University of Groningen

Work design in future industrial production

Waschull, S.; Bokhorst, J. A.C.; Molleman, E.; Wortmann, J. C.

Published in:
Computers and Industrial Engineering

DOI:
[10.1016/j.cie.2019.01.053](https://doi.org/10.1016/j.cie.2019.01.053)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2020

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Waschull, S., Bokhorst, J. A. C., Molleman, E., & Wortmann, J. C. (2020). Work design in future industrial production: Transforming towards cyber-physical systems. *Computers and Industrial Engineering*, 139, [105679]. <https://doi.org/10.1016/j.cie.2019.01.053>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Work design in future industrial production: Transforming towards cyber-physical systems

S. Waschull*, J.A.C. Bokhorst, E. Molleman, J.C. Wortmann

Faculty of Economics and Business, University of Groningen, PO Box 800, 9700 AV Groningen, The Netherlands

ARTICLE INFO

Keywords:

Cyber-physical systems
Work design
Job characteristics
Information processing functions
Automation
Management choice

ABSTRACT

Rapid advancements in an array of digital technologies and applications promote the transformation of industrial production into cyber-physical systems (CPS). This process is projected to lead to a completely new level of process automation, thereby redefining the role of humans and altering current work designs in yet unknown ways. However, existing literature is rather ambiguous and not explicit on how the transformation towards CPS affects work design. In this study, we therefore consider this transformation at a much more detailed level. Our main contribution is the development of a framework to assess work design changes in the transformation towards CPS, and the consideration of the role of management choice therein. The framework relates (future) capabilities of CPS on the machine, production line, factory and supply chain scope to functions of human information processing. We then evaluate how the potential automation or augmentation of those functions by CPS affects job characteristics. Automation in this context is defined as the transfer of control and decision-making from humans to CPS, while augmentation means that technology is used to enhance human productivity or capability. We expect that the transformation towards CPS and the resulting automation and augmentation of tasks will shift the majority of human work to jobs characterized by high levels of job complexity, job autonomy and skill variety. This effect will become more severe when tasks are increasingly automated in the transformation towards CPS. During this development, human skills and knowledge will presumably remain critical in near future industrial production. Nevertheless, the ultimate implications for work design are strongly dependent on management choice. Strategic decisions are required on (1) which functions to automate across different scopes of operations and (2) how to group the resulting pool of tasks into jobs. This may result in various work designs. However, this choice is to a certain degree limited, and the role of technology is to restrict, rather than determine management choice.

1. Introduction

In literature and in practice, work design is often positioned as a central mean for organizational success. Work design refers to the processes and outcomes of how work is structured, organized, experienced and enacted (Morgeson & Humphrey, 2008). Specifically, the way that work is structured and organized determines a number of job characteristics as experienced by the employee, in turn affecting personal and organizational outcomes (Hackman & Oldham, 1976, 1980). Hence, understanding what induces changes in work design is essential for the success of every business.

It is well understood that the presence or absence of respective jobs characteristics ultimately results in personal and organizational outcomes (Oldham & Fried, 2016). What we do not yet fully understand is

what exactly leads to variations in these work designs (Parker, Morgeson, & Johns, 2017). One source of variation stems from the implementation of innovative digital technologies in industrial production, linked to the concept of Industry 4.0 (Hirsch-Kreinsen, 2016; Hirsch-Kreinsen & Ten Hompel, 2015). Industry 4.0 is an umbrella term comprising an array of different high-tech technologies and is characterized by Cyber-Physical Systems (CPS) in the context of industrial production (Colombo, Karnouskos, Kaynak, Shi, & Yin, 2017; Hermann, Pentek, & Otto, 2016).

In essence, CPS are systems of interconnected physical and computational objects, resulting in a close coupling of the cyber and physical contexts (Lee, Bagheri, & Kao, 2015). In industrial production, this means that physical objects, such as machines or products, are integrated with computational components. As a consequence, CPS are

* Corresponding author.

E-mail addresses: s.waschull@rug.nl (S. Waschull), j.a.c.bokhorst@rug.nl (J.A.C. Bokhorst), h.b.m.molleman@rug.nl (E. Molleman), j.c.wortmann@rug.nl (J.C. Wortmann).

<https://doi.org/10.1016/j.cie.2019.01.053>

characterized by interconnectedness and intelligence, the latter referring to their increasing ability to act autonomously and automatically (Monostori, 2014). In contrast to earlier developments such as Computer Integrated Manufacturing (CIM) which is often perceived as a predecessor of Industry 4.0 (Kinkel, 2007; Kinkel, Friedewald, Hüsing, Lay, & Lindner, 2008; Zuehlke, 2010), it is expected that CPS introduce new potentials for the planning, control and the organization of production processes as well as supply chains (Hirsch-Kreinsen, 2016). Furthermore, CPS will lead to new forms of interaction between workers and machines (Hancock et al., 2013; Hermann et al., 2016). These developments will not only change current methods of production (Brennan et al., 2015), but significantly affect current work designs too.

In general, technological change has been shown to positively and negatively affect work design (Parker, Morgeson, et al., 2017). Technology can substitute tasks previously executed by humans, simplify jobs and enrich jobs (Dworschak & Zaiser, 2014; Dworschak, Zaiser, Martinetz, & Windelband, 2011; Hirsch-Kreinsen, 2016). These effects are also prominent in the transformation towards CPS (Hirsch-Kreinsen et al., 2018). On the one hand, a growing share of complex information processing tasks can be automated. These tasks on the medium skill level relate to business support functions concerned with the overall control of industrial production. As a result, a large share of these tasks might disappear, or be strongly simplified (Windelband, 2014). On the other hand, remaining human tasks are expected to be enriched by higher complexity requirements. However, whether CPS enrich or simplify jobs is not solely determined by the technology itself, it also depends on a number of choices made by management. These include not only choices related to the technology itself, but also choices made on organizing work around the new technology (Holman, Wood, Wall, & Howard, 2005; Snell & Dean, 1992; Wall, Corbett, Martin, Clegg, & Jackson, 1990; Williams, 1994).

Organizations are currently just starting to transform their production towards CPS. Based on the existing literature, we know little about how this change affects people's work (Hirsch-Kreinsen, 2016; Parker, Morgeson, et al., 2017). We currently can only sketch a rather broad expectation on its impact. Hence, there is a need for a systematic investigation on how the technological capabilities provided by CPS induce changes in work design. The contribution of this paper therefore is to develop a detailed framework of the transformation towards CPS, to analyze its impact on work design and job characteristics, and to describe the role of management choice therein. Specifically, the framework developed in this study dissects the technological capabilities provided by CPS and relates these to functions of human information processing across different scopes of operations in industrial production. The framework allows a detailed description of various work designs and corresponding job characteristics when transforming towards CPS. It also elaborates on the management choice to allocate functions

to either CPS or humans and to organize the resulting pool of human tasks into jobs. These concepts and their relations are outlined in Fig. 1.

The paper is structured as follows. In Section 2 we briefly present the theoretical developments concerning work design, specifically relating it to different types of automation, and describe the role of management in the creation of new organizational forms of work. In Section 3, we develop a framework of CPS information processing capabilities across different scopes of operations in industrial production. Afterwards, the framework is applied to evaluate the implications of CPS for specific job characteristics in Section 4. Finally, Section 5 presents a discussion and Section 6 concludes.

2. Theoretical background

In this section, we first elaborate on the theory of work design and job characteristics, which is used as a theoretical lens in this research. Second, we specify different types of automation and augmentation in industrial production, and their impact on work. Third, the role of management choice in the context of technological change is considered.

2.1. Work design and job characteristics

Work design refers to the processes and outcomes of how work is structured, organized, experienced and enacted (Morgeson & Humphrey, 2008). We apply this definition as it reflects our understanding that work is not designed into static jobs encompassing fixed tasks, but that it changes dynamically due to, among others, technological changes (Parker, 2014; Parker, Wall, & Cordery, 2001). Typically, a job is defined as an aggregation of tasks assigned to a worker (Wong & Campion, 1991).

We use the job characteristics theory as a theoretical lens to describe the changes of jobs in the context of modern technologies. Based on the understanding that jobs can be designed in such a way as to increase motivation and satisfaction, a set of job characteristics are proposed to describe the objective properties of the structure of tasks assigned to employees and their cognitive demands (Hackman & Oldham, 1976; Humphrey, Nahrgang, & Morgeson, 2007; Morgeson & Campion, 2003).

Preceding research on work design changes in the context of modern technologies evolves around the potential of new technology to change job characteristics, resulting in simplified jobs or enriched jobs (Hirsch-Kreinsen & Ten Hompel, 2015; Zuboff, 1985). Job enrichment is achieved through increasing employees' autonomy over the planning, control and execution of their work and is characterized by a high level of skill variety, job complexity, and job autonomy, resulting in work with higher mental demands (Parker, 2014). Simplified jobs are characterized by the absence of these characteristics, resulting in jobs in which mental work is allocated to engineers and managers and other

Fig. 1. Work design in the context of cyber-physical systems.

remaining jobs encompass physical, often routinized tasks that are tightly controlled (Parker, 2014; Turner & Lawrence, 1965). In the transformation towards CPS, revealing the impact of work design includes more than considering whether tasks are assigned to either humans or machines. New forms of human-machine interfaces and techniques like augmented reality result in a stronger interaction between workers and machines or information systems (Krevelen & Poelman, 2010). Furthermore, this may lead to an environment where humans also collaboratively work with machines/robots (Bruno & Antonelli, 2018). In these settings, technology does not substitute but rather augments workers. Therefore, we are interested in assessing how job characteristics change when transforming towards CPS, and how this in turn affects job enrichment and/or job simplification. We selected the job characteristics skill variety, job complexity, and job autonomy as they link well with previous and anticipated changes in work design originating from digital technologies (Dworschak & Zaiser, 2014; Kinkel et al., 2008; Wall et al., 1990).

Specifically, the level of skill variety describes how many different skills and capabilities are needed to perform the job (Hackman & Oldham, 1976). A job requiring multiple skills is often more challenging and engaging, as a variety of different tasks requiring different skills are part of the job (Morgeson & Humphrey, 2008). Jobs characterized by high job complexity are often more mentally demanding and require a high level of information processing (Humphrey et al., 2007). This is specified as the extent to which the employee is required to pay attention, to monitor data, to manage information and to actively use cognitive abilities for decision-making (Wall et al., 1990). Jobs with high information processing requirements demand higher levels of knowledge (Morgeson & Humphrey, 2008). The final job characteristic relevant in this context is the multidimensional concept of job autonomy. Job autonomy describes the amount of freedom and independence the employees have in carrying out their work (Hackman & Oldham, 1975). Autonomy includes three dimensions. Work scheduling refers to how much discretion and freedom is given in the scheduling of work, as opposed to responding when the technology requires. Work methods refers to the control over the type of work methods and decision-making refers to the decision-making autonomy assigned (Morgeson & Humphrey, 2006; Wall, Jackson, & Davids, 1992).

The majority of research in the field of work design has focused on how work should be designed to lead to a set of superior employee and organizational outcomes (Grant, Fried, & Juillerat, 2011; Morgeson & Humphrey, 2006; Oldham & Hackman, 2010). To the best of our knowledge, the literature often neglects to report where variations in work design, such as enriched or simplified jobs, come from (Oldham & Fried, 2016; Oldham & Hackman, 2010; Parker, Morgeson, et al., 2017).

So in most research, work design is measured as the independent variable, while the antecedents of work design are largely ignored. However, a number of factors can actually impact work design under a new manufacturing paradigm in sometimes unintended ways (Snell & Dean, 1992), in turn not producing the desired effects for employees and organizational outcomes. These antecedents are the focus of the current paper, specifically the impact of the transformation towards CPS in future industrial production, including the management choices therein.

2.2. Work design and technology in industrial production

Through the application of mechanical, electronic, and computer-based systems, technology can be applied to either operate or to control physical equipment and processes, i.e. supervisory control (Groover, 1984; Williams, 1994). First, the actual automation of the manufacturing systems in the factory (the physical process), replaces human muscle power and this is referred to as mechanization. Second, the application of computers or information technology to transform data and manage information to control physical processes substitutes or

augments cognitive tasks, which is referred to as computerization (Terwiesch & Ganz, 2009). Depending on the level of automation, computerization is transferring control, regulating and decision-making from humans to technical systems (Frohm & Bellgran, 2005). In the factory, this includes for example supervisory control and data acquisition systems (SCADA) or enterprise information systems. Both mechanization and computerization have shown to have significant impact on work design by substituting or augmenting work, e.g. the adoption of Computer Integrated Manufacturing (CIM). CIM may substitute both manual production tasks or routine information processing tasks, thereby freeing employees to potentially take on new and complex tasks that are primarily cognitive in nature resulting in enriched work (e.g. supervisory control including monitoring, solving problems, maintaining) (Badham, 1989; Molleman & Slomp, 2001; Sinclair, 1986; Wall et al., 1990). Yet, CIM can also simplify work due to increased standardization and routinization (Corbett, 1987; Wall et al., 1990), with employees having little local control (Clegg, 1984).

But a purely technology-centered approach in an 'all or none' fashion to automation where everything will be automated that can be automated has shown to result in often poor human 'out-of-the-loop' performances (i.e. low situation awareness or vigilance) (Endsley & Kaber, 1999). Therefore, a human-centered automation philosophy promotes a cooperative relationship in the control and management of a system. Here, the human remains in control and stays responsible for meaningful and well-designed tasks (Sheridan, 2012), resulting in human-automation symbiosis work systems (Romero, Bernus, Noran, & Stahre, 2016). One of these approaches is referred to as adaptive automation, in which machines adapt to the cognitive and physical needs of the worker and provide support only when needed. With an increasing sophistication of cognitive and physical aids due to the ongoing technological developments in computers, displays (i.e. human-technology interfaces) and sensors, these new emerging forms of human-machine/computer interaction with the human 'in-the-loop' will become even more prominent (Hancock et al., 2013; Romero, Stahre, et al., 2016; Sheridan, 2012).

The literature shows that the effects of technology on work design are not uniform (Clegg & Corbett, 1986; Kelley, 1990; Parker, Broek, & Holman, 2017), nor does the technology alone determine work design (Liker, Haddad, & Karlin, 1999). There is a significant degree of discretion involved.

2.3. Role of management choice

Typically, managers and system designers implicitly or explicitly have a significant influence and control over the design of work through a number of inherent technological and organizational choices (Clegg & Corbett, 1986; Hirsch-Kreinsen, 2014; McLoughlin & Clark, 1988; Parker, Broek, et al., 2017). The choices of management are generally influenced by several factors. Among them, economic, political, social and technological factors play a significant role (Williams, 1994, 1999). So, based on some rationale, management will (design and) implement technology to automate or to augment a specific task/function to varying extents ranging from manual control to full automation (Kaber & Endsley, 2004). This leads to further decisions on the required skills and abilities of the workers. As such, these management decisions can result in a far going substitution, but also in the augmentation of human work, for example in cases where humans and technology need to interact to fulfill a specific task (Dworschak & Zaiser, 2014; Lee & Seppelt, 2009; Windelband, 2014). To assess and structure potential social and organizational changes, reference architectures such as the Purdue Enterprise Reference Architecture (PERA) are helpful as they explicitly represent the human role in the system (Romero, Wuest, Stahre, & Gorecky, 2017; Williams, 1994). After considering the technological choices to augment or substitute work, management has choices in how to organize remaining human tasks into different jobs. For instance, easy and complex work can be separated into different jobs or be

Box 1

Real-life example of different management philosophies concerning work design.

The leading airplane manufacturers Boeing and Airbus possess different philosophies on the use of automation systems for flight control in airplane cockpits, in turn significantly impacting how pilots perceive their jobs (Young, Stanton, & Harris, 2007). Boeing strongly advocates self-awareness and promotes a more human-centric automation as a tool to aid the pilot having ultimate control of the automation system (e.g. preventing the system from overriding the pilot decision). In contrast, Airbus presses for the reduction of human error, and its automation system is designed to prevent the pilot from exceeding safety limits. It automatically makes flight control inputs which are normally done by a pilot, and at any time is able to override decisions taken by pilot, rendering the pilot to solely react to decisions taken by the automated system.

integrated into one and the same job (McLoughlin & Clark, 1988), with varying implications for job characteristics. For an example, see Box 1.

3. A CPS classification framework to assess work design changes

In this section, we develop a framework to specify what capabilities of CPS can potentially induce or constrain changes in work design and job characteristics. One dimension of the framework includes the CPS capabilities, which are based on the properties of the technology. The other dimension includes four scopes of operations in which these capabilities can be applied. We apply this framework in section 4 to analyze potential changes in work design when transforming towards CPS.

3.1. CPS in industrial production

CPS are envisioned to be the backbone of future industrial production, projected to be able to meet the changing customer requirements and increasing market competitiveness of the upcoming years (Kagermann, 2013). Similar to the development around CIM in the beginning of the 1990s, CPS are characterized by the increasing penetration of innovative ICT technologies in existing industrial production to substitute or augment human tasks. Considered as a predecessor of CPS (Zuehlke, 2010), CIM focused on integrated manufacturing systems and databases, as well as computerized work cells and large scale automation (Nagalingam & Lin, 2006). Traditionally, CIM resulted in a rather static form of automation. CPS further advances CIM and includes technologies such as e.g. wireless communication, robotics, sensor networks and the internet of things (IoT) (Monostori, 2014; Walter & Karnouskos, 2014). CPS are integrations of computational and physical processes to monitor and control physical systems (Colombo et al., 2017; Lee et al., 2015). Sensors and actuators actually allow the physical processes to be monitored in real-time (Rajkumar, Lee, Sha, & Stankovic, 2010). While both CIM and CPS focus on digitization and interconnection, CIM focuses mainly on the CAD/CAM coupling and digitization of the shop floor equipment, whereas CPS focus in addition on intelligent products and connected devices (Yu, Xu, & Lu, 2015). Furthermore, in CIM a centralized computer system plans production, monitors execution and reacts to the environment (machines, processes), while in CPS decentralized systems (such as manufacturing resources and intelligent products) plan production, monitor execution and negotiate appropriate reaction to adapt operations. Through linkage of different data levels with real factory processes, new potentials for planning, control and organization of production processes and value chains are created in CPS (Hirsch-Kreinsen, 2016).

Increasingly, CPS are envisioned to overcome static automation to feature adaptive automation that dynamically allocates tasks between humans and machines based on the cognitive and physical demands of the user, and to facilitate both economic and social benefits (Hancock et al., 2013; Romero, Bernus, et al., 2016). For example, collaborative robotics or augmented reality applications provide new opportunities to augment humans in physical tasks. In line of this thought, the Operator 4.0 concept proposes a design and engineering philosophy based on

human-centric automation where technology is designed to enhance human's physical, sensorial and cognitive abilities (Romero, Bernus, et al., 2016). Some key enabling technologies for supporting the Operator 4.0, referred to as a smart and skilled operator, include e.g. augmented and virtual reality, collaborative robots and big data analytics (Romero, Stahre, et al., 2016).

These developments are forecasted to change current methods of production, and the role of workers. Therefore, it is worth revisiting old assumptions and insights and evaluate what this means for the nature of work in industrial production.

3.2. CPS and functions of human information processing

We consider the implications of CPS from a human information processing perspective and hence focus purely on cognitive tasks. We do so because CPS allow the increasing integration of information and decision capabilities into industrial production (Lee, Lapira, Bagheri, & Kao, 2013; Meyer, Wortmann, & Szirbik, 2011; Monostori, 2014). However, this definition is rather abstract and not specific enough to link CPS to changes in work design. To evaluate the impact on work design and job characteristics, we therefore link the capabilities of CPS to four broad classes of functions of human information processing as defined in the model of Parasuraman, Sheridan, and Wickens (2000). The function of information acquisition refers to the sensing and registration of information, which is subsequently analyzed involving conscious perception and manipulation (information analysis). The next function of decision selection involves decision-making based on cognitive processing. The reached decision then leads to the implementation of responses/actions (decision implementation).

In our framework we propose that these four types of functions in turn have its equivalent in manufacturing system functions that can be automated (Endsley & Kaber, 1999; Parasuraman et al., 2000; Parasuraman & Wickens, 2008) or augmented (Groover, 2001). We define automation in the context of CPS as the capabilities to substitute these human information processing functions, while augmentation refers to enhancing human productivity.

Because of the fact that the scheme of Parasuraman et al. (2000) is now more than 19 years old, it is likely that the scheme lacks capabilities, which are concerned with innovations of the system under consideration or its products. Such innovations may be labeled from a quality management perspective as continuous improvement, from a learning perspective as double loop learning, or from a production engineering perspective as production system configuration. All these terms refer to innovation in products, in services or in production systems, which until now is completely within the realms of humans. Accordingly, industrial production where no innovation is foreseen can often be largely automated, whereas industrial production that has to be reconfigured still regularly needs human expertise to pursue the innovation. Somewhere in the future, artificial intelligence software may take a leading role in such innovations, and we thus added it as a following step in the classification of Parasuraman et al. (2000). Table 1 presents increased capability levels of CPS with respect to information processing functions and provides some illustrative examples.

Table 1
Levels of CPS information processing capabilities.

Level 1: Information acquisition Capability to acquire and share reliable data from different manufacturing resources	A CPS capable of information acquisition can acquire information by being equipped with a unique ID, to sense and register input data, and to communicate this data to other objects horizontally (to similar objects on the same level) or vertically (at a higher hierarchical level to a control system or other information system). Example: current production lines for discrete consumer products (e.g. in food or electronics). Note that products as intelligent objects are not yet common practice.
Level 2: Information analysis Capability to derive meaningful information from the data	A CPS capable of information analysis is specified as being able to analyze and present data, to notify in case of problems by assessing and monitoring incoming data on some pre-specified criteria and, if needed, collect and share information in the network. Increasingly, CPS will be able to provide intelligent and context dependent assistance to aid users. Example: current systems for transport of energy (e.g. electricity or gas). Note that here products cannot be intelligent due to their non-discrete nature.
Level 3: Decision selection Capability to analyze information for decision-making purposes	A CPS capable of decision selection can determine alternative plans to overcome a certain disturbance or problem. This includes the capability of CPS to negotiate with other objects to achieve an individual or common goal. It thereby replaces human decision-making by computational decision-making. Example: automatic planning of shop floor and material movement in warehouses and factories, to be authorized by people.
Level 4: Decision implementation Capability to process the feedback from the cyber to physical space, resulting in the implementation of that decision	A CPS capable of decision implementation is able to execute the decision choice by inducing the adjustment of resources (actuation). Example: an interesting development lies in smart glasses, which allow humans to get information on the spot when needed, collaborating robots or intelligent vehicles (e.g. self-driving cars and buses or automatically-guided vehicles in shop floors or warehouses).
Level 5: Innovation Capability to innovate based on the acquired and analyzed information	Innovation includes functions of knowledge creation, knowledge sharing, improvement proposals and implementation (organizational change). A CPS capable of artificial intelligence and deep learning (in combination with techniques to analyze 'Big Data') allowing systematic learning in case of well-defined problems.

Generally speaking, it is expected that the development of CPS capabilities follows a sequential path (Lee et al., 2015), from the automation of initial information acquisition, to information analysis, to decision selection, to the final decision implementation, to innovation. We acknowledge that traditionally the automation of these information processing functions were not always cumulative in nature. For example, a system providing information analysis functionality could receive that information/data as manual input acquired through an employee, and not through sensors. However, we assume that to ultimately achieve the full benefits of CPS in future industrial production, lower information processing functions generally will be automated through CPS technology first, before the full benefits through automating higher information processing functions can be achieved. Currently, CPS technologies largely focus on aspects of data collection and data analysis. The automation of these functions introduces great potentials for augmenting workers in higher level control functions (e.g. decision-making).

3.3. Scopes of operations in industrial production

CPS capabilities can address different scopes of operations. Scopes of operations are characterized by different reaction times to pre-specified triggers and by different planning horizons. Based on the ISA95 standard (ISA, 2014), the scopes of operations considered in this research are:

1. Machine scope

Monitoring, supervising and controlling the physical production process or respective machines with a short reaction and planning time (seconds and minutes respectively), e.g. individual machines but also a fleet of machines.

2. Production line scope or cell-system scope

Monitoring and coordinating of the entire workflow and production execution to produce end products of line or cell. Reaction time is minutes, planning horizon amounts to hours/days.

3. Factory scope

Developing and following-up on the achievement of long term plans, e.g. providing material and capacity planning and scheduling functionality. Reaction time is hours/days, and planning horizon often addresses weeks.

4. Supply chain scope

Based on the sales and operations plan, checking suppliers' capacity and negotiating alternative sourcing if applicable. Managing tracking and tracing information from raw materials to end user consumption. Developing and managing services for products in the field, and collecting usage information about such products for future innovations. Establishing programs for the circular economy where products are re-used, re-furbished, materials are upgraded and value is captured in all products and packaging materials returned to the company.

3.4. CPS capabilities across scopes of operations – a framework

Combining the scopes of operations with the CPS information processing capabilities, a framework is generated as shown in Fig. 2. The framework dissects the different stages in the transformation process towards CPS. The horizontal axis shows the different levels of CPS information processing capabilities, whereas the vertical axis specifies the different scopes of operations where these CPS capabilities can be applied. Moving from bottom-left to top-right in the Fig. 2 (indicated as the grey line), more tasks are assigned to CPS and fewer to humans, ending up in a fully configured CPS. This schematic representation provides generic insights into the forces and factors at play, but we realize that this transformation is in reality much more complex. For illustration purposes, we included some examples of concrete technologies that can be applied in the transformation towards CPS.

3.4.1. CPS information acquisition across scopes of operations

The function of information acquisition within the scope of a machine is concerned with the collection of data on the state or location of manufacturing resources, for example the state of machines, products, tooling or environmental conditions. This information is either

Fig. 2. CPS transformation framework including technology examples.

analyzed and used for local control of the resource itself, or shared with higher scopes of operations. Taking the scope of a production line, this includes the progress of a production order, the capacity and state of equipment, or as-built information of a production order. In turn, information collection at the scope of a factory system focuses on the business transactions, e.g. on the achievement of a production plan or the inventory level. Finally, at the scope of a supply chain, this function pertains to tracking and tracing information of individual products or batches. Their where-used information in manufacturing leads to digital twins of manufactured products in assembly, up to product usage information and malfunctioning reports when the product is in the field. Also, this includes information collection when the product is being refurbished and re-used.

3.4.2. CPS information analysis across scopes of operations

When restricting the scope to a machine, information analysis refers to the monitoring of a machine (fleet of machines) or a process, e.g. if a machine or process is producing within tolerances and specifications. This function is often implemented by SCADA or computer numerical control (CNC) systems, conducting both data collection and data analysis. At a larger scope, information analysis refers to monitoring the status of the production execution or the factory system, e.g. if a production schedule or a delivery date of an order can be met. This is often executed by a manufacturing execution system (MES) or an Enterprise Resource Planning (ERP) system. Taking the scope of a supply chain, similar analysis of e.g. quality related data can be encountered.

3.4.3. CPS decision selection across scopes of operations

At the machine scope, decisions could relate to the maintenance of a machine, the quality of a product, a dispatching decision or the assignment of production resources to a production order. At the production line scope, decisions address e.g. sequencing of operations, quality management, performance analysis, maintenance management, product tracking, document control or human resources. At the factory scope, decisions address planning and optimizing the manufacturing capacity and logistics. At the supply chain scope, decision-making is concerned with supplier material requisitions, distribution requirements planning and planning for circular economy.

3.4.4. CPS decision implementation across scopes of operations

The function of decision implementation at the machine scope is often implemented through actuation, for example the production of a product, adjusting the tooling of a machine or conducting the maintenance action. Taking the production line scope or the factory system scope, decision implementation is concerned with implementing the

decisions taken related to the areas described above, for example changing the sequence of a production order or adjusting the weekly production plan. When the scope covers the supply chain, the digital twin of a product (e.g. photocopier) cannot only signal its own maintenance request at the Original Equipment Manufacturing (OEM) company, but also request its own replacement if the usage of the machine becomes higher than the technical upper bound or lower than the economic lower bound.

3.4.5. CPS innovation across scopes of operations

Taking the scope of the machine, CPS innovation is concerned with e.g. self-learning applications in the context of total productive maintenance or asset management. For the scope of a production line, CPS innovations may pertain to quality management over the line, e.g. by representing the digital twins of manufactured products in such a way that quality issues anywhere in the line can be related to parameter settings earlier in the line and result in reconfiguration by e.g. inserting or deleting stations where the products are tested. Innovations in factory systems are often also concerned with re-organizing physical space. Innovation in such factory reorganization is currently still largely a human endeavor, but can be supported by assets that have knowledge about their own properties, both physically and technologically, which gradually can lead to software support for such reorganizations. Another area of innovation at the factory scope is the whole field of factory logistics, from customer-order acceptance to resources planning and scheduling, including inventory control, where applicable. Classical planning logic from demand to supply is increasingly replaced by optimization logic or by a mixture of supply-driven and demand-driven considerations. This is a promising area for future innovation. Innovations at the supply chain scope are concerned with intelligent products that are linked to digital twins throughout their life cycle. These products capture data that can be re-used for product innovation, but also for process innovation. Many applications ranging from apps supporting the final customer to (big) data gathered during refurbishment may be deployed for innovations in the supply chain, but also in the return chain of used products in the journey towards the circular economy. However, it is currently a matter of speculation whether the future will deliver anything like a self-organizing supply chain.

The transformation of industrial production towards CPS is not a one-time activity, but a complex process concerning an array of different design choices on the automation and augmentation of different types of information processing functions across large differences in scope. This design discretion concerns the freedom to allocate information processing functions to humans and/or technology (horizontal axis) and the freedom to apply technology at different scopes

(vertical axis).

To summarize, in this section we developed a framework that specifies CPS capabilities across different scopes of operations, ranging from the local machine, to production line and factory up to supply chain. The application of CPS technology encompasses capabilities to automate and augment functions of information acquisition, information analysis, decision selection, decision implementation and eventually innovation. This simplified framework helps to assess these choices and the resulting implications for the design of work in CPS.

4. Implications of CPS for work design and job characteristics

Since CPS contain physical and computational objects, investing in these systems could potentially impact work design through changed physical and cognitive tasks. The physical objects mainly impact direct production tasks at the machine scope, production line system scope or cell scope. Simple human direct production tasks are substituted or assistance is provided which creates a collaborative environment where human workers work side by side with autonomous machines/robots. The computational objects of CPS mainly impact cognitive tasks, which are also found at a larger scope of operations and may involve indirect tasks such as planning, quality management, maintenance etc. Since we focused on CPS information processing capabilities across different scopes of operations (see Fig. 2), we mainly study its impact on the cognitive tasks of humans as opposed to the direct physical tasks. The following implications for job complexity, skill variety and job autonomy can then be drawn.

4.1. Implications for job characteristics

4.1.1. Job complexity

As stated, CPS increasingly take over or augment information-processing functions across different scopes of operations through their distinct capabilities. What we can deduct from the framework is that the transformation towards CPS, and hence its different stages, can have varying effects on job complexity. We specify two developments that together will shift the focus of humans to tasks characterized by higher job complexity.

First, we expect that through increasing CPS information processing capabilities (i.e. the automation of information collection and analysis), the human work shifts towards more complex tasks. Depending on the degree of automation, complex tasks will focus on decision-making, implementation and innovation and will hence be characterized as higher information processing functions. In general, these higher information processing functions are more difficult to perform and more mentally demanding. They include more activities and events the workers need to be aware of, tasks are more unstructured and in itself more challenging.

Second, by implementing CPS across different scopes of operations, from machine, to production line, to factory and supply chain, human work will shift accordingly. Human tasks will focus more on functions covering a larger scope of operations, which are more complex and characterized by an increased amount of information to be processed in the fulfilment of a function. This is because more information and data from a wider collection of resources and processes is acquired, analyzed and consequently used for decision-making, decision implementation or innovation. In addition, a higher number of resources need to be considered and coordinated. For example, planning activities do not only address the planning of individual machines, but take into account production line processes or whole departments. The same applies to other functional areas such as quality, maintenance and logistics.

By generally following a sequential path towards a fully implemented CPS, the transformation will induce a gradual shift towards more complex tasks for humans, either because human tasks will shift towards a higher level of information processing functions, or because they will have to take a larger scope of operations into account, or

both. This form of job enrichment and the automation of simple, routine information processing tasks is also discussed in current literature, describing CPS as to further increase or support the performance and capabilities of a user or process (Dworschak & Zaiser, 2014; Spath, Dworschak, Zaiser, & Kremer, 2015; Windelband, 2014).

Referring to the framework in Fig. 2, this means that moving from the bottom left to the top-right, first the simple information processing tasks will be substituted (increasing the average complexity of the tasks remaining for humans), then the tasks with moderate complexity, and finally, even the complex tasks. This would imply that the transformation towards CPS could potentially include a scenario in which the human is fully excluded from the decision-making loop, assigning responsibility from humans to technology. Such a development can be seen in certain branches of industry, such as process industries, energy transmission and e.g. aircraft navigation by automated pilots. However, in the foreseeable future human workers are still dominant in the actions related to innovation. Simultaneously, the transformation implies the creation of new tasks related to the tuning, adjustment, modification and maintenance of CPS, which will run largely automated, but also require periodic human intervention.

4.1.2. Skill variety

During the transformation towards CPS, a gradual shift towards functions with higher complexity requirements is anticipated. An increase in knowledge and skill requirements is potentially a direct result of this.

With increasing CPS information processing capabilities there is a shift of human work to tasks that in themselves are more complex and difficult to perform. Especially work that focuses on information processing functions related to a larger scope require workers to understand, control and coordinate complex, integrated and automated processes. Due to these broader task roles, workers need to be able to understand how different processes and resources interact. This will require increased cognitive skills to obtain, interpret and use a wide range of incoming types of information to make decisions, to solve problems, to plan, to optimize and to modify the production parameters. Besides this increase in cognitive skills, future workers will need to be able to interact with a number of different actors across departments, processes or even supply chains. Hence, social skills with regard to communication and cooperation are increasingly required. Moreover, technical skills will be required with increased automation and the growing integration of IT into production systems. Workers will need to interact with technical systems in a collaborative production setting, or they need to monitor and control these systems. Hence, knowledge on IT, electronics and mechanical systems is needed to be able to understand how the (collaborative) processes work, but also to be able to respond to malfunctioning. As the transformation towards CPS will create new tasks related to the tuning, adjustment and maintenance of automation systems, workers need to deploy problem-solving skills and be able to understand how complex technical systems work.

4.1.3. Job autonomy

The degree of job autonomy is one of the central themes evolving around CPS and its implications for work design. The scenarios discussed in the literature describe future workers to either guide CPS, or be guided by CPS, also referred to as a human-centered versus a technology centered approach (Dworschak & Zaiser, 2014; Hirsch-Kreinsen et al., 2018; Windelband, 2014). In the first case, humans make the major decisions augmented by CPS by providing crucial and tailored information. A development relevant in this context is when machines/computers and humans work in a collaborative setting taking advantage of one's strengths.

In the second case, technology takes on control, decision-making tasks, and thereby for the most part determines human work. CPS then runs the production and workers are needed when systems are installed,

modified or maintained.

What we can conclude from our framework is that the transformation towards CPS can have significant effects on the degree of job autonomy perceived. This is because the automation of simple information processing functions through CPS implies that control over that function is transferred from humans to the CPS. By doing so, human decision making is reduced or eliminated and technology then often standardizes work methods and dictates the timing of (remaining) human work. Workers lose control over the type of tasks they perform and the timing of their tasks. In this case, workers are required to solely intervene during malfunctions, to set and modify the production parameters. However, while simple and repetitive tasks will be automated, we concluded that this opens up opportunities to jobs that shift towards higher levels of complexity. This means that even though humans may be increasingly excluded from decisions related to lower scopes of operations (i.e. machines), they will focus on higher-level decisions related to the production strategy, to decisions related to the installation, modification and maintenance of CPS or to decisions related to innovation functions, such as knowledge management. Therefore, while CPS may lead to a significant reduction of job autonomy of lower and medium-skilled jobs, CPS may also lead to an increase of job autonomy of complex jobs located at larger scopes of operations.

Ultimately, the distribution of decision-making authority between humans and technology and the resulting impact on job characteristics is largely dependent on the actual design of the technical and organizational system, which leads us to our findings on management choice.

4.2. Management choice

The framework outlined in the previous section allows us to formulate expectations on how work design and respective job characteristics can be affected by the transformation towards CPS in industrial production. What we can deduct is that the actual implications for work design are to a very high degree dependent on how the functions of information processing across different scopes of operations are configured. Specifically, this means that there is a degree of choice on what function to automate and at which scope of operations. Managers usually have a significant influence over these decisions.

We find management choice is relevant at two moments in the design process. First, when transforming into CPS, management has choices regarding what information processing functions to automate or augment and at what scope of operation. This results in substituted tasks (as automated by CPS) and a changed pool of remaining human tasks together with newly created (or modified) human tasks. Even though management can choose what functions and corresponding tasks to automate or augment, their choices are to a certain extent restricted as can be seen in Fig. 2. Moving from bottom-left to top-right, a development path is more or less enforced. Generally, this results in a reduction of the total number of human tasks in the system. However, managers can decide on the speed with which one transforms towards CPS, and the steepness of the line in Fig. 2. We realize that this schematic representation is in reality much more complex, but it helps to better understand management choices and restrictions. Second, the resulting pool of human tasks consisting of some unchanged tasks, adapted or new tasks are subsequently grouped into jobs. Here, managers have a subsequent choice on how to regroup these tasks into different jobs, which can result in enriched and simplified jobs. To an extent, this choice is also limited as it is often not realistic to assign very simple and complex tasks to the same job (van den Beukel & Molleman, 2002). An operator who masters the most complex task will likely not be motivated to do many simple tasks besides the complex ones.

This decision ultimately determines the impact that the technology has on work design, as the grouping of tasks into jobs leads to job simplification and/or job enrichment. These two design choices are illustrated in Fig. 3.

Fig. 3. Schematic work design in the context of CPS.

To summarize, in this section we applied the framework to assess work design changes. Specifically, the application of CPS capabilities across different scopes of operations will potentially impact job complexity, skill variety and job autonomy, which are the most prominent job characteristics relating to CPS. The transformation process might gradually shift all human work to focus on functions of complex decision making, implementation and innovation, aided by technology that collects and analyzes information as a basis for decision-making. Specifically, job complexity may increase due to a shift to more complex information processing functions located at larger scopes of operations. This development, together with the creation of new tasks and interactions will increase skill requirements. These adapted jobs that comprise more complex tasks may be characterized by higher job autonomy at higher scopes of operation (process, factory, supply chain). As this relationship is not expected to be uniform nor deterministic, the extent that work design will be impacted is highly affected by management choice relating to designing the technology and grouping work into jobs.

5. Discussion

The current body of knowledge on work design in the sphere of CPS is not yet well developed. One of the reasons is that the practical application of CPS in industrial applications is still at its infancy. In current literature, different scenarios for work design are being discussed, i.e. substitution, augmentation and increased human-machine collaboration. The framework developed in this paper helps to specify and better understand how CPS can potentially augment or substitute cognitive work. As opposed to the expectations that autonomous CPS will push human work to the background, our expectation is that in the future, human insights and interventions will remain critical in complex functions of information processing related to decision-making, decision implementation and especially innovation. Because remaining human work in CPS will supposedly become more complex, new forms of human-machine interaction (e.g. augmented reality, intelligent user-interfaces) can equip workers better to cope with these changes. Therefore, in line with previous literature, we expect that CPS will increasingly automate low and medium skilled jobs, which were traditionally too complex to automate. Furthermore, it will create complex demanding jobs which focus on aspects of decision-making, implementation and innovation covering larger scopes of operations. These include newly created tasks relating to the installation, maintenance and control of the CPS itself.

As stated, the shift of human work to more complex jobs will strongly affect skill and knowledge requirements, resulting in upskilling. Particularly, future workers need to be equipped with a variety of skills, namely cognitive skills, technical skills and social skills. Consequently, training and learning will become a key competence of organizations to ensure that their workers obtain the right skills. At the same time, new possibilities to augment and better support the worker in increasingly complex jobs are presented through CPS and must be further explored. Due to the dynamic nature of CPS, workers need to engage in life-long learning to meet the changing skill requirements of future work.

An interesting question that arises in this context is the question whether technical systems should become fully autonomous if they cannot take the final responsibility for the consequences of their decisions. CPS are often envisioned as an enabler of a smart factory which is so intelligent and autonomous that it is eventually able to “self-configure and self-adapt” (Lee et al., 2015). This vision implies that the actual decision is assigned to the technology itself, and thereby fully excludes the human from the decision-making loop. This technical possibility is also illustrated in our framework of Fig. 2, represented in the top-right corner. For an example, see Box 2.

Ultimately, we believe that a technical system cannot have the final responsibility and therefore we do not expect that future factories will be fully automated without any human interference. In line with other authors (Hirsch-Kreinsen et al., 2018; Romero, Noran, Stahre, & Bernus, 2015), human-centricity should remain key in factories of the future, by taking advantage of current technological advancements to aid humans in their work. As we have shown, humans will be needed to take on the final responsibility and they will remain critical in the near future especially for aspects related to innovation and overall supervision of complex automated processes. Considering that the implications of CPS for job complexity, skill variety and job autonomy are neither uniform nor deterministic, management has considerable influence on how its approaches future technological developments. Discussions revolving around social aspects of manufacturing therefore must continue in order to better understand the upcoming challenges but also to promote the new possibilities offered by CPS technologies.

6. Conclusions

In this paper, we developed a framework of the sequential transformation towards CPS. This framework helps to better understand how different stages of CPS affect human work. Specifically, it dissects different CPS capabilities of information processing at different scopes of operations and shows their relationship with work design. These range from information collection, information analysis, decision selection, decision implementation and innovation and are applicable at different scopes of operations (i.e. machine, production line, factory and supply chain).

Whereas the literature stated that the transformation of industrial production towards CPS was expected to significantly change the role of the human worker, our framework enabled a more detailed analysis. This analysis included both technological and organizational choices.

Box 2

Real-life example of a fully autonomous technology.

Autonomous vehicles that possess advanced driver-assistance systems (e.g. cruise control, emergency braking) have been around for a while now. Throughout the last decade, driving automation has minimized the role of the driver in driving the car. To evolve driving automation towards full autonomy in which no human intervention is needed, many car manufacturers are currently experimenting with self-driving cars that can sense their environment and navigate without human input. However, it is still unclear how these autonomous cars are able to handle various extreme and unpredictable situations. Hence, despite the readiness of the technology, an important question that still remains unanswered is who is responsible when a self-driving car has an accident? Up until now, there is still a considerable gap between self-drive technology and regulation on this topic.

We have found that the transformation towards CPS will gradually shift human work to focus on tasks characterized by higher information processing requirements at a larger scope of operations (e.g. decision-making, implementation and innovation at the scope of the factory). This work will potentially increase in complexity, skill requirements and autonomy. Here, we see a human-centered approach where decisions can be augmented by CPS. However, we expect that technology will play a smaller role in aspects of innovation, which will largely remain a human endeavor. For tasks at the lower levels of information processing at a lower scope of operation (e.g. information collection and information analysis at the machine level), CPS have a strong potential to substitute human work. Remaining work may be subject to a technology-centered automation approach where CPS for the most part determine work.

Ultimately, these implications for work design are highly dependent on CPS technology choices made regarding the level of automation of information processing functions across different scopes of operations. Additionally, the implications are affected by the management choice how to group tasks into jobs. Both choices affect work design through their potential to substitute tasks, simplify jobs and enrich jobs. Linking this back to previous literature, a technology-centered versus a human-centered automation approach thereby is not determined solely by the technology itself, but greatly depends on decisions taken by managers. Organizations that are implementing CPS should therefore be aware and alert what implications their decisions have for employees' job characteristics, and eventually their job motivation or job satisfaction. In addition, organizations must pay attention to the changing skills and knowledge requirements of future employees. They must develop a clear plan on how to employ the right people for future jobs or train their existing employees to be able to cope with the changing skill requirements of future industrial production.

There are several limitations of this research which pose interesting directions for future research. The framework as presented in Fig. 2 assumes for simplification reasons that the transformation towards CPS in general follows a sequential path. This means that both the CPS capabilities and the scopes of operations seem cumulative in nature. We acknowledge that reality is much more complex and that this sequential path may not always be valid for all practical cases. Future research could explore other practical cases to further extend the framework. Another limitation is that our approach of the impact of CPS on work design is somewhat static in the sense that we have largely postponed more recent discussions about symbiotic relationships between humans and automation (e.g. Romero et al., 2015). Romero et al. (2016), for example, discuss the emergence of the operator 4.0, where the operator is highly skilled and central and automation is adaptive. The automated system senses, for example, when operators become tired or have advanced their skills through learning and adapts its support to the operator accordingly by initiating or limiting sensorial, physical or cognitive support. Studying the impact of these developments on work design is an important direction for future research. In line with this, it is relevant to pursue this thinking in the realm of cognitive tasks, specifically possibilities for adaptive automation or collaboration in cognitive tasks such as decision-making or innovation. Moreover, we only

considered a limited number of job characteristics in this research, which we believe to be the most relevant for our study. The impact on other job characteristics is neglected and should be further explored. Also, this research focused on discrete industrial production. Other industries with different product and process characteristics can potentially have different implications for work design and job characteristics and can provide an interesting insight for the framework. Finally, the schematic presentation of managerial decisions on work design in Fig. 3 is strongly simplified. The freedom of management to decide on the technological design and on how to organize work around it is probably contingent upon an array of other factors, such as existing legacy systems, organizational culture, implementation processes and/or the industry wide environment.

References

- Badham, R. (1989). Computer-aided design, work organization, and the integrated factory. *IEEE Transactions on Engineering Management*, 36(3), 216–226. <https://doi.org/10.1109/17.35326>.
- Brennan, L., Ferdows, K., Godsell, J., Golini, R., Keegan, R., Kinkel, S., ... Taylor, M. (2015). Manufacturing in the world: Where next? *International Journal of Operations and Production Management*, 35(9), 1253–1274.
- Bruno, G., & Antonelli, D. (2018). Dynamic task classification and assignment for the management of human-robot collaborative teams in workcells. *International Journal of Advanced Manufacturing Technology*, 98(9–12), 2415–2427. <https://doi.org/10.1007/s00170-018-2400-4>.
- Clegg, C. W. (1984). The derivation of job designs. *Journal of Occupational Behavior (Pre-1986)*, 5(2), 131. <https://doi.org/10.2307/3000123>.
- Clegg, C. W., & Corbett, M. (1986). Psychological and organizational aspects of computer-aided manufacturing. *Current Psychological Research & Reviews*, 5(2), 189–204.
- Colombo, A. W., Karnouskos, S., Kaynak, O., Shi, Y., & Yin, S. (2017). Industrial cyber-physical systems: A backbone of the fourth industrial revolution. *IEEE Industrial Electronics Magazine*, 11(1).
- Corbett, J. M. (1987). A psychological study of advanced manufacturing technology. *Behaviour & Information Technology*, 6(4), 441–453.
- Dworschak, B., & Zaiser, H. (2014). Competences for cyber-physical systems in manufacturing—First findings and scenarios. *Procedia CIRP*, 25(C), 345–350. <https://doi.org/10.1016/j.procir.2014.10.048>.
- Dworschak, B., Zaiser, H., Martinetz, S., & Windelband, L. (2011). Zukünftige Qualifikationsanforderungen in der industriellen Produktion.
- Endsley, M. R., & Kaber, D. B. (1999). Level of automation effects on performance, situation awareness and workload in a dynamic control task. *Ergonomics*, 42(3), 462–492. <https://doi.org/10.1080/001401399185595>.
- Frohman, J., & Bellgran, M. (2005). A model for parallel levels of automation within manufacturing. *Proceedings of the 18th International Conference on Production Research, Fisciano, Italy*.
- Grant, A. M., Fried, Y., & Juillerat, T. (2011). Work matters: Job design in classic and contemporary perspectives. *APA handbook of industrial and organizational psychology: Building and developing the organization: Vol. 1*, (pp. 417–453). <https://doi.org/10.1037/12169-013>.
- Groover, M. P. (1984). *Computer-aided design and manufacturing*. Englewood Cliffs: Prentice Hall.
- Groover, M. P. (2001). Automation, production systems and computer-integrated manufacturing.
- Hackman, J. R., & Oldham, G. R. (1975). Development of the job diagnostic survey. *Journal of Applied Psychology*, 60(2), 159–170. <https://doi.org/10.1037/h0076546>.
- Hackman, J. R., & Oldham, G. R. (1976). Motivation through the design of work: Test of a theory. *Organizational Behavior and Human Performance*, 16(2), 250–279. [https://doi.org/10.1016/0030-5073\(76\)90016-7](https://doi.org/10.1016/0030-5073(76)90016-7).
- Hackman, J. R., & Oldham, G. R. (1980). *Work redesign reading*. Addison-Wesley.
- Hancock, P. A., Jagacinski, R. J., Parasuraman, R., Wickens, C. D., Wilson, G. F., & Kaber, D. B. (2013). Human-automation interaction research: Past, present, and future. *Ergonomics in Design*, 21(2), 9–14. <https://doi.org/10.1177/1064804613477099>.
- Hermann, M., Pentek, T., & Otto, B. (2016). Design principles for industrie 4.0 scenarios. *System Sciences (HICSS)*, 2016 49th Hawaii International Conference (pp. 3928–3937). <https://doi.org/10.1109/HICSS.2016.488>.
- Hirsch-Kreinsen, H. (2014). *Smart production systems: A new type of industrial process innovation*. *Smart production systems: A new type of industrial process innovation. DRUID Society Conference 2014*.
- Hirsch-Kreinsen, H. (2016). Digitization of industrial work: Development paths and prospects. *Journal for Labour Market Research*, 1–14. <https://doi.org/10.1007/s12651-016-0200-6>.
- Hirsch-Kreinsen, H., & Ten Hompel, M. (2015). Digitalisierung von Industriearbeit: Forschungsstand und Entwicklungsperspektiven. *Social Manufacturing and Logistics*.
- Hirsch-Kreinsen, H., Ten Hompel, M., Dregger, J., Niehaus, J., Kirks, T., & Maettig, B. (2018). “Social Manufacturing and Logistics” – Arbeit in der digitalisierten Produktion. *Zukunft der Arbeit – Eine praxisnahe Betrachtung* (pp. 175–194).
- Holman, D., Wood, S., Wall, T. D., & Howard, A. (2005). *Introduction to the essentials of the new workplace. The Essentials of the New Workplace: A Guide to the Human Impact of Modern Working Practices*. New York: John Wiley and Sons.
- Humphrey, S. E., Nahrgang, J. D., & Morgeson, F. P. (2007). Integrating motivational, social, and contextual work design features: A meta-analytic summary and theoretical extension of the work design literature. *The Journal of Applied Psychology*, 92(5), 1332–1356. <https://doi.org/10.1037/0021-9010.92.5.1332>.
- ISA (2014). ISA 95 Standards. Retrieved from <http://www.isa-95.com/>.
- Kaber, D. B., & Endsley, M. R. (2004). The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task. *Theoretical Issues in Ergonomics Science*, 5(2), 113–153. <https://doi.org/10.1080/1463922021000054335>.
- Kagermann, H. (2013). Recommendations for implementing the strategic initiative Industrie 4.0, (April).
- Kelley, M. R. (1990). New process technology, job design, and work organization: A contingency model. *American Sociological Review*, 55(2), 191–208.
- Kinkel, S. (2007). *Arbeiten in der Zukunft – Strukturen und Trends der Industriearbeit*. Berlin.
- Kinkel, S., Friedewald, M., Hüsing, B., Lay, G., & Lindner, R. (2008). *Arbeiten in der Zukunft: Strukturen und Trends*. Berlin.
- Krevelen, R. Van, & Poelman, R. (2010). A survey of augmented reality technologies, applications and limitations. *International Journal of Virtual Reality*, 9(2), 1–20.
- Lee, J. D., Bagheri, B., & Kao, H. A. (2015). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3(April 2016), 18–23. <https://doi.org/10.1016/j.mfglet.2014.12.001>.
- Lee, J. D., Lapira, E., Bagheri, B., & Kao, H. (2013). Recent advances and trend in predictive manufacturing systems in big data environment. *Manufacturing Letters*, 1(1), 38–41.
- Lee, J. D., & Seppelt, B. D. (2009). Human factors in automation design. Springer handbook of automation (Vol. 53). <https://doi.org/10.1017/CBO9781107415324.004>.
- Liker, J. K., Haddad, C. J., & Karlin, J. (1999). Perspectives on technology and work organization. *Annual Review of Sociology*, 25, 575–596.
- McLoughlin, I., & Clark, J. (1988). *Technological change at work*. Open University.
- Meyer, G. G., Wortmann, J. C., & Szirbik, N. B. (2011). Production monitoring and control with intelligent products. *International Journal of Production Research*, 49(5), 1303–1317. <https://doi.org/10.1080/00207543.2010.518742>.
- Mollemann, E., & Slomp, J. (2001). The impact of technological innovations on work design in a cellular manufacturing environment. *New Technology, Work and Employment*, 16(3), 152–163. <https://doi.org/10.1111/1468-005X.00085>.
- Monostori, L. (2014). Cyber-physical production systems: Roots, expectations and R&D challenges. *Procedia CIRP*, 17, 9–13. <https://doi.org/10.1016/j.procir.2014.03.115>.
- Morgeson, F. P., & Campion, M. A. (2003). Work design. *Handbook of psychology: Industrial and organizational psychology: Vol. 12*, (pp. 423–452). Hoboken, NJ.
- Morgeson, F. P., & Humphrey, S. E. (2006). The Work Design Questionnaire (WDQ): Developing and validating a comprehensive measure for assessing job design and the nature of work. *Journal of Applied Psychology*, 91(6), 1321–1339. <https://doi.org/10.1037/0021-9010.91.6.1321>.
- Morgeson, F. P., & Humphrey, S. E. (2008). Job and team design: Toward a more integrative conceptualization of work design. *Research in personnel and human resource management* (pp. 39–91). Emerald Group Publishing Limited.
- Nagalingam, S. V., & Lin, G. C. I. (2006). CIM-still the solution for manufacturing industry. *Robotics and Computer-Integrated Manufacturing*, 24(3), 332–344. <https://doi.org/10.1016/j.rcim.2007.01.002>.
- Oldham, G. R., & Fried, Y. (2016). Job design research and theory: Past, present and future. *Organizational Behavior and Human Decision Processes*, 136, 20–35. <https://doi.org/10.1016/j.obhdp.2016.05.002>.
- Oldham, G. R., & Hackman, J. R. (2010). Not what it was and not what it will be: The future of job design research. *Journal of Organizational Behavior*, 31(2–3), 463–479. <https://doi.org/10.1002/job.678>.
- Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation. *IEEE Transactions on Engineering Management*, 30(3), 286–297.
- Parasuraman, R., & Wickens, C. D. (2008). Humans: Still vital after all these years of automation. *Human Factors*, 50(3), 511–520. <https://doi.org/10.1518/001872008X312198>.
- Parker, S. K. (2014). Beyond motivation: Job and work design for development, health, ambidexterity, and more. *Annual Review of Psychology*, 65, 661–691. <https://doi.org/10.1146/annurev-psych-010213-115208>.
- Parker, S. K., van den Broek, A., & Holman, D. (2017a). Work design influences: A synthesis of multilevel factors that affect the design of jobs. *Academy of Management Annals*, 9(1), 267–308.
- Parker, S. K., Morgeson, F. P., & Johns, G. (2017b). One hundred years of work design research: Looking back and looking forward. *Journal of Applied Psychology*, 102(3), 403–420. <https://doi.org/10.1037/apl0000106>.
- Parker, S. K., Wall, T. D., & Cordery, J. L. (2001). Future work design research and practice: Towards an elaborated model of work design. *Journal of Occupational and Organizational Psychology*, 74, 413–440. <https://doi.org/10.1348/09631790167460>.
- Rajkumar, R., Lee, J. D., Sha, L., & Stankovic, J. (2010). Cyber-physical systems: The next computing revolution. *Proceedings of the 47th ACM/IEEE Design Automation Conference* (pp. 731–736).
- Romero, D., Noran, O., Stahre, J., & Bernus, P. (2015). Towards a Human-Centred reference architecture for next generation balanced automation systems: human-automation symbiosis. *Advanced in production management systems: innovative production management towards sustainable growth* <https://doi.org/10.1007/978-3-319-22759-7>.
- Romero, D., Bernus, P., Noran, O., & Stahre, J. (2016a). The operator 4.0: Human cyber-physical systems & adaptive automation towards human-automation symbiosis work systems. *Advanced production management systems: The path to: Vol. 488*, (pp. 677–686). <https://doi.org/10.1007/978-3-319-51133-7>.

- Romero, D., Stahre, J., Wuest, T., Noran, O., Bernus, P., Fast-berglund, Å., & Gorecky, D. (2016b). Towards an Operator 4.0 typology: A human-centric perspective on the fourth industrial revolution technologies. *CIE46 Proceedings, 29–31 October 2016, Tianjin/China, ISSN 2164-8670 CD-ROM, ISSN 2164-8689 ON-LINE, (October)* (pp. 0–11). .
- Romero, D., Wuest, T., Stahre, J., & Gorecky, D. (2017). Advances in production management systems. *The Path to Intelligent, Collaborative and Sustainable Manufacturing*, 514, 265–273. <https://doi.org/10.1007/978-3-319-66926-7>.
- Sheridan, T. B. (2012). Human supervisory control. In G. Salvendy (Ed.). *Handbook of human factors and ergonomics*. John Wiley and Sons.
- Sinclair, M. A. (1986). Ergonomics aspects of the automated factory. *Ergonomics*, 29(12).
- Snell, S., & Dean, J. W. (1992). Integrated manufacturing and human resource management: A human capital perspective. *The Academy of Management Journal*, 35(3), 467–504.
- Spath, D., Dworschak, B., Zaiser, H., & Kremer, D. (2015). *Kompetenzentwicklung in der Industrie 4.0. Lehren. Und Lernen Für Die Moderne Arbeitswelt* 113–124.
- Terwiesch, P., & Ganz, C. (2009). Trends in Automation. *Springer Handbook of Automation*, 127–143.
- Turner, A. N., & Lawrence, P. R. (1965). *Industrial jobs and the worker*. Harvard University.
- van den Beukel, A. L., & Molleman, E. (2002). Too little, too much Downsides of multifunctionality in team-based work. *Personnel Review*, 31(4), 482–494. <https://doi.org/10.1108/00483480210430382>.
- Wall, T. D., Corbett, J. M., Martin, R., Clegg, C. W., & Jackson, P. R. (1990). Advanced manufacturing technology, work design, and performance: A change study. *Journal of Applied Psychology*, 75(6), 691–697. <https://doi.org/10.1037/0021-9010.75.6.691>.
- Wall, T. D., Jackson, P. R., & Davids, K. (1992). Operator work design and robotics system performance: A serendipitous field study. *Journal of Applied Psychology*, 77(3), 353.
- Walter, A., & Karnouskos, S. (2014). Towards the next generation of industrial cyber-physical systems. *Industrial cloud-based cyber-physical systems* (pp. 1–22). Springer International Publishing. <https://doi.org/10.1007/978-3-319-05624-1>.
- Williams, T. J. (1994). The purdue enterprise reference architecture. *Computers in Industry*, 24, 141–158.
- Williams, T. J. (1999). Establishment of the place of the human in enterprise integration. *IFAC Proceedings Volumes*, 32(2), 157–162. [https://doi.org/10.1016/S1474-6670\(17\)56029-2](https://doi.org/10.1016/S1474-6670(17)56029-2).
- Windelband, L. (2014). Zukunft der Facharbeit um Zeitalter Industrie 4.0. *Journal of Technical Education*, 2.
- Wong, C., & Campion, M. A. (1991). Development and test of a task level model of motivational job design. *Journal of Applied Psychology*, 76(6), 825. <https://doi.org/10.1037/0021-9010.76.6.825>.
- Young, M., Stanton, N., & Harris, D. (2007). Driving automation: Learning from aviation about design philosophies. *International Journal of Vehicle Design*, 45(3), 323–338. <https://doi.org/10.1504/IJVD.2007.014908>.
- Yu, C., Xu, X., & Lu, Y. (2015). Computer-integrated manufacturing, cyber-physical systems and cloud manufacturing – Concepts and relationships. *Manufacturing Letters*, 6, 5–9. <https://doi.org/10.1016/j.mfglet.2015.11.005>.
- Zuboff, S. (1985). Automate/informate: The two faces of intelligent technology. *Organizational Dynamics*, 14(2), 5–18.
- Zuehlke, D. (2010). SmartFactory-Towards a factory-of-things. *Annual Reviews in Control*, 34(1), 129–138. <https://doi.org/10.1016/j.arcontrol.2010.02.008>.