Towards Designing Adaptive and Personalized Work Systems in Manufacturing

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1. Introduction

The manufacturing sector in Europe still holds significant importance. Within the European Union's (EU) non-financial business economy, manufacturing industry accounts for around 29.7 per cent of the gross value added and 23.1 per cent of the employment (Eurostat 2021). For Austria, the number of employees in industry is even expected to increase over the upcoming five years (Patsch et al. 2021). Thus, human labour still plays a significant part in manufacturing.

However, the future of EU labour will be impacted by demographic change. As the average age of workers is expected to increase, the development of age-appropriate work systems will become more important (Dombrowski et al. 2013). This evolution will push the concept of adaptive work systems. Adaptive work systems are systems that, besides taking requirements of various age groups into account, also focus on the idea of personalization – from age appropriateness to other diversity parameters such as gender, cultural background, or experience. The adaptation of work to human's characteristics, instead of humans adapting to the work environment, has been a central goal of human factors/ergonomics since its origins as a scientific discipline in the 19th century (Jastrzębowski 1857). Furthermore, this concept could also contribute to achieve the sustainable development goals (SDGs) set up by United Nations, like 'Good health and wellbeing', 'Decent work and economic growth', and 'Industry, innovation and infrastructure' (UN 2012). Recent aspirations towards human-centric manufacturing systems as one of the goals of the Industry 5.0 initiative (European Commission 2021) further push the concept of adaptivity.

Up to the present day, personalization of the work environment has not been fully exploited in real-life settings. This could potentially change with the continuous integration of advanced sensory skills into work systems. This trend has been largely driven by the development towards Cyber Physical Production Systems (CPPS) as integration and exploitation of the concept of cyber-physical systems (CPS) within manufacturing operations over the last decade (Monostori et al. 2016). Ever since the concept of CPS, the integration of sensors to allow perception drives the development towards context-aware systems. Various sensors, sensor fusion, and wireless data transmission enable the creation of digital twins as digital representations of objects and product-services (Stark/Damerau 2019). However, to this day, there is a lack of underlying standards for the development

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and deployment of context-aware systems, which is often attributed to a high diversity within domain-specific requirements (Li et al. 2015). As a result, these systems are developed in a somewhat ad-hoc manner. A transferable body of advice could benefit the scalability of applications and ease the deployment (Augusto et al. 2022). In manufacturing, a unified framework that covers the transformation from the trend of CPPS to human-centred, adaptive, and personalized work systems is still not available.

In this paper, we explore the current status of conceptual consideration of adaptation and personalization within the scope of socio-technical work system design. For the latter, we lean on the principles of socio-technical theory (Trist 1981), to consider both the social and technical dimensions and parameters within a systematic process across the entire life cycle of a work system as, among others, suggested by (Sony/Naik 2020). We collected and analysed existing approaches, both methodological and application-oriented, and aim to contribute to the following research question:

How can adaptivity and personalisation be integrated into the design of work systems in manufacturing?

The paper explores roots of the concepts of adaptive and personalized work systems and shows possible individualization dimensions for work systems in manufacturing. Based on this, exemplary concepts and implementations of individual dimensions are presented and placed in the overall context. The focus is set on implementations within the TU Wien Pilot Factory that cover adaptability concepts on workplace, process, and system level:

- Adaptive projection of work instructions and additional information
- Adaptive task sharing between humans and cobots within operation
- Natural user interfaces for assembly processes (speech, voice, hand-guiding)

Based on these results, the next necessary prerequisites and development steps are discussed and put into the context of the current great challenges within production management and human-computer interaction (Stephanidis et al. 2019).

2. Research Background

Reconfiguration has been considered as one of the main fields of interest for digitalization and enhanced data collection. This has led to an interconnection between the virtual and the physical world, also known as twinning (Jones 2020). Digital twins and CPPS allow digital processing and planning with closely interconnected physical manipulation to create self-X capabilities, thus self-aware, self-configurable, self-optimizing, and self-predictive systems or artefacts (Oliff et al., 2020). The notion of self-X implies the adaptation and alignment of behaviour, state and positions of objects towards desired system output. This allows for better recognition of the work environment and the actual state of the system. Together with actuator capabilities, it enables adaptive systems that adjust their structure and behaviour according to changing requirements (Keddis et al. 2013). The concepts of flexibility and changeability of manufacturing systems have long been some of the main objectives within the scope of manufacturing research. CPS capabilities now allow to adapt to changing demands, order volumes and their unexpected changes and even shocks from the outside environment.

Adaptation as adjustment of a system's shape and behaviour to changing conditions combines decision making, decision informatics, and human interface (Tien 2008). The degree of complexity increases in four dimensions according to the scope of the actions considered. For the first two dimensions, monitoring and feedback, adaptation is based on a set of expected (standardized, procedural, or algorithmic) actions. Cybernetic adaptation as the third dimension additionally includes dynamic actions in unknown states. Lastly, learning adaptation considers unstructured actions based on cognition, evidence, and improvisation (Tien 2008).

However, as Tien (Tien 2008) further points out, "adaption is a uniquely human characteristic", hence, adaptivity does not only cover the adaptation of technical systems but also socio-technical systems. Real-time capable perception enables adjustments of technical artefacts towards anthropometric and cognitive features and requirements of the users. This adaptation of work to human characteristics has been a central goal of human factors and ergonomics. Up to the present day, for work systems, this paradigm has been approximated to the best of our knowledge via the detour of percentile logic and orientation to the statistical normal distribution of, for example, anthropometric characteristics. The actual adaptation of work to the specific features, conditions, and requirements of individual users has so far only taken place in rudimentary form (e.g., height-adjustable workstations or adaptation of lighting parameters in accordance with circadian patterns). However, the possibilities that have opened up in recent years by the advances of CPPS, and also intrinsically safe robotics or self-learning data evaluation systems are now enabling a renewed attempt to implement the goal of adapting work to people through symbiotic human-machine work systems (Wang et al. 2019).

As work systems are socio-technical systems, participation and self-organization of work, coordination and cooperation of the organization improve performance (Gittell at al. 2009) and increase comparative advantages (Appelbaum et al. 2000). The roles, tasks and degrees of freedom of human workers are considered beyond the strictly technical understanding of humans as 'resources'. Over the last decade, the focus of work systems design in manufacturing shifted from operator-less factories and autonomous CPS (Benkamoun et al. 2014) towards the importance of human-centric work design (Ganschar et al. 2013) and worker-centric approaches like Operator 4.0 (Romero et al 2016) or Industry 5.0 (Xu et al. 2021). Recent approaches emphasize the importance of synergetic interaction of the involved agents and objects within the notion of symbiotic human-robot collaborative assembly (Wang et al. 2019) or even towards living manufacturing systems (Monostori/Váncza 2020). However, most of the work emerged in this area only handles the conceptual principles and benefits of human-centred, context-aware work systems. Standards and frameworks on which information is relevant for the agents, what data to collect, and how to infer and interpret this data to adapt the system are still absent (Malik 2007). This results in significant engineering challenges. As developers lack guidelines or at least good practices to follow during the engineering process, systems have to be developed in an ad-hoc fashion (Augusto et al. 2022). As a consequence, transferring prototypes into real-life applications presents a rocky road, while interoperability can be hindered by the absence of common practices (Alegre et al. 2016).

While adaptivity of man-machine systems is a seemingly new concept within manufacturing, in the area of human-computer interaction, transferring the technological concept of reconfiguration into man-machine systems has been a core topic for many years. Adaptivity within human-centred computing is closely connected to the emergence of artificial intelligence and motivated by the increasing availability of computers, smart phones, and internet (Ahmad et al. 2004). As these trends redefined the way technology is used, usability, i.e., the extent to which the product can be used (Yazdi/Göhner 2021), has been gaining importance. Hence, it became necessary to adjust the services to accommodate requirements with respect to the environment the technology is used in to ensure high usability. Furthermore, with the ever-widening diversity of the audience, adaptivity is considered to be the key to universal accessibility of technology (Miraz et al. 2021). Adaptive and Intelligent User Interfaces have been developed to cope with these challenges (Akiki et al. 2014). Using data collected through context sensors and artificial intelligence for advanced decision making, the goal is to meet the demands of users to achieve specific goals when using technology. As proposed by (Yazdi/Göhner 2021), the interaction between humans and machines or computers should be adapted to be *environment-specific, task-oriented*, and *user-specific*.

Environment-specificity denotes the adaptation of technology to the conditions (auditory, visual, thermal, etc.) of the environment (Yazdi/Göhner 2021). A prompt example of this concept is the use of light sensors for adaptive adjustment of brightness, common for smart phones and displays (Yigitbas et al. 2020). *Task-oriented* adaptation focuses on understanding the interaction between the human and the machine through data collection and subsequent task recognition (Yazdi/Göhner 2021). Upon gaining knowledge of the task currently performed, a machine can adapt and take over tasks from users, allowing them to focus on other activities (Álvarez-Cortés et al. 2007). Finally, *user-specificity* refers to the personalisation of systems, accommodating user's needs. As individual users differ in various dimensions such as habits, expertise, or experience, an ideal system should adapt and personalize its services to user characteristics (Norcio/Stanley 1989).

However, it is important to note that accommodating the individual characteristics of the users is achievable either through adaptability or adaptivity. While adaptive systems are marked by the system dominating the adaptation process, actively initialising actions and tailoring itself to the user in an intelligent fashion, adaptable systems are still dominated by the user. Hence, an adaptable system requires user action or user approval to confirm the personalization process (Gulla et al. 2015).

In recent years, these concepts for adaptive human-machine systems have begun to find their way into work systems. Personalization of a work system to human characteristics, preferences, and behaviour is discussed in (Cohen et al. 2018) within a framework for human-machine interaction at the workstation level. On a work organization level adaptations due to worker's fatigue and reliability (El Mouayni et al. 2019), different performance levels and human limitations (d'Avella/Tripicchio 2020) are considered. User-centric and self-configured workstations that adapt to anthropometric characteristics of individual workers are described on a framework level in (Bortolini et al. 2017), regarding specific personalization options in (Rupprecht/Schlund 2021), and by the example of an assembly system for aircraft parts in (Mayrhofer et al. 2019).

Besides conceptual and theoretical contributions, adaptivity and personalisation in terms of industrial man-machine systems have been addressed by various practical works. Personalized adaptation within multi-operator industrial processes has been shown to improve the interaction with the machine, resulting in better performance and less errors, as showcased in (Reguera-Bakhache et al. 2021). The adaptation of lighting conditions was studied in (Bauer et al. 2015), presenting an adaptable solution for personalisation of the work environment. Task-oriented systems for adaptive task sharing between workers and robots can propose optimal task allocation, increasing the cost efficiency of human-machine systems (Schmidbauer et al. 2020). Other applications of task-oriented cyber physical systems include the recognition of human activities through wearables for automated augmentation of work instructions and evaluation of work performance (Tao et al. 2018) or cameras for interaction with industrial robots (Roitberg et al. 2014).

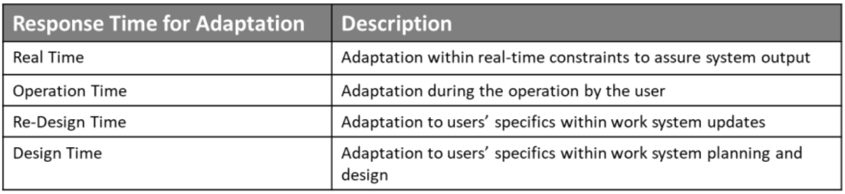
As presented in this selection, a broad range of approaches towards adaptive and personalized work systems have been proposed in the literature. In the following section and in Table 1, we cluster these approaches and different concepts of adaptability with regard to human-centricity.

Concept	**Description**	**Human Centricity**
Adaptable Work System	The system is technically capable to be adjusted to the changes in the work environment (e.g., work process, status)	
Adaptive Work System	The system can detect changes in the work environment and adjust itself accordingly (e.g., work process, status)	
Adaptive Human-Machine Interface	The system can adjust itself to user-specific parameters which dynamically occur during the work process (e.g., activities performed by the users, errors, or stress levels)	
Personalized Human-Machine Interface	The system can dynamically adjust itself to the different user characteristics (e.g., physical parameters, level of expertise)	

Table 1: Concepts of adaptive and personalized work systems

Adaptable work systems can be adjusted to changes in the work environment. This adaptation does not have to be performed in an automated fashion but can be achieved with manual manipulations. With respect to the integrated sensory capabilities *adaptive* work systems can detect changes in the work environment and autonomously adjust themselves accordingly. Typical triggers are changes in the work environment, such as reconfigurations of assembly lines. *Adaptive human-machine interfaces* can adjust themselves to user parameters, which dynamically occur during the work process. The system therefore monitors, and analyses activities performed by the users, poses, or work positions with specific assistance needs such as overhead work, or stress levels. However, these interfaces do not differentiate between individual users. *Personalized human-machine interfaces* dynamically adapt to the individual characteristics of different users. These might be anthropometric parameters such as reach, preferred hand, level of expertise, or working habits. According to the orientation of the system's behaviour on the worker, the human-centricity of the discussed concepts improves and peaks in personalized human-machine interfaces.

The adaptation itself takes place within different time frames. Existing concepts consider quite different scopes ranging from design adjustments in reconfiguration and replanning options to hard real time adjustments. We summarized these time frames in Table 2. The response for *real time* adaptations usually covers milliseconds. These requirements usually are relevant for adaptive work systems in close interaction with the user such as active exoskeletons. If the adaptations take place within the work process, e.g., within the repositioning of material, tools and information for subsequent work tasks, *operation time* adaptations are sufficient. For update purposes, e.g., the adjustment of the work system to the anthropometric characteristics of the workers of the following shift, *re-design response times* are considered. In case adaptation is used for planning and reconfiguration purposes, adaptations take place in *design time*.



Response Time for Adaptation	Description
Real Time	Adaptation within real-time constraints to assure system output
Operation Time	Adaptation during the operation by the user
Re-Design Time	Adaptation to users' specifics within work system updates
Design Time	Adaptation to users' specifics within work system planning and design

Table 2: Response times for adaptation

3. Design Framework

The concept of work systems within the domain of manufacturing is per definition following a socio-technical perspective. Relevant normative approaches therefore follow an understanding of the respective system as selection of technological, organizational, and human-related system elements and their interrelations. The DIN guideline 6385 (DIN 2016) presents a work system model that contains the transformation of input into output by work procedures that are executed to fulfil a given task by humans and work equipment at a defined workplace under the impact of various conditions of the work environment.

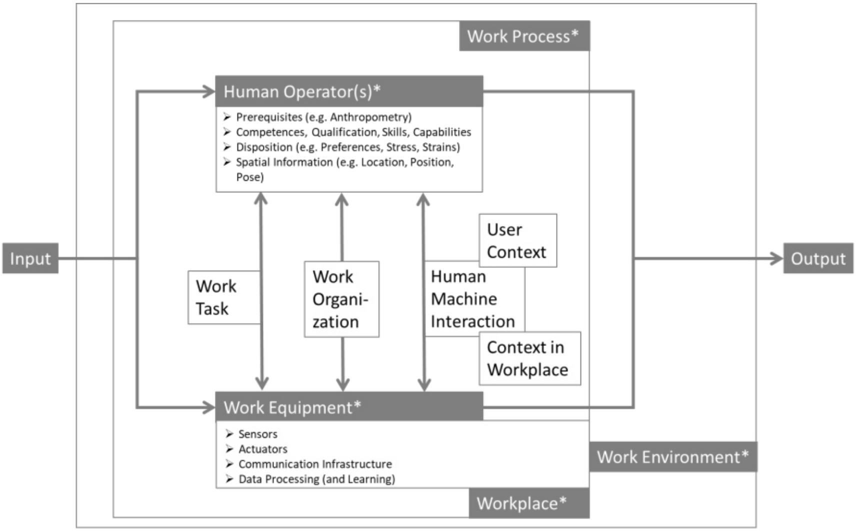
As aspects of adaptation and personalization build up on information about the actual status and changes of work environment, digital representations of human parameters and behaviour as well as of the work environment are necessary. The consideration of the *work environment* includes parameters that have to be taken into account for adaptation purposes like adjustments regarding noise and exceeding temperature limits. The work environment dimension additionally represents the demarcation of the work system and the interface to adjacent ones.

In order to be capable of any adaptation, the *work equipment* contains sensors and actuators. For data analysis and data handling, it is necessary to consider cognitive functionalities (data processing, perception, cognitive control, learning) and communication infrastructure. Depending on the setting of the work system design, work equipment and *workplace* might be closely interrelated or even integrated. The use of mobile manipulators as personal companions for the material provisioning (Schlund et al. 2018) or height-adjustable workplace carriers (Nguyen et al. 2014) integrate the two dimensions.

The *human operator* brings in his or hers physical and psychological prerequisites and disposition. The operator induces context changes through the interaction with the environment like changes in the spatial information, e.g., location, orientation, and pose of the human.

In between the two principal agents - *human (operator)* and *work equipment (machine)* - information about further interrelations might be necessary. If specific adjustments are triggered by certain work tasks like special lighting in case of error-prone or quality-critic assembly tasks, start and end time as well as spatial information about the *work task* is needed. Information about *work organization* covers defined, possible, or preferred task allocation patterns for one-to-one relations between human and machine agents, as well as for individual preferences and skill sets. *Human machine interaction* includes the context of the user within the interaction with other agents and environment. Information is necessary for the adaptation of implemented modes and combinations of bidirectional feedback between humans and machines. Task orientation through the recognition of human activities (human activity recognition, HAR) allows for analytics and tracking of the *work process* and together with the human machine interaction adaptations of the work system. The conceptual framework for the work system model is visualised in Figure 1.

The presented conceptual framework aims to map the transition from today's work systems towards dynamic adjustability and contribute to a closer integration of digital enabled capabilities into work system design. Traditional work system design within the scope of manufacturing is based mainly on the principles and methods of ergonomics (DIN EN ISO 6385 2016), process organisation, and internal logistics, taking into account the interests of functional, economic, reliable, ecological, user-adapted, and safe solutions (REFA 2022). Our proposed framework extends the traditional system elements towards requirements and interrelations that are considered to be helpful to design adaptive and personalized work systems. While still building on the roots of a well-founded socio-technical system approach, it places focus on the integration of cognitive features and capabilities.



* + respective digital representation

Figure 1: Work system model for personalized work systems

All dimensions of the work system (human operator, work equipment, work process, workplace, and work environment) are subject to modelling and simulation of digital representations. A digital twin of the entire work system therefore covers the dimensions and combines existing approaches like digital human models, CAD-CAM-based processes, workplace models and state trackers. For the realization of real time or operation time adjustments, fast and precise sensors, and robust datasets need to be present. Otherwise, adjustments can only take place at a very limited scope, e.g., closed feedback loops between a very specific worker pose and a predefined parameter setting of the workplace, implemented in a hard-coded fashion. For a truly adaptive work system within the understanding of Figure 1, an integrated work system twin or at least interconnected twins of the respective dimensions are necessary.

4. Examples

Despite adaptive work systems on a larger scale are still being subject of various challenges, realizations of separate adaptive or personalized functionalities already exist. Following, exemplary contributions of TU Wien are introduced that contribute to the adaptive interconnection between human operators and work equipment.

4.1. Adaptive projection of work instructions and additional information

Information provisioning for industrial site assembly, e.g., the manufacturing of larger aircraft parts, trains, or prefabricated building components, is today mainly executed via terminal displays. Projector systems enable the display of information directly on the workplace or other surfaces in direct relation to the work task, such as walls, desks or the floor. This approach prevents walking routes to static terminals, enables hands-free work, and is ergonomically favourable to head mounted devices (HMDs), especially when used over a longer period of time - like a shift. Within a setup of a carbon tape-laying process of a fan cowl, an adaptive spatial augmented system was implemented. Using a projector and a mirror-head to dynamically move the projection, the information is displayed where needed, depending on the specific task and the position of the worker. Cameras are used to detect user context and interact with the system. This is performed using the YOLO object detection algorithm (Redmon/Farhadi 2018), capturing the position of the worker and his or hers gestures to interact with the system. Figure 2 shows the concept, the demonstration setup in the TU Wien Pilotfabrik and the results of the selected evaluation metrics (Rupprecht et al. 2021). Regarding the work system model presented in Figure 1, the example is directly related to an adaptive system, considering the interaction between the operator and the equipment on a task level.

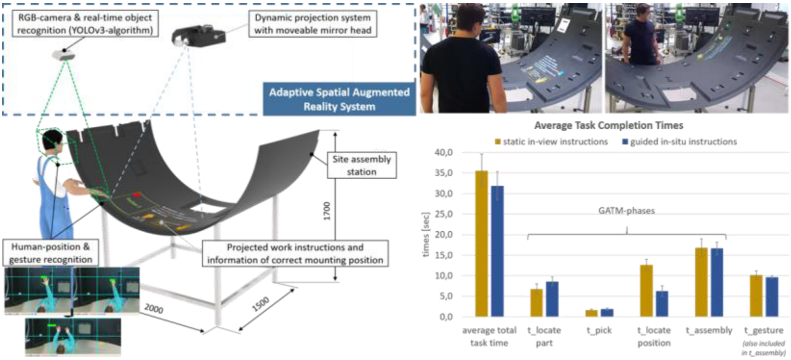


Figure 2: Adaptive projection of work instructions and additional information

4.2. Adaptive task sharing between humans and cobots within operation

The allocation of work tasks to human and machine interaction partners has been a research question since the beginning of industrial automation. Beyond leftover and compensatory approaches, complimentary task allocation is considered to be favourable from an ergonomics point of view, but up to date not often realized. The adaptive task sharing (ATS) approach (Schmidbauer et al. 2020) allows ad hoc changes in the selection of tasks that are attributed to either the human or the machine. First, the task allocation is pre-assigned by the system according to specific requirements like lot size, ergonomics, and individual (worker) preferences. Hence, the task allocation patterns are adaptive and can be personalized to a specific user. Within operation, the system allows a fast reattribution of tasks to the interaction partners. The system was implemented using a BPMN engine and Node.js Task Client. The communicating between the robot and the web interface is performed via REST API, utilising a state machine to monitor the task status. The workflow sequences have to be pre-programmed in advanced and are later retrieved during the process. Tasks that are executable by either the cobot or the human (shareables) are subject of possible reallocation before any new process operation (Schmidbauer et al. 2021). Regarding the work system model, the example is situated at the work organization level between the human and the machine and expands towards work settings with multiple human and machine agents.

Static task allocation

Human	Shareable	Cobot
Tasks not-executable by a cobot (leftover) or effort for automation is too high (compensatory)	Not foreseen	Tasks executable by a cobot at reasonable costs or tasks that are disadvantageous for humans

Adaptive task sharing

Human	Shareable	Cobot
Tasks not-executable by a cobot (leftover) or effort for automation is too high (compensatory)	Tasks executable by humans and cobots that can be shared adaptively according to decision criteria	Tasks executable by a cobot at reasonable costs or tasks that are disadvantageous for humans

Figure 3: Adaptive task sharing between humans and cobots in manufacturing

4.3. Natural user interfaces for assembly processes

In order to simplify programming of cobot applications for more flexible reconfiguration and task allocation approaches, natural as well as multimodal user interfaces tend to be more intuitive and productive. Tests with a combination of hand guiding of a cobot and voice control show up to 46 percent decrease in teach-in time for simple pick and place operations (Ionescu/Schlund 2021). Besides the productivity increase, flexible set-ups of different interaction modes, such as textual and graphical user interfaces, hand guiding, gesture and voice control, or even brain-computer interfaces are possible. The integration of these different interaction modes has been made easier by open libraries, such as (Zhang 2017). Most of these approaches to the interface are adaptable, e.g., the user can adapt the voice-user interface to return voice information in either male or female voice, adjust the speed, or train personal commands for brain-computer interface. In order to upgrade from adaptable to adaptive and even personalized human-machine interfaces, automated recognition of the user context and the context in the actual workplace setting has to be considered.

4.4. Challenges towards designing adaptive and personalized work systems in manufacturing

Following a socio-technical approach in designing and implementing the presented use cases, we address some challenges encountered during the design of adaptive and personalized work systems. Overall, there is an evident lack of implementation standards and dedicated open datasets for the retrieval of user context, e.g., for activity recognition in manufacturing. For example, the dataset for the gesture control utilised in example 5.1 had to be created from scratch. As a consequence of the lack of open datasets and standards, data generation and system development are time-consuming. This makes the transfer of these applications into industrial settings difficult. Data privacy and data security pose further challenges. As adaptive work systems rely on data collected by sensors integrated in the environment, they could potentially expose the privacy of workers, if not secured through the use of appropriate processing techniques. Furthermore, while employees expect to have control over the data they provide to the employer, company-related data is also under threat in the event of a security breach. This poses a potential risk to internal know-how. Due to a lack of experience and established implementation solutions, there are reservations in many companies about fully exploiting the advantages of digitalisation to the extent that is technically possible.

5. Conclusion

Within the context of sensor integration, ubiquitous computing, and real-time-capable over-the-air communication of large data streams, adaptive work systems have already become feasible within small, isolated applications. Adaptivity can be triggered by changes in the context in the work system or individual characteristics and preferences. Adaptive and personalized work systems have the potential to implement human-centricity and therefore to fulfil one of the oldest imperatives of ergonomics: to adapt work systems to the workers. However, in order to design and implement adaptive and personalized work systems on a large scale, modelling approaches of different domains (engineering, human factors, human-computer engineering) have to be brought together to create a common framework. This paper introduces first steps in this direction in enlarging the work system model of DIN EN ISO 6385 towards the integration of further elements and to show the relevant direction of future development towards adaptive and personalized work systems in manufacturing. However, the conceptual work is far from being finished. To date, reference models for human-centric manufacturing approach this goal from a more production-technology related angle (cf. Lu et al. 2022). As the topic per se is transdisciplinary, shared or at least known agreed and mutually accepted models across the disciplines of engineering, human factors, human-computer engineering are needed.

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