series of tasks (problems) to be resolved and to determine the best team or workforce for a particular problem. They used semantic characteristics of system *problems* (i.e. tasks) and *problem solvers* (i.e. human or cyber agent) characteristics to allocate tasks and model system components, recreated in Figure 3. They modelled these problem solvers in terms of *competence level*, from novice to mastery as well as *complementarity* characteristics. Complementarity referred to the utility of the problem solver in terms of (i) *cost* (variable for people and CPS depending on investment and scaling), (ii) *flexibility*: fulfilment of tasks (humans depend on training,

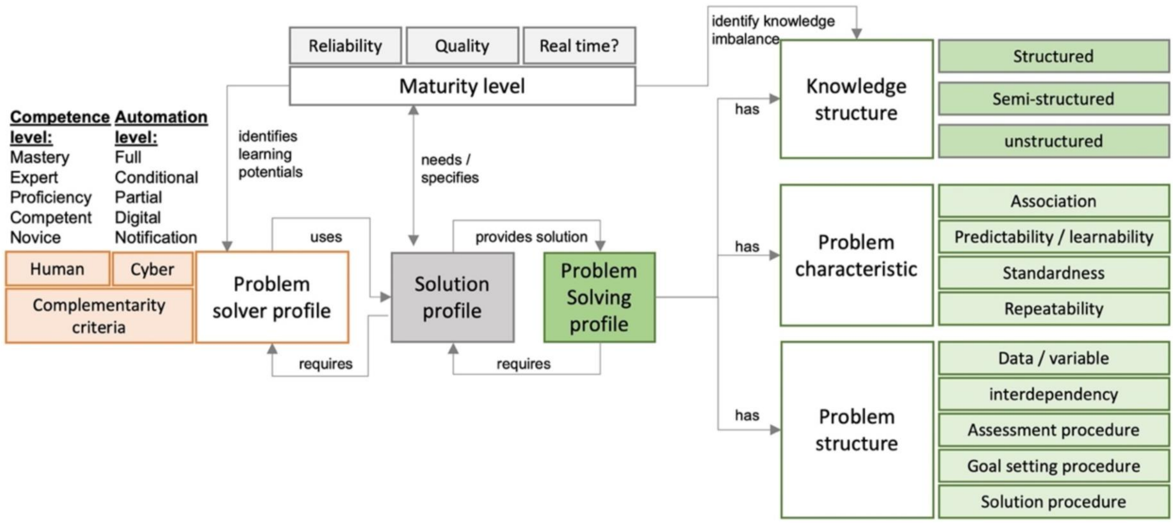

FIGURE 3 Semantic approach to matching problem with problem solver characteristics, redrawn, and simplified from ref. [31].

CPS on type of technology or algorithm), temporal availability (humans are relatively low and increased by shift work, CPS can operate 24 h), (iii) *capacity*: mechanical jobs (high variation in human, no limit in CPS), information processing (time intensive and unreliable in humans for high volume but good performance in unstructured or error detection, CPS reliable in high volume less in unstructured or unknowns), problem solving (humans for key concepts and heuristics as well as exceptions and CPS for formalised and routine or standard problems), (iv) *performance* (high variability in humans low in CPS) and (v) *quality:* (humans are variable, CPS tend to be more consistent in performance).

The framework was analysed in a theoretical case study considering the purchase of new equipment, which resulted in an unclear solution. Further work concerning trade-off studies between reliability and quality of decision were required. They suggest opportunities in the development of fuzzy mapping of variables as well as considering risk factor trade-offs for both routine and unusual situations. Their approach considered the assignment of tasks, but not the resulting characteristics of the job nor job design.

To develop systems which truly collaborate, it is necessary for the CPS elements to be aware of their environment and adapt effectively. Yilma et al. [6] developed a metamodel for cyber-physical-social systems based on a review of social CPS and demonstrated it as a smart factory model. They considered personalisation as the key to successful collaboration between humans and machines. Through personalisation, automated systems could be afforded the ability to recognise human preference, limitations and opportunities and suitably adapt level of support and behaviour. They consider teams and team working comprising both human and non-human system agents or actors. They suggest the use of reinforcement learning algorithms, or artificial agent and using deep Q-network to achieve this through the ability to 'learn' from interaction and enable robot colleagues or 'co-bots' to become free to interact by exploration. The acceptance of such freely autonomous systems in collaboration with human workers is not considered. They acknowledge the significant challenge of modelling intangible elements (e.g. social interactions) and the need to explore true social dynamics in the context of CPSS for socialised machines. Additional challenges include interpreting social data from sensors which is beyond current capabilities and will require continued cross discipline efforts.

Allocation of function was a challenge addressed by Sahinel et al. [32]. They proposed an architecture to support interaction and task allocation between human and robotic co-workers within IoT environments. Their approach assessed workers from a 'pool'of options and allocated the 'best' worker according to metrics of performance, availability, and skill via a multi-agent abstraction layer. They suggest several technology-based improvements to support real time feedback through improved response time, including offloading of services to distributed devices and edge computing. However, they do not adequately consider HFE, the effect on work design or on the worker allocated the tasks.

It is necessary to consider situation awareness and safe control of equipment when CPS and humans are collaborating. Gil et al. [33] proposed a framework to support shared control in HCPS, demonstrated in a case study of simulated shared vehicle control. To appropriately share control with a human a CPS system must: get human attention, share control, avoid obtrusiveness, and achieve understandability. To enable detection of the human capacity for taking over control, they modelled the human according to *willingness*, *opportunity*, and *capacity* to take over control based on the detected context, condition and action required. They evaluated their framework using a desktop simulator and identify a need for real world evaluations. They propose future work to develop automated simulations of shared control scenarios across a range of domains and scenarios. Lu et al. [34] developed an industrial human needs hierarchy (redrawn in Figure 4) to ensure human—system coevolution in their framework. Their framework was intended to aid transition from technology

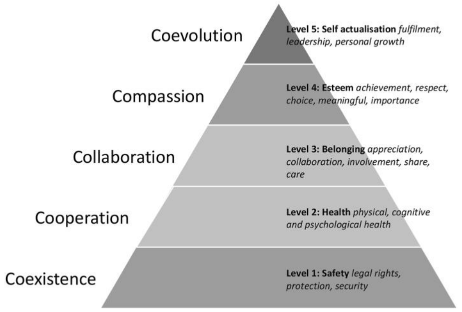

FIGURE 4 Hierarchy of industrial human needs against type of human–system interaction (e.g. robot, AI) based on Lu et al. [39].

focused I4.0 to human centric I5.0 with the inclusion of metrics associated with wellbeing and higher needs of human collaborators in the system. They highlight concerns and further work required to ensure trust and acceptance of work with intelligent systems, of bi-directional interaction between human and system as well as the development of appropriate feedback mechanisms to detect and adjust according to the attained status of the human.

Although their framework indicates the requirement to consider human needs with the intention of assigning suitable tasks for system performance and wellbeing (examples given include capability, availability, wellbeing states, and preferences), they do not address how this information could be obtained, maintained nor consented to in a workplace system whilst maintaining wellbeing, dignity and system performance. Additionally, their machine determined the status of humans by the use of world model and observations to generate empathic behaviour, the level of model fidelity required and complexity of modelling the interactions between humans and environments were not discussed in detail.

Holons and agents

Holons and agents are defined as autonomous elements that interact in a social manner, proactively and reactively cooperating towards shared goals, including humans, robots, and machines [35]. The framework Cimini et al. [35] proposed suggested that these agents could retain connection and collaboration from physical (Op4) to control (multi-agent) and cyber layers (decision making and digital twins). As illustrated in Figure 4, humans engage with a system at multiple levels and can effect change to systems both behaviourally and physically. Further analysis is required to identify the distinctions between operational, tactical and strategic decisions in smart factories. They identified a need to develop rules and instructions to select the best technology to support human workers and appropriate collaboration between system agents according to production typologies. Additionally, they state a need to extend frameworks to design systems considering multi-stakeholder negotiations across the supply chain. There is limited consideration to the HFE concerning complex data interaction and Op4 use which both rely on the idea of *magical humans* as described in ref. [36]. The framework presented by Pacaux-Lemoine [36] proposed human-machine cooperation principles to transition away from this problematic idea of *magical humans* (i.e. always make perfect decisions and perform as required) or *nefarious humans* (i.e. always make deliberately wrong decisions and actions). Their proposal considers autonomous holons collaborating socially towards a common system goal by modelling the practical and knowledge concerns of *know-how* and the interactive concerns of *know how to collaborate.* Their framework was evaluated in a lab-based study but they were unable to model the human effectively and only modelled the CPS *know how* and *know how to collaborate*. The effect of the CPS on the human and the human comprehension of the machine were not evaluated. Future work included more comprehensive modelling of human knowledge, comprehension of task, and identification of risk as well as determining the effect of non-ideal situations and understanding of agent behaviour.

Customers and crowd sourcing

To address challenges of mass customisation and ubiquitous manufacturing, production may be supported via 'social sensors'. Social sensors included social media, crowd sourced social production facilities [37] or connected smart devices as a people centric IoT [38]. Social manufacturing networks, using 'social sensors' within social media networks and cloud connected stakeholders, was proposed by ref. [46] and later developed by ref. [37]. The framework proposed social interaction and smart operators as integral to the success of ubiquitous manufacturing. The prototype system was technology centric, outlining the technologies to be used for the sensing of activity, and comprised various sensors, and a robot arm. Their framework evaluation ignored the complexities of the 'social sensing' aspect of the work. Future work was indicated as exploring computational intelligence and multi-agent reinforcement learning to support collaboration and analyse heterogenous manufacturing data. Yang et al. [38] proposed three interacting layers: physical (P2P) interaction, device to device (D2D) and social interaction. The *physical resource* layer collected data and communicated these via a cloud server, a D2D *interaction* layer where data and interaction graphs inform services using the cyber *social graphs* for analysis of social and device connections and interactions. Interpretation of social interactions and media, to understand complex human needs and map these onto products and services, remains a challenge and was not addressed by the frameworks.

3.1.3 | Cognitive augmentation

Cognitive augmentations use technology to support knowledge share, training [39], and decision making [40, 47]. Longo et al. [39] proposed an AR-based training framework for cognitive augmentation using Natural Language Processing (NLP) and information extraction algorithms with rule-based and supervised machine learning. They tested the efficacy of their framework to develop training support with 2 experts and 20 non-experts for a CNC milling activity in a lab-based prototype. Improvements in training were reported through improvements to learning curve (i.e. setup time, number of batches produced, and rate of change in time for setup) and learning rate (i.e. traditional at 91.85% and AR at 89.82% where a lower percentage represents faster learning rate). However the methods for recording performance were unclear and the improvement result could be an artefact of the recording method. They propose reducing lag time between question and response as part of future work and standardisation of AR for industrial scale deployment. Additionally, they suggest there is a need to develop prognostic capabilities in training tools including development of real time monitoring and predictive maintenance. The framework proposed by ref. [40] is for a human 'on the loop'. Within their paper, they suggest that future manufacturing environments will require humans to support decision making tasks. The example used in the paper is the refinement of production scheduling. In their framework the human is supported via a genetic algorithm providing a pareto front of scheduling options to be selected according to preference. This approach is further reliant on the magical human idea and does not consider the other roles of humans in the system nor the suitability of pareto front assessment. Future work included improved interaction in the framework and test using real world scenarios and data. The human–AI collaborative decision making framework proposed by ref. [39] builds digital twins from expert human knowledge and a continual learning and feedback loop. The framework uses digital augmentation to maintain situation awareness through personal assistants and coaches that help to monitor and interpret shop floor data based on models of knowledge, simulation of process and product, and data analytics. Knowledge management and elicitation is required to support each of these frameworks, however methods to access and maintain such knowledge are not explored in the frameworks.

3.1.4 | Physical augmentation

Most of the frameworks required physical augmentation of workers to capture physiological or activity-based data for translation into behaviour or action. One framework specifically focused on physical augmentation in order to support a 'healthy operator' through the use of wearables and sensitive data collection [41]. Their approach was developed through a review of IoT and wearable technology used to alert operators to hazards, prevent unergonomic movements and provide holistic health management data and analytics. The use of interconnected ontologies to standardise data interpretation and mitigation strategies is a promising approach to dealing with the complexities of agile systems, different domains, and working practices.

3.2 | RQ2: How are humans considered?

Representation of humans most commonly concerned their knowledge, skill, qualification and learning [20, 21, 32, 39]. These attributes were mapped according to existing models of job role and skill requirement. However, [20] note that there are insufficient taxonomies available to define the services of CPS towards supporting the human, suggesting that the roles of humans in CPS are not yet clear in the transition towards smarter factories. An extensive list of attributes to be modelled was provided by ref. [16] including: *anthropometric measurements* (height, weight, and body part measurements), *functional capabilities* (balance, strength, eyesight, movement), *cognitive capabilities* (problem solving, pattern recognition, language, initiative, collaboration, and skills) and various social attributes including family life, diet, and leisure. The result is an impracticable and invasive list. To map abilities to task characteristics, humans should be modelled according to *competence level* (i.e. skill) and should be considered with *complementarity criteria* such as quality, performance, capacity, flexibility, and cost [31]. Skills, knowledge, and the capability to collaborate and problem solve were modelled in refs. [31, 36] including profiles of the task to be solved (*problem*) and of the task solver (*problem solver*). Additionally, the knowledge required to collaborate should be modelled in the form of *know how* (to complete a task) and *know how to collaborate* [36]. These approaches are reliant on overcoming the significant challenge of eliciting and managing knowledge in a dynamic system as well as social factors relating to collaboration. The reviewed frameworks acknowledge these complex and open areas of research with plans to develop more comprehensive models relating to interactions in the future and across domains. For example, ref. [32] intend to extend their simplified model of the human to include stamina, confidence, and self-management but were unclear on how this could be achieved. ref. [36] plan to develop models of behaviour at strategic, tactical, and operational levels that can be utilised to help maintain system wide situation awareness, however this was not realised in their research.

Several authors state the need for better tools and guidance for assessing HFE and representing humans in the design of HCPS [23, 24]. Furthermore there is a clear need to understand the effects of technology and changes to work on the humans and overall system performance [23–25, 33]. The characteristics and activities identified in the literature review are combined and mapped to illustrate the complexity and how they interact within I4.0 HCPS in Figure 5.

Many of the required identified elements were reported with no clear method of analysis, measurement, assessment, or comparison (marked with * or – in the figure). The directly measurable items were age, anthropometry, performance, cost, time, formally documented experience and qualifications, quality in the form of errors, physical states (of environment), physical interactions with tasks (e.g. control or movement of objects), and known infrastructure or legislation. Many of the measurements required to assess the effect of technology on HCPS performance and psychosocial factors were undefined, unclear or reliant on secondary interpretation of data and qualitative feedback. It remains unclear how different features (of the technology, worker, and context) explicitly link to system performance and how implementing technology changes these outcomes.

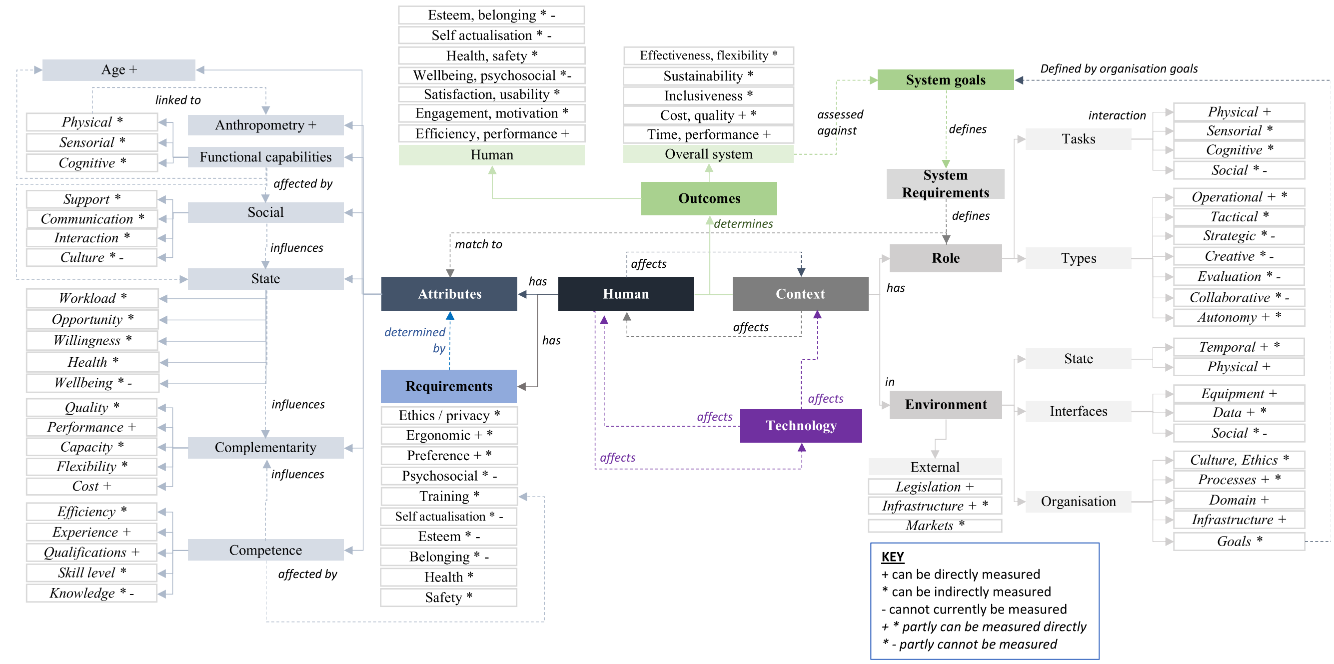

FIGURE 5 Mapping of the roles and attributes used to model humans in the reviewed. Symbols used to indicate potential for measuring each aspect: + can be directly measured, * can be derived from or interpreted from measurements, − cannot be measured currently, + * can be partly measured directly and * − has parts that cannot be measured.

3.3 | RQ3: What are the HFE challenges?

Challenges include, but are not limited to, comfort, cognitive load, interaction technique, acceptance, perception, practicalities (e.g. charging, hygiene, ergonomics, and cost) and change of working practices [48]. Many of the frameworks rely on extensive collection and modelling of data obtained from workers but do not consider suitability of the data nor the impact on person. The comprehensive data capture proposed by ref. [16] might result in improved accuracy of models but the approach is impractical and invasive. It should be noted that the framework was developed in 2015, prior to GDPR, and does not align with privacy and dignity required for the transition to I5.0. The use of wearable sensors to detect activity and update levels of experience, cognitive and affective levels is required in ref. [17]; however, the practicalities and the suitability of sensors to detect these is not considered. Additionally, reactance or acceptance of sensor use was not considered in most of the reviewed frameworks and would be a significant challenge to the success of Op4. They suggest achieving continual learning and training via the semantic web as well as co-evolving systems but do not address challenges of veracity and relevance of knowledge, potential overwhelm nor maintaining situation awareness. The reliance on quantifiable data, particularly to measure cognitive working thresholds, is an open and complex area of research and poses significant challenges in terms of HFE. There is a lack of standardisation regarding the data obtained from wearables which is not addressed in the reviewed frameworks.

The importance of eliciting and sharing knowledge was a common requirement of system design. Significant challenges include the elicitation, representation and management of knowledge, appropriate allocation of function and job design, safety, and well-being of human operators. The approach proposed in ref. [18] was reliant on humans interpreting the system and its components, as well as the system interpreting human behaviour and intent for self-regulating learning. Psychosocial factors, wellbeing and safety were not considered. Sony and Naik [19] suggest that the connectedness of industry through I4.0 would result in a shared culture but are not specific regarding the nature of culture, nor the impact of nationality, organisational, domain, or individual differences. Open challenges identified included the need for extensive system modelling, knowledge engineering, and human-machine symbiosis.

Several frameworks require the modelling of detailed human factors and assessment of human activities (e.g. ref. [21]). Although the frameworks proposed by refs. [23, 24] provide guidance for the identification of HFE issues, there is no guidance regarding how to redesign nor rectify these. Successful implementation of these framework would be reliant on consultation with HFE and technology experts. Further work is required to understand which support, tools, and analysis might be needed to help managers and design teams analyse the potential change and develop mitigation strategies to assess conflicting outcomes. There is also a need for psychosocial analysis tools, which are currently missing and require more participative and engaging development methods to capture these factors [23].

Organisations tend to drift towards 'unsafe states' through isolated implementation and lack of consideration of HFE through system design. Neuman et al. [23] summarise the importance of HFE in I4.0 system design and present the following recommendations. Attention to HFE must occur early (to minimise cost and issues later) and throughout system design lifecycle and use. Because human system interaction engages perceptual, cognitive, and motor systems continuously and within environmental context, these should be considered at all levels of design. People have psychosocial needs which require system designers to consider working environment, job demands, control, supervisory and co-worker support and satisfaction which should be considered in the design.

The approach proposed by Gil et al. [49] is reliant on expertise from both interaction designers and domain experts to map the action with the system interface and desired outcome. Although they do evaluate the approach with human participants, they acknowledge that the simulated environment (low risk) is not representative of the real task (high risk) and behaviour of participants and their feelings towards the system may not reflect reality. The approach requires interaction designers and domain experts to model their control environment in explicit detail and understand all interactions within the system which may limit the applicability to very dynamic scenarios. Lastly, they utilise an approach assessing opportunity, willingness and capacity to take over control but it remains unclear how this could be assessed in real time or be personalised to variable users and scenarios. The framework proposed by ref. [25] acknowledge the significant challenge of implementing such a framework in practice and considering various perspectives as well as the differences in each of the potential evaluation activities. Additionally, the framework was only assessed theoretically during conceptual design and the complexity of implementing the framework in industrial scenarios and is intended as further work. There was a need for extensive HFE expertise in several of the reviewed frameworks state the need for the development of practice-oriented guidance, to allow transfer of knowledge from academia into industry [23, 50]. The framework by ref. [28] does not consider how the introduction of technology may affect processes or people and assumes change will be positive, this was common in frameworks utilising Op4 and is a challenge that should be addressed through further analysis. The selection of the best technology for desired outcomes is suggested as future work. The initial phase of the process requires extensive understanding of the system, methods for effective knowledge elicitation, communication and management will be critical.

3.3.1 | Concerning job design

A job is defined as collection of work tasks that are assigned to a worker [22]. Jobs can be aggregated with additional responsibilities and duties to define a particular job role. The automation of various tasks or jobs in a system, as technology allows, may result in a disparate range of 'left over' tasks for a human operative. There is a significant body of research considering allocation of function within the socio-technical system literature (e.g. Fitts List [51, 52]) which can be used as a guide for allocation of function. However, these do not consider partial automation, collaborative human—automation nor consider effects of implementing automated systems on human or system behaviour such as trust, adaptation, control, and mental workload [52]. Job design theory should be considered to allocate function appropriately, considering the human needs of the worker, but was not generally considered in the reviewed frameworks. Jobs should be designed to increase experienced meaningfulness, responsibility, and knowledge of results, which would improve employee efficiency and satisfaction [53]. To ensure maximum efficacy of the humans and therefore the system as a whole, care should be taken to ensure that tasks allocated to human include a variety of skills, comprise whole and identifiable tasks that make significant impact on others, allow employees autonomy and freedom within the role and provision appropriate job-based feedback [53, 54]. Additional recommendations from socio-technical systems theory [55, 56] for the design of human job roles are summarised in Table 2. These design principles remain important as technological advances offer increasing opportunities for changing worker's roles.

3.3.2 | Ethics and privacy of digital twins

Several of the reviewed frameworks utilised digital twins. A Human Digital Twin (HDT) was proposed as a crucial connection between the human and cyber worlds [47],

TABLE 2 Summary of the concerns for socio elements of socio-technical systems from Cherns 1987, Clegg 2000.

Aspect	How
Congruence and compatibility and control	Role design must match requirements. Responsibility for variance control should be located as close to the source of the variance as possible (i.e. some human job roles will be required to be on site).
Multi-functionality of roles	Enable sharing of tasks and related knowledge (avoiding bottlenecks). Support knowledge gain (through experience and training)
Minimal specification of role and maximal flexibility within role	Specify only what needs to be specified (conciseness) Allow flexibility between roles (as per above). Allow adaptation to prevailing conditions (with quality checking and record keeping ensuring system does not degrade to unstable form)
Match to human needs and values	Support creative problem solving and allow for autonomy. Provide feedback (what happened) and feedforward (what will happen) to support decisions.

providing a tool to ensure health and wellbeing [17, 28] analysing system change through virtual commissioning [26]. However, potential issues of GDPR, privacy and (human) twin ownership were not considered. The increasing amount of data and sensing required for HCPS creates additional issues regarding data privacy and threats, such as misuse, security breaches and health and safety issues. Data integrity is particularly important with regards to compliance with the GDPR as the human component of HCPS means that some of the data may be personally identifiable or sensitive. Two frameworks propose approaches to address this problem. The high-level framework by ref. [29] may be used to address ethics throughout the lifecycle of systems and help organisations establish ethical checkpoints. The recommendations include reference to classical moral codes from philosophy, responsible innovation, ethical AI/ML and governmental regulations or multinational frameworks. However, due to the philosophical nature of ethics, the guidance remains open to interpretation. Although the framework highlights the importance of ethics for social sustainability, it does not deal with the difficult issues with conflicting ethics (e.g. nuclear, defence, or cultural challenges) nor provide practical assistance in implementing changes due to ethical concerns. Petersen et al. [30] recommend use of the GDPR as design guidelines; however, this is particularly challenging as the GDPR does not specify how to achieve the recommendations, rather it sets 'targets' to be achieved. The framework was assessed through discussion in a workshop and, although this process helped to determine whether people understood the principles of their approach, it did not identify issues that would be encountered when this is applied.

3.3.3 | Collaboration and allocation of function

The characterisation of problem and solver characteristics through an ontology is a promising approach to allocation of function (AoF) which was proposed by ref. [31], breaking down complex issues into quantifiable components and using these to allocate tasks. However, it was unclear how the details for 'problem solver' profiles would be elicited, managed, maintained, and adapted as work and workers evolve, nor how task allocation would be communicated to system 'agents'. Their approach does not consider how the method might alter job design or workload on human staff and whether resulting jobs would be meaningful and satisfying. The approach did not consider possibility of overloading workers, reducing autonomy, trust, ethics or teams and teamworking. Yilma et al. [6] acknowledged the grand challenges of inferring social interactions, emotions, personalities and behaviour from sensor data as an open area for further research.

Suitable measures for assessing cognitive load in dynamic environments whilst minimising invasiveness of data capture are required. Sahinel et al. [32] suggest the use of NASA TLX [57] to evaluate cognitive load, but this rating scale would be complex to implement in real time and add cognitive load to tasks. They also suggest that a robot may intervene with the human if a fault is detected, without consideration on the effect of this intervention on human behaviour and wellbeing. Job design, privacy, and autonomy are not considered with regards to the role of the.

In ref. [35] human data are used to facilitate negotiations between these 'agents' and to determine social interactions. They do not consider the effect of rigorous monitoring of activity on the psychosocial factors of humans in the system. The focus of their architecture is the decision-making layer, where all profitable data are used and is reliant on data quality (completeness, conformity, validity, and accuracy). However, they acknowledge that reliability and suitability of data to facilitate decision making is far from complete and human expertise will remain essential for a long time. Their approach utilises digital twins, the development of which requires a significant digitalisation and modelling strategy within the organisation and necessitates accurate modelling and representation of all elements of an enterprise. This would be challenging in practice due to the range of agents, machines, activities, interactions, processes and communication methods. A further consideration is variability in behaviour, team dynamics, action and intent and change over time. The assumption is that augmentation through data and digital twins will result in improved decision making, ignoring the potential of increased task complexity, additional data requirements (including storage) and issues with collection. Lastly, the presentation of the data to workers throughout the system would require careful curation and monitoring of interpretation to minimise perceptual and cognitive misunderstandings. The information may also require bespoke presentation to suit individual job roles or needs such as accessibility requirements.

3.3.4 | Customer and crowdsourcing

The smart operator in the framework proposed by ref. [37] was facilitated by a handheld tablet and radio frequency identification tag reader. However, the description of the testing did not include human users and did not consider the HFE of using these handheld items whilst conducting manual tasks. Their future work centred on improvements related to the technology and data processing. In their earlier work, Ding and Jiang [46] suggested future work to address complex issues such as mining social media, handling large scale in-network data, addressing authority, access, mechanisms, authorisation and multi-role sharing and collaboration. These challenges were not addressed, rather the social sensors were considered as addressing human interaction when used in conjunction with a Smart Operator. However, the original work identified that these are non-trivial challenges and remain an area for further work. A similar approach was proposed in the framework presented by ref. [38] to support customer participation and organise decentralised manufacturing. Again, the approach is reliant on the accuracy and suitability of devices to monitor actions and identify human needs. Job design and production management methods were unclear. Security and privacy are mentioned as part of the intended services layer. Psychosocial factors, individual requirements and needs are not considered within the framework but were derived from interaction analysis. Understanding the needs of the humans is mentioned as future work and would be critical to the success of this approach.

3.4 | Cognitive augmentation

Longo et al. [39] proposed the use of AR to support training in HCPS. Their framework did not consider HFE concerns of AR such as comfort and legibility of instruction nor organisational factors (ergonomics, hygiene, content creation, charging time, and battery life) nor how AR devices may affect process. The use of voice recognition is recommended in their approach for interaction with the system however they do not consider language, accent or preference. Additionally, voice and audio interactions may not be best suited to shop floor activities where noise levels may be higher and multiple people may be talking simultaneously. Although the framework proposed by ref. [40] is reported to be human centric and mentions the importance of humans throughout, the overall framework is technology focused. User testing and efficacy of pareto fronts, for selection of optimal decisions, was not considered and could be part of future work to assess the efficacy of this approach. The framework proposed by ref. [47] puts the human at the centre to create human—AI symbiosis, but the reliance on Op4 and application of data *to* the worker implies a more technology and data centric approach. The HFE considerations of using the digital augmentations in Op4 are not addressed. Again, representation, explanation and verification of information received by the human is not addressed and will be a significant challenge.

3.5 | Physical augmentation

The prototype system presented by ref. [41] was developed to send health data to the operator, in the form of charts and graphs to show them their stress and health status. Although they link to an ontology developed to assess human stress and mitigation, there was no indication how the corrective action would be incorporated into the system design, nor the effect of the act of recording or receiving such information on the operator's state. An additional concern related to trust and privacy, is the consideration of how these data could be used by management. Issues of trust and privacy were not addressed.

4 | DISCUSSION: OPEN ISSUES AND FUTURE PERSPECTIVES

There are significant challenges to be addressed to realise the Op4 and I4.0 paradigms, moving towards I5.0 in a manner that ensures wellbeing and social sustainability of future systems. The challenges relating to wearables include practical considerations such as cost, suitable interfacing, ergonomics, security, charging, shift work, device losses and hygiene as well as privacy, appropriateness of data capture and acceptance by workers. Reactance and acceptance of monitoring systems is an open area of research, with various metrics for the evaluation of acceptability [58], although how to address issues once identified remains unclear. The reliance on sensors to capture data for analysis to determine human activity contains numerous challenges including accuracy of data (reliability of sensors), suitability of data to monitor intangible human activities (social interactions, intention, and psychosocial factors) and the ownership of data created by a wearer or user of device (digital twin, knowledge). One of the main challenges underpinning the reviewed frameworks is the need for extensive (and often exhaustive) requirements and knowledge engineering expertise, including how to elicit, validate, verify, quantify and maintain or manage knowledge within and to develop a smart system. An overview of the challenges and areas for further research is provided in Figure 6.

Due to the variability of available technology, sensors, and methods for assessing work and systems, several of the reviewed frameworks expressed the need for standards and libraries to establish work thresholds, mapping technology to outcomes, to select the best technology for the task or user. The need for implementation guidelines and tools to support use of frameworks in industrial settings was indicated as a requirement for future system design. Suggestions included toolkits and practical implementation guidelines [24]. Although several of the frameworks proposed methods to enable evaluation of the effect of change, or to support evaluation of humans in a system, they did not propose what to do with the evaluation once complete. There is a need for guidance to support the next steps for improvement after evaluation as well as how to apply Human-centred design (HCD) frameworks. Furthermore, there is a need for empirical testing of the frameworks, their theories and to develop standard libraries and tools to enable application across different domains and by non-HFE experts.

Understanding psychosocial factors is a challenging and open area of research which should be further explored through longitudinal studies where Op4 and technology have been implemented in systems and in a cross-discipline research endeavour to establish frameworks and standards that allow mapping of technology and system outcomes. There is also a need to understand the state of a human in these complex systems more clearly, particularly to assess the higher level of industrial human needs. Social network data were indicated as a potential input to improve integration of customers and wider society needs in production; however, this has several challenges such as managing and interpreting complex social network data and the effect of social collaboration and job design.

Job design and allocation of function require further research to understand the changes of work and the nature of human work when technology is introduced. The effect of job changes on psychosocial factors as well as efficacy of system performance and situational awareness should be further explored in longitudinal and industrial applications of frameworks.

System and Work Design

- Extensive system modelling, knowledge engineering, human-machine symbiosis needed
- Determining skill, experience and knowledge levels
- Knowledge and skill gaps
- Privacy, ethics and GDPR
- Safety, wellbeing and
- Knowledge elicitation, representation, management and verification
- Need for practice-oriented guidance for implementing tech. considering HFE at micro, meso and macro levels.
- Understanding effect of technology on process, people at individual and organisation level
- Identifying best technology for outcome and user
- Standardisation of working levels for human activity
- Job design: consider satisfaction, overwhelm, trust, comprehension of role

Social

Sustainability

- Psychosocial factors are not standardised
- Gap in considering teams and teamworking

Ethics and Privacy

- Ethics are not standardised
- GDPR is hard to implement

Collaboration& Allocation of Function

- AoF remains difficult
- Modelling human as more than job role, skill and task is complex
- Need situation awareness
- Human feedback and accuracy of wearables
- Acceptance and trust for human – ai
- Transparency and explainability
- Development of performance measures that fit to wellness and human state

Customers and crowdsourcing

- AoF remains difficult
- Situation awareness and autonomy
- Job design for satisfaction

Cognitive

Training

- Understanding and modelling human skill level in dynamic environment
- Improved NLP and voice interaction

Decision Support

Physical

- Privacy, dignity and ergonomics of wearables
- Accuracy of sensor data to capture human activity
- Response to feedback from autonomous systems
- Developing ontologies of mitigations for HFE issues whilst considering effect of change on system

FIGURE 6 Gaps and challenges identified in the framework review.

Future perspectives should consider a wider view of the system design for inclusion of; the whole lifecycle of the system, the supply chain and additional stakeholders, evaluating the effect of any technology across the system. In addition, the societal and environmental effects of introducing technology from an ethical viewpoint should be addressed.

5 | CONCLUSIONS

The research presented in this paper contributes to the discussion of human centred or socio-technical system design through identification of current and future frameworks and discussion of how the humans are considered within these frameworks. The presented review is intended to help support future design of I4.0–I5.0 systems which involve human and automation or data interaction. It endeavours to consider the HFE requirements in more detail by providing a starting point, developed from current best practice and through knowledge share between HFE and technical domains, to establish true socio-technical systems of the future. A systematic literature review approach was adopted for the framework review to ensure a thorough search of the research space; however, this approach has inherent limitations such as the terms and databases used as well as research access restrictions. Due to the scope of the domains and I4.0 applications, and the rate of publication in the space, it is impossible to include all relevant terms. A review of the system design approaches from social, behavioural, and psychological research perspectives may be explored in the future.

Future directions for HCPS I4.0 framework development were summarised and considered from a HFE perspective. Research is needed to provide guidance for real world implementation of system design frameworks, aiding identification of best practice, key performance indicators and job role changes related to the use of HCPS. There is significant research needed to identify, formalise, and represent knowledge exchange between CPS and humans. The social sustainability and psychosocial factors involved, in addition to the ethical implications of increased digitalisation, should be further explored. Privacy by design needs to be extended to support workers in these smart systems and as part of the Op4 paradigm, the collection, use and representation of personal or sensitive data (as defined by the GDPR [45]) are of particular significance when building digital twins involving status and activity detection of human workers in smart systems. Future frameworks should consider the human as more than Op4 with limitations to be overcome and should consider human workers as contributing to system behaviour, dynamics, veracity, and validity. No consideration was given to the change to worker wellbeing when interacting with increasingly digitalised environments with the potential for digital overload, downtime, offline interactions which could all be profitable areas of research. Emotional engagement, aside from satisfaction, was largely ignored in the frameworks and could be a beneficial direction to improve system performance, well-being and for stakeholder engagement.

AUTHOR CONTRIBUTIONS

Katherine van-Lopik: Conceptualisation; data curation; investigation; methodology; visualisation; writing – original draft; writing – review & editing. **Steven Hayward**: Writing – review & editing. **Rebecca Grant**: Writing – review & editing. **Laura McGirr**: Writing – review & editing. **Paul Goodall**: Writing – review & editing. **Yan Jin**: Funding acquisition; supervision; writing – review & editing. **Mark Price**: Funding acquisition; writing – review & editing. **Andrew A. West**: Funding acquisition; supervision. **Paul P. Conway**: Funding acquisition.

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The authors declare no conflicts of interest.

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