Conceptualising the robotisation of manufacturing work: A thematic analysis of the literature using soft systems thinking as lens

Stingl, Verena; Christiansen, Lasse; Cheng, Yang; Lassen, Astrid Heidemann; Hansen, Andreas Kornmaaler

Published in:
Journal of Manufacturing Technology Management

DOI (link to publication from Publisher):
10.1108/JMTM-09-2022-0332

Publication date:
2024

Conceptualising the robotisation of manufacturing work: A thematic analysis of the literature using soft systems thinking as lens

Version as accepted for publication in: Journal of Manufacturing Technology Management

Cite as: Stingl, V., Christiansen, L., Hansen, A.K., Lassen, A.H. and Cheng, Y. (2024), "Conceptualising the robotisation of manufacturing work: a thematic analysis of the literature using soft systems thinking as lens", Journal of Manufacturing Technology Management, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/JMTM-09-2022-0332

Purpose: The introduction of robots as value-adding 'workers' on the shop floor triggers complex changes to manufacturing work. Such changes involve highly entangled relationships between technology, organisation and people. Understanding such entanglements requires a holistic assessment of contemporary robotised manufacturing work, to anticipate the dynamically emerging opportunities and risks of robotised work.

Methodology: A systematic literature review of 87 papers was conducted to capture relevant themes of change in robotised manufacturing work. The literature was analysed using a thematic analysis approach, with Checkland's soft systems thinking as an analytical framework.

Findings: Based on the literature analysis, we present a systemic conceptualisation of robotised manufacturing work. Specifically, the conceptualisation highlights four entangled themes of change: Work, Organisation of Labour, Worker*s' (experiences) and the firm's* Environment*. Moreover, we discuss the complex patterns of interactions between these objects as relationships that defy straightforward cause–effect models.*

Originality: We present a novel approach to studying and designing robotised manufacturing work as a conceptual system. In particular, the paper shifts the focus towards crucial properties of the system, which are subject to complex changes alongside the introduction of robot technology in manufacturing. Soft systems thinking enables new research avenues to explain complex phenomena at the intersection of robotisation and manufacturing work.

Practical implications: The findings draw attention to complex interactions between robotisation and manufacturing work. It can therefore inform strategic decisions and support projects for robotisation from a holistic perspective.

1. Introduction

The prevalence of robots in manufacturing has increased steadily over the last few decades, with the operational stock of robots seeing a global annual increase of 14% between 2016 and 2021 (IFR, 2022). While the robotisation of manufacturing industries is not a new phenomenon, the accessibility of robot technologies and the diversity of application areas have grown substantially. Collaborative robots (cobots), in particular, are one of the fastest-growing robot technologies, with an annual increase in installations of 37% between 2017 and 2021 (IFR, 2022).

Rapid technological changes introduced through increased robotisation bring opportunities but have consequences for the organisation of work (Barrett *et al.*, 2012), which is in line with the impacts of digital technologies generally suggested by Parker and Grote (2022). Similarly, robotisation will likely alter the structures of industries (Teixeira *et al.*, 2019) and thus the labour market in manufacturing (Acemoglu and Restrepo, 2018). Consequently, significant changes in the role played by the human worker in manufacturing can be expected, as robots will increasingly act as workers rather than tools (Ford, 2015).

Robotisation projects often encounter unexpected difficulties once technology and human worker meet. For example, Boeing had to abolish a multi-year, multi-million-dollar robotisation project, as the new organisation of work between robots and humans resulted in more–rather than less–human work and unacceptable quality issues (Gates, 2019). Another example is the reported 50% increase in serious work-related injuries at the Amazon warehouses that employed automated robot solutions (compared to those without for the period from 2016 to 2019), which led to concerns about increased risks associated with robotised workplaces (Evans, 2020).

While these real-world examples highlight the importance to anticipate both planned and unexpected effects of robotisation on manufacturing work, current research provides only a fragmented and inconsistent picture of such effects. Some studies have found that robots reduce the number of jobs (Acemoglu and Restrepo, 2017; Ni and Obashi, 2021), whereas others have reported on job numbers rising alongside the growing degree of robotisation in manufacturing firms (Dixon *et al.*, 2021) and industries (Dottori, 2020; World Economic Forum, 2018). In terms of worker well-being, studies have reported decreasing happiness following perceived job insecurity after robotisation (Stankevičiūtė *et al.*, 2021) while others have found that workers feel positively empowered by their new robotic colleagues (Lei, 2022). Moreover, while some studies have reported on the need for an increasingly skilled workforce with enhanced digital and cognitive skills (Romero *et al.*, 2016), others have discussed the polarisation in job roles, with a rising demand for unskilled workers on the robotised shop floor (Dixon *et al.*, 2021; Weiss *et al.*, 2021). Thus, various authors have discussed potential mediating, moderating or correlating factors that may explain contradictory findings. For example, Dixon et al. (2021) and Leigh et al. (2020) discussed the potential effects of labour laws and economic development on job numbers in the robotising industries. In terms of worker well-being, the role of sociodemographic factors, such as age or gender (Stankevičiūtė *et al.*, 2021), or the family context (Lei, 2022) in workers' emotional responses to robotisation have been considered. However, the emerging picture is a complex one that likely defies modelling based on cause–effect relationships.

The increasing prevalence of cobots adds further complexity to the interactions between workers and robots. In their discussion of the cobot literature, Weiss et al. (2021) pointed to new safety risks associated with a shared physical space and highlighted the need for new modes of planning and executing work with a responsive and adaptive cobot. Thus, cobots can trigger fast and far-reaching yet hard-to-predict changes to manufacturing work.

The characteristics of problems associated with designing and managing the robotisation of manufacturing work are thus similar to the characteristics of ill-structured problems that Rittel and Webber (1973) called 'wicked'. Wicked problems are impossible to capture as a whole (Farrell and Hooker, 2013) or optimise (Checkland and Poulter, 2010). Rittel and Webber (1973, p. 160) argued that for such problems, the paradigm of science-and-engineering falls short, as this paradigm conceptualises the issue as an optimisable and predictable system rather than as an ambiguous open social system.

However, current research on the robotisation of manufacturing work has predominantly focused on the quantifiable relationships between robot technology and concrete aspects of manufacturing work, such as workers' cognitive load (Kuz *et al.*, 2018), the number and types of jobs (e.g. Dottori, 2020; Leigh et al., 2020) or the optimal distribution of tasks between workers and robots (Bänziger *et al.*, 2020). However, if we were to consider the design and management of robotised work in manufacturing as a wicked problem, we need to adopt a holistic perspective that helps to broaden the perspective rather than narrow it to a few causal relationships, given the high complexity, social embeddedness and multitude of stakeholder perspectives involved.

Soft systems thinking (Checkland, 1985; Checkland and Poulter, 2010) offers such a holistic perspective enabling inquiries into and designs for wicked problems. Checkland's notion of *soft systems thinking*, presented in his work as a distinct paradigm for exploring systems (Checkland, 1985, p. 764), proposes looking at the entanglement of organisations and technology as an 'adaptive whole' (Checkland, 2012, p. 469). Soft systems thinking thus aims to conceptualise the system not based on its objective features (e.g., hierarchies, modules, or roles) but based on themes and concepts that help to *think* about the phenomenon and the patterns of interrelation between these themes. Applied to the phenomenon of robotised manufacturing work, this work explores the themes of change to which practice and research pay attention, as well as the co-evolution of these changes.

Therefore, the purpose of this study is to develop a holistic perspective on robotised manufacturing work based on the notion of interrelated but non-determinant patterns of change. Following a systematic literature review, we first outline the central themes of change understood as topical areas that are the focus of the research on robotised manufacturing work. From the literature, we then identify links between those themes of change as patterns of interaction. The emerging picture of the deep entanglement between the themes of change and the patterns of their interactions allows us to formulate new research directions following a systemic conceptualisation. Furthermore, it allows us to provide a promising alternative to the dominant engineering-and-science paradigm. Presenting soft systems thinking as essentially pragmatic, we discuss how the findings can inform practices related to the design and management of robotised manufacturing work.

2. Robotising Manufacturing Work: A Wicked Problem

We broadly define manufacturing work as *intentional human activities directly related to the production of physical goods.*[1] Thus, our focus is on what shop floor workers do in a physical production environment, recognising that such work is 'organised' through both explicit structures and informal routines (Feldman and Pentland, 2003).

Furthermore, we understand robot technology—also referred to as 'robots' in this paper—as '*automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications*', following the definition presented by the International Federation of Robotics (IFR, n.d.). We delimit that definition to robots that are capable of interacting with the environment. Moreover, this study is only concerned with robots executing value-added manufacturing tasks and robots that are capable of automatic operations. This definition excludes automated guided vehicles (AGVs), which are solely used for (non-value-added) transportation, and exoskeletons and telerobots that cannot operate independently of human control.

Following this definition, robots can be flexibly deployed for numerous tasks and are not necessarily limited to predefined purposes. Hence, robots are, to some degree, flexible tool *users* rather than tools themselves, setting them apart from less flexible technologies (Ford, 2015). While digital tools may offer similar task flexibility, they do not incorporate the material aspect of robots, that is, the ability for physical 'doing work' (Phan *et al.*, 2017, p. 253).

The study of robotised manufacturing work thus needs to pay particular attention to the characteristics of robots, such as their increasingly worker-like role in manufacturing, their physical materiality and the relationships that seem to develop between humans and robots. These characteristics create a complex web of interdependencies between robot technology, manufacturing work and human workers. This web is characterised by numerous dynamic interactions, in line with the complex

[1] This narrows the generic dictionary definition of work as 'activity in which one exerts strength or faculties to do or perform something' (Merriam-Webster).

interrelations that Zammuto et al. (2007) suggested existing between general digital technologies and organisations. Furthermore, the robotisation of manufacturing often follows strategic objectives and is thus exposed to the common strategic ambiguity concerning objectives, their interpretation and priorities (Abdallah and Langley, 2014).

The design and management of effective robotised manufacturing work is thus akin to the types challenges that Rittel & Webber (1973) characterised as ill-structured or 'wicked' problems. Such problems are characterised by ambiguity, information deficiencies and dynamic interrelations and are impossible to solve when considered an optimisation problem (Dekkers, 2017, p. 85). Instead, they require a different problem-solving approach guided by learning (Checkland and Poulter, 2010; Larsen *et al.*, 2023). Yet, the extant research on the robotisation of manufacturing work investigates causal effects rather than an entangled whole, thus follows a 'science-and-engineering paradigm' which Rittel and Webber (1973, p. 160) suggested as unsuitable for such problems.

To appreciate the complexity of the challenge in both research and industrial practice, a different perspective that holistically captures the entanglement of robot technology and manufacturing work is required. Such a holistic conceptualisation allows for the formulation of novel research propositions and serves as a basis for contextualised design in practice. Thus, our research aims to *create a holistic perspective on robotised manufacturing work based on the notion of interrelated patterns of change.*

Checkland (1983, 2000) suggested that *soft systems thinking* as particularly suitable for addressing ill-structured problems holistically. Soft systems thinking seeks systemicity in *thinking* about the problem; it aims to structure a problem around concepts that experts use to systematise their thinking, rather than around real-world objects or units (Checkland, 1999). Soft systems thinking consequently adopts a paradigm that differs from other systems theories on the interplay between technology and organisations (McMahon, 2022), most notably the socio-technical systems theory (Appelbaum, 1997; Trist and Bamforth, 1951).

The first paradigmatic difference is related to epistemology—that is, what can be known and learnt about a phenomenon. Socio-technical systems presume the objective existence of parts of the system and their relationships in the real world. Thus, socio-technical systems structure the analysis around 'aggregation strata', such as organisational roles, units, hierarchies or technical modules. Analysis of such systems focuses on describing the real-world boundaries, relationships and characteristics of these units. Commonly, the identity of these system components is described through their functional or internal autonomy, concepts that have also been discussed in the study of organisations as social systems (Morgan, 1981). In contrast, the soft systems methodology does not presume the systemicity of the world but merely aims to develop a useful representation of a complex reality through explanatory 'layers' (Checkland, 1999, 2012) that do not necessarily represent real-world structures. Thus, the conceptual models developed through soft systems thinking serve only as *devices* to structure the exploration of an otherwise ill-structured problem (Checkland, 2000, p. S26). They create meaning in a chaotic reality (Mingers, 2006), or in the words of Beer (1966, p. 243), 'permit an interpretation of what might otherwise be a meaningless cavalcade of arbitrary events'.

The second paradigmatic difference relates to the notion of how a systems view can contribute to the design of work in organisations. Following the notion that 'soft systems' are related to 'soft problems', soft systems thinking supports an iterative learning approach where the focus is on problem understanding rather than problem solving (Checkland, 2000). In contrast, the focus of socio-technical systems is solution oriented, with an aim to enhance work performance through a design process called 'joint optimisation' (Fox, 1995).

3. Methodology

Following the above reasoning, we propose that soft systems thinking is a suitable paradigmatic choice for exploring ill-structured problems, such as the complex interrelations between robot technology and work in manufacturing. It allows for the development of a generic conceptual map of possible interdependencies, which can provide a basis for localised analysis and the design of interventions.

To support our overall purpose of developing a holistic perspective on robotised manufacturing work based on the notion of interrelated but non-determinant patterns of change, we approach the literature thus with the following question: *What are themes of change discussed in the literature, and which patterns or interaction between these themes are presented in the literature on robotisation of manufacturing?*

We presumed that the expert knowledge necessary to construct the conceptual representation was already present during the decades of research on robotisation in manufacturing, albeit fragmented and unstructured. Thus, we engaged with the literature through thematic analysis (Terry *et al.*, 2017), using Checkland's (1999) core systems concepts as an analytical framework. As a conceptual study, we determined saturation of the sample based on whether it was sufficient to reach 'theoretical saturation' (Glaser and Strauss, 1970) in our analysis. That is, we determined the representativeness of our sample not following the question whether we could discover more studies on the topic, but rather whether further studies would likely add to the conceptual development. Figure 1 outlines the selection process for the sample.

3.1. Scoping, Structured Literature Sampling and Screening

The scoping concerned a) the definition of keywords, search terms, sources and periods and b) the development of inclusion and exclusion criteria (Tranfield *et al.*, 2003).

Three of the authors screened the abstracts based on the following four exclusion criteria:

(1) Is the manuscript written in English?

(2) Is it concerned with manufacturing or production?

(3) Is it explicitly concerned with robotics (as defined in Section 2)?

(4) Is the research directly concerned with human work in manufacturing?

We then reviewed the first sample's shortlisted papers (126 papers) through a series of categorisations and open-ended questions (Supplementary file, Part A). The papers were coded for type of robot technology, types of changes and research methodology. The full-text screening led to the further exclusion of 49 papers from the first sample, as the papers were either unavailable or, on reading of the full text, were not specific to manufacturing, robot technology, work or change properties. This initial coding and structuring also allowed for familiarisation with the data.

=== INSERT FIGURE 1 ABOUT HERE ===

3.2. Coding, Analysis and Model Development

A thematic analysis of the remaining 77 papers in the first sample was conducted, starting with an inductive bottom-up approach (Terry *et al.*, 2017). For the analysis, these steps inspired by the Gioia methodology were followed (Gioia *et al.*, 2013):

- First, we created structured summaries of the papers to capture their main findings or arguments in relation to instances of change and suggested interrelations between aspects of change.
- Second, we coded in these summaries occurring mentions of types of change, such as 'fewer accidents', 'new skill requirements' and 'new roles', as first-order concepts (the lowest level of the data structure in the Gioia methodology). This represents our operationalisation of 'emergent properties', which are, in soft systems thinking, a core concept relating to properties that make the 'whole entity "more than the sum of its parts"' (Checkland, 1999, p. 50). In line with Georgiou's (2003) general definition of emergent properties, such attention to particular changes following robotisation highlights those specific properties that give identity to the considered system.
- Third, following the Gioia methodology, we engaged in several iterations of discussion to generate abstractions of these first-order codes as sub-themes, second-order themes and aggregate dimensions (similar to the process of recursive abstraction). We organised the aggregate dimensions as four different themes of change, capturing the underlying second-order themes (Table 1). The aggregate dimensions are *work* that is executed in manufacturing, the *worker* as an individual person, the *organisation of labour* as how companies structure work through jobs and roles, and the *environment* (i.e. demographics and the regulatory and economic environment).

- Fourth, we used these findings to discuss patterns of interaction between the themes and aggregate dimensions. Following the concept of 'processes of communication and control' (Checkland, 2012), our discussion of the data aimed to identify patterns or processes through which the system automatically or deliberately adapts to internal and external conditions or initiates change. We thus structured the conceptualised subsystems as a holistic, entangled system and discussed the patterns of interactions following insights from the systematic literature review. To support the analysis, we represented the co-occurrence of different themes as a matrix that served as the data basis for graph network, visualising the frequency 8ccurence of individual themes and the co-occurrence of themes (Figure 2; Supplementary file, Part B).

3.3. Establishing Validity and Theoretical Saturation

Throughout the screening and coding, we ensured validity through double data extraction (Tranfield *et al.*, 2003) of a subset of the sample (see Supplementary file, Part A). The data were coded and reviewed in collaboration to ensure alignment.

We tested for theoretical saturation (Glaser and Strauss, 1970) of our sample by coding an additional set of 10 relevant manuscripts (obtained through Web of Science) against the developed data structure. The additional data did not mandate changes to structure second-order themes and aggregate dimensions but yielded three new first-order concepts (these are marked with an asterisk in Table 1)).

4. Entangled Changes in Robotising Manufacturing Work

Before developing a holistic view of robotised work in manufacturing, we first introduce the aggregate dimensions that we formulated based on our analysis. The identified aggregate dimensions are four themes of change: *work, organisation of labour, worker* and *environment*. The aggregate dimensions entail several second-order themes and sub-themes (aspects of change) that have been discussed in the literature (Table 1).

=== INSERT TABLE 1 ABOUT HERE ===

4.1. Changes to Human Work

The introduction of robots typically relates to deliberate changes to the *physical tasks* executed by human workers, especially regarding the nature or way these tasks are carried out. This change is often motivated by desires for efficiency, particularly when it comes to repetitive tasks, such as the screwing or welding of standard products. Additionally, robots have taken over strenuous physical tasks, such as rotating heavy objects during assembly or tool use in hard-to-access places, to reduce the amount of less ergonomic human work, which can also result in novel designs for human–robot workspaces using cobots.

Following this altered division of labour on the shop floor, the *coordinative tasks* for both shop floor workers and their supervisors shift. For industrial robots designed for specific tasks and confined in cages, such coordination has to do with the monitoring and control of the robot and the planning of the human work surrounding the caged robot. Thus, the coordination of the robot's work falls in line with the classical worker–supervisor dichotomy, where the human instructs the robot and oversees work execution. However, Weiss et al.'s (2021) review of the literature on cobots in manufacturing noted a change to this dichotomy towards more collaborative interaction, where humans and robots have formed teams. Bragança et al.'s (2019) unstructured literature review concluded that through adequate coordination of task allocation, humans' coordinative capabilities—their creativity, cognitive flexibility and unique experiences—are complemented by a robot's superior strength, stamina and consistency. This collaborative interaction may further allow the deployment of robots for tasks within highly flexible work environments.

With the shift towards more collaborative interaction, the nature of the *communicative tasks* also changes. For industrial robots, communication between humans and robots mainly concerns mechanistic interactions through specialised programming environments and reports from the robot. Collaborative work environments enhance the need for immediate and intuitive two-way communication, allowing real-time flexible task allocation and supporting less tech-savvy workers. Consequently, intuitive communication modes, such as natural language or gestures, have become relevant topics of study to promote technological advances. Similarly, we find increased importance of the human workers' ability to understand and anticipate a robot's intentions and upcoming actions based on their haptic or visual cues, to avoid collisions and accidents.

The introduction of robot technology also creates a range of novel *digital tasks* and activities for purposeful interaction with digital technologies. These tasks span from new, specialised activities related to systems design, mechatronics and programming to changes to existing tasks regarding controlling the machinery, maintenance or quality management.

Thus, the 56 papers that discussed aspects of robotised work provide insights into the shift in human work in manufacturing beyond the mere decline of physical tasks resulting from robotic automation. Specifically, our analysis highlights that the design of work in a robotised manufacturing setting needs to account for new or changed coordinative, communicative and digital tasks. These changes in the nature and constellation of tasks are relevant to the design and optimisation of manufacturing processes and workflows, where the reviewed literature focussed only on the planning of physical tasks (See supplementary file, Part C), thus creating a relevant research gap.

4.2. Changes to the Organisation of Labour

The shift in tasks leads to adjustments in the organisation of labour, such as changing the numbers and types of jobs in individual manufacturing firms and the skill profiles for these jobs. These shifts also affect working conditions.

The introduction of new technology often raises concerns about a decreasing *number of jobs*, which is also referred to as 'labour displacement' (see Acemoglu & Restrepo, 2017). While contemporary research and public discourse mainly attends to the undesirable effects of labour displacement, early authors like Nof (1999) - building on Asimov's laws of robotics - suggested that robots *should* replace workers on jobs for safety and economy. Yet, evidence regarding the effect of robotisation on the overall number of jobs at the individual firm level is inconclusive. This was highlighted by Dixon et al. (2021) who discussed their own findings drawn from Canadian national labour data on firm-level effects of robot investments on jobs against the literature. However, we found that shifts in the *types of jobs* and the resulting changes in the workforce composition have garnered increasing attention. Despite earlier conceptual arguments that robotisation would lead to the decline of low-skilled jobs (Romero *et al.*, 2016), Weiss et al.'s (2021) review of the cobot literature found an indication of the polarisation of jobs based on skill level. At the 'low-skill' pole, unskilled workers may carry out manual tasks that require no skill or experience to complete and are unsuited for robots. Jobs at the 'high-skill' pole may increase in importance, as they require a distinct digital skill profile related to the design, programming or maintenance of cyber-physical systems. Additionally, Dixon et al.'s (2021) study of Canadian labour data noted a decline in middle management as workers were assigned more decision autonomy.

Concomitantly, the *skill profiles* of jobs on robotised shop floors are changing. These skill profiles encompass both hard skills, such as technical knowledge and competences needed for the design and operation of robot technology, and soft skills, such as creativity, flexibility and problem-solving. However, studies that have explicitly mapped these new skill profiles have usually based their findings on the opinions of managers or experts (e.g. Jerman et al., 2020; Kannan & Garad, 2021), or analysed competencies mentioned in job listings (Li *et al.*, 2021). They have failed to investigate the actual skill profiles of workers in robotised work environments.

A change in job profiles at the organisational and industry levels may also affect *work conditions,* such as pay, work hours or tenure. However, such effects are likely to be mediated by contextual factors. For example, Cho and Kim (2018) analysed Korean labour data to determine the effects of robotisation on wage and work hours, finding significant effects on size, level of worker unionisation and complexity of production work.

The 38 reviewed papers discussing aspects of the organisation of labour within robotised firms thus show a complex picture concerning *which* changes may occur in a concrete context. While automation through robots indeed can and will render certain jobs obsolete, not all industries and production systems – especially those with high variation of tasks - will see a clear benefit from replacing human workers with robots. Moreover, robotisation may merely mean a shift from workers executing manual work to work that assists, instructs, monitors or maintains the robot. Thus, the job profiles and associated required skills will change. This change would not only demand more proficiency in digital skills but also skills related to problem-solving, flexibility, creativity and autonomy, as shop floor workers may be handed a broader scope of decision-making responsibilities. This shifting demand for advanced personal and cognitive skills can put pressure on workers and employers alike. Similarly, a more systematic consideration of future job (role) designs could enhance the quality of discussions regarding future skill needs.

4.3. Changes in Workers' Experiences

The changes concerning workers' tasks and how their work is organised may, in turn, also alter their physical and affective experiences. The physical experience concerns the effects of labour on a worker's body. Robotisation can serve to *reduce physical strain* by automating repetitive, non-ergonomic or hazardous tasks. Laboratory-based experimental studies, such as Colim et al. (2021), have provided evidence of improved ergonomics through workstations with cobots, finding that they reduced the mechanical load on the human body.

Moreover, the introduction of robots on the shop floor changes the *risk of accidents.* These changes can mean either reducing exposure to accidents when using robots in dangerous work situations or introducing novel risks associated with a robotised workplace. Preventing these novel accidents becomes an even more crucial task as cobots start to share physical workspaces with their human collaborators. The literature review conducted by Gopinath and Johansen (2019) highlighted the importance of situational and mode awareness as a factor in reducing the risk of collisions and accidents, which relates back to the novel communication tasks between human workers and robots.

Regarding workers' *affective experience,* the literature recently showed a stronger focus on diverse factors shaping workers' emotional well-being than physical well-being. Specifically, the literature has covered both *experience within a robotised workplace* and *workers' anticipation of a robotised workplace*. A robotised workplace can shift the levels of stress or cognitive load experienced by workers. Specifically, Moniz (2015) conceptualised the importance of reducing cognitive load through more intuitive interactions and predictable robot behaviours. They noted that cognitive load is an important design parameter for ergonomic robot systems, as it 'interferes with the task performance and with operational safety' (ibid., p. 68). Beyond the objectively conceptualised dimensions of cognitive load, the robotisation of manufacturing also influences subjective experiences across the human affective spectrum. Regarding the subjective experience of an already robotised shop floor, Moniz (2015) and Weiss et al. (2021) highlighted the role of trust in the robot's behaviour as a factor influencing affective experiences.

Concerning the anticipation of a to-be-(more)-robotised workplace, a particular theme of interest is job-loss anxiety and its possible effects on job satisfaction or happiness at work. The literature has indicated that numerous factors could influence the level of individually experienced job-loss anxiety. For example, Stankevičiūtė et al. (2021) surveyed 350 workers across five heavily robotised Lithuanian furniture manufacturers and found significant effects of demographic factors, such as age and gender (though not education or tenure), on perceived job insecurity. Furthermore, they postulated (ibid., p. 1563) that the current degree of robotisation in the industry and the general economic context may influence subjective experiences of job insecurity. Lei's (2022) interview study of 65 unskilled Chinese manufacturing workers further considered social context, such as dependent children, as a potential explanation for the different experiences of job-loss anxiety. Adopting a sociological perspective, Barker and Jewitt's (2021) ethnographical study of two robotised manufacturers highlighted that workers also experience a shift in perceived identity. Rangraz and Pareto (2021, p. 20) suggested that such a shift of identity from skilled craftsmen to novice robot operators also altered the workers' sense of belonging and, in turn, well-being.

In summary, the 43 papers that discussed workers' experiences show a complex pattern of physical and affective experiences. The literature shows that either types of experiences can be positively or negatively affected by the introduction of robots, as guided by several contextual factors that merit closer investigation. Negative physical effects (risks to health and safety) are typically addressed through safety standards and regulations (see Chemweno *et al.*, 2020). However, the untangling of the more complex roots of both positive and negative affective experiences requires novel approaches that we did not encounter in the reviewed literature.

4.4. Changes in a Firm's Environment

The previously reported changes in a firm's labour composition alter the supply and demand of labour within markets. However, these effects are influenced by several environmental conditions, such as labour laws, economic development and demographics.

The findings of studies that analysed employment data on the statistical effects of robotisation on overall employment in the industry are heterogeneous. Leigh et al. (2020, p. 79) thus suggested grouping this literature based on whether it treats 'robots-as-status-quo' and 'robots-as-displacers'. The former refers to studies reporting a neutral or slightly positive effect on employment (in our sample: Cho and Kim, 2018; Dauth *et al.*, 2018; Dixon *et al.*, 2021; Dottori, 2020; Kariel, 2021). The latter refers to studies that report a negative effect (in our sample: Acemoglu and Restrepo, 2017; Borjas and Freeman, 2019; Ni and Obashi, 2021). To explain the heterogeneity, some authors have suggested that the stronger *labour protection laws* in Italy, Germany or Japan, for example, contribute to a lower displacement of labourers. However, for the less restrictive UK labour market Kariel (2021) reported also only insignificant effects of robotisation on net employment, while Ni and Obashi (2021) contradicted Adachi's (2020) finding for the Japanese market, reporting negative effects on overall employment. Moreover, Dixon et al. (2021) and Adachi (2020) argued that employment is causally linked to robotisation and instead suggested that employment and robotisation may be correlated outcomes of general *economic development.* Additionally, policies and incentives may shift the economic rationale for robotisation, which can alter the effect of robotisation on employment.

In addition to the total number of available jobs in the market, robotisation can also influence who can assume certain positions; thus, employment becomes linked to the *demographics* of its labour market. Robots can reduce the need for physical strength, so they may open certain jobs to new groups of workers. Similarly, some robots may lower the necessary skill or experience level required to complete specific tasks, as robots or other augmentation systems can guide and instruct workers. By increasing the adoption of robot systems with a lower need for digital literacy, employers can potentially broaden the pool of workers from which they can recruit to meet their needs. Yet, given the previously discussed more nuanced skill profile required for jobs in robotised industries, employers are also likely to encounter labour shortages, not only for high-skilled technicians but also for sufficiently digital-savvy operators or workers willing to assume jobs with higher demands for flexibility, autonomy and responsibility. This may lead to a division between workers who can understand and adapt to new requirements, thus strengthening their position in the labour market, and those who cannot.

Adopting a similar view on differentiated effects on various demographic groups, other studies have explored the effects of robotisation on specific demographics. For example, Borjas and Freeman's (2019) analysis of 15 years of cross-industry US labour data reported the negative effects of robotisation on the employment of immigrants, female or low-skilled workers. Dottori's (2020) analysis of 23 years of individual career patterns for more than 157,000 Italian manufacturing workers found a positive effect of robotisation for those workers already employed in certain sectors but also a decline in new workers entering the sector.

In summary, the 19 papers that discussed a firm's environment showed that robotisation can induce different changes to the labour market with which the firm interacts, resulting in both job depletion and creation. Although robotisation may lead to a scarcity of sufficiently highly skilled workers, a broader worker demographic may be unlocked, which in turn can mitigate some of the labour shortages seen today. Moreover, contextual factors, such as the regulatory environment for labour and labour safety, and economic trends play a role in how robotisation leads to changes in manufacturing work.

5. A Soft Systems Conceptualisation of the Robotisation of Manufacturing Work

Based on the review of the literature, we have introduced the idea of different themes of change—conceptual areas in which relevant changes happen concomitantly with the introduction of robot technology. Within these themes of change, we have described concrete sub-themes of particular interest to research and practice, to which change happens, such as the physical or emotional well-being of workers, definitions of tasks, jobs and roles, or competences and skills required in a robotised industry. In accordance with the initially suggested complexity or entanglement of changes, we noted that many of the themes were discussed in relation to other themes across the literature. Figure 2 shows the observed connections between the themes, illustrated as a graph network. Each theme represents a node, and the observed patterns of interactions are represented as lines.

=== INSERT FIGURE 2 about here ===

Patterns of interaction relate to changes happening concomitantly across different sub-themes. Following soft systems thinking, we describe such patterns of interaction through descriptive verbs (Checkland and Poulter, 2010), acknowledging that there might be bidirectional interactions or loops of interactions. As a simple example, while new digital tasks can shift skill and competence requirements for specific jobs, the available competences and skills within an organisation (or workers' motivation to acquire such competences) can, in turn, influence the technological choices and the resulting digital tasks necessary to operate the robot.

Table 2 provides an overview of the most salient patterns of interaction among the themes. Given the previously discussed complexity and contextual dependency of these patterns of interaction, these examples are neither exhaustive nor generally applicable. In many cases, they also only indicate an effect without specifying the direction of the effect, reflecting the heterogenous findings presented by the reviewed literature, such as the discussed contradicting findings on the effects of job number, skill profiles, or workers' physical and emotional well-being. However, as illustrated, they are suitable for triggering further exploration enriched through practical expert knowledge related to the concrete industry, firm or production site.

=== INSERT TABLE 2 ABOUT HERE ===

To illustrate the complex interdependencies, we consider a specific example of broadened job responsibilities ('job enrichment'). While job enrichment is typically considered desirable for workers, holistic considerations pay attention to the interrelations between shifting job profiles and workers' experiences. Specifically, soft systems thinking draws attention to instances where enrichment may result in undesired levels of responsibility (Rangraz and Pareto, 2021) or changes to tasks that were identity creating for workers (McMeel, 2021) and thus also lead to negative experiences. Similarly, depending on their professional or social context, not all workers perceive the broadening of the required skills for their jobs to be positive; instead, they may feel threatened by the requirements (Chin *et al.*, 2019). Thus, what may be intended as desirable job enrichment can negatively affect workers' (perceived) opportunities in a job market, their attitude towards robot technologies, the manners in which they interact or their willingness to build up skills, which may affect safe and effective robot–human collaboration.

5.1. Implications for Research and Practice

Soft systems thinking provides a different perspective to *think* about the phenomenon of robotised manufacturing work. Owing to the constructivist foundations of soft systems thinking, this approach cannot and does not seek to offer generalizable truths about concrete effects of robots on manufacturing work. This work therefore cannot give any conclusive answers to pressing questions of the robotisation literature, such as: What happens to the number of jobs? How does worker wellbeing change? How much more efficient is robotised manufacturing? The answer is always: it depends. Our review has shown that the factors on which it may depend are numerous, and by far not fully known or understood. Research following the science-and-engineering paradigm is likely to uncover more factors and more dependencies in the future, yet given the 'wickedness' of the problem, will always retain blind spots. The conceptualisation as a soft system enables both researchers and practitioners to navigate these inevitable blind spots in the following way.

For research, this conceptualisation enables, first, novel theorising and subsequent theory testing of the interdependencies for which findings in the literature—based on causal models—are inconclusive. For example, soft systems thinking allows us to formulate new propositions about how technological choices and innovations are embedded in interrelating factors concerning a firm's current workforce, existing tasks, the surrounding labour market, and related regulations. However, given the emergent complexity of the propositions and the consequent difficulty in controlling for and measuring distinct variables, a suitable research approach could be Van de Ven's (2007) engaged scholarship approach. Specifically, the model may inform research by following an action research approach (Coughlan and Coghlan, 2002) or help structure and evaluate design science research in the formative phase of research (Venable *et al.*, 2016).

Second, this conceptualisation emphasises the relevance of studying loops rather than linear causal chains and allows for the identification of potentially self-amplifying interactions. Following the notion of loops, the offered conceptualisation also emphasises the temporal dimension of interdependencies. Studies could follow the development of these changes over time, both quantitatively through time series and qualitatively by exploring the underlying dynamics through process studies (Langley *et al.*, 2013).

Third, future work could enrich the conceptualisation by considering certain internal drivers within the robotising firm that our model did not capture. For example, we did not consider manufacturing capabilities, which could explain the dynamics and outcomes of different system configurations (Banker *et al.*, 2006). Moreover, we did not assess the effects of interactions on firms' specific criteria for evaluating the success of their robotisation initiatives – which can range from improved performance metrics to more ambiguous expectations like learning and strategic positioning. The enrichment of the conceptualisation could also elucidate the role of different drivers of robotisation on outcomes for manufacturing work. Future refinements could also focus on the sub-themes of the robot technology itself, an aspect on which our review did not focus. By developing a set of central properties, such as the technology's flexibility, sensing abilities or physical characteristics, the further conceptualisation can accommodate the interdependencies of characteristics of different robot technologies. For practice, the conceptualisation as a soft system allows reflection on robotisation as one of many interrelated enablers of successful strategy implementation. Thus, it allows us to discuss robotisation not as a distinct strategic objective but as a means that only in the right configuration—together with strategic choices for location, production portfolio, employee development, process organisation and so forth—enables the achievement of specific goals related to efficiency, quality and other factors. Moreover, it visualises the complexity of robotisation and can facilitate discussions about internal and external uncertainties related to technological change. The soft systems conceptualisation can thus inform and support strategy tools, such as Van der Heijden's (2005) Scenario Thinking.

Second, the conceptualisation offered can serve as a starting point for the application of the soft systems methodology in concrete robot implementation initiatives. Following Checkland's suggestion that 'hard' systems thinking is complementary to soft systems thinking (Checkland, 1985, p. 765), the representation as a soft system can guide practitioners to explore the challenge of robotisation holistically and identify concrete risks and opportunities that merit closer exploration through hard systems thinking. Thus, the linkages between the properties may be used as triggers to ask: 'How may X affect Y *in our context?', to formulate hypotheses,* and to evaluate the concrete relations and effects in the local setting. This conceptualisation can also inform more holistic evaluations of robotisation opportunities and guide learning-oriented design and organisational change processes around a concrete robotisation project.

5.2. Limitations

A limitation of this study is the nature of the data used, specifically: academic literature. While we would expect that academic research on the management of manufacturing technology closely follows the central challenges of practice, there might be biases. First, our sample might be prone to researcher bias, concerning the selection of topics worthy of research by the researchers in the field and, secondly, publication bias, concerning the selection of findings worthy of publication. Thus, certain themes of change, which could be of relevance might have been absent in our sample. Discussion of the findings with a panel of practitioners could have been used to further validate the thematic completeness of the findings.

Second, as a qualitative study, relying on thematic interpretation through the researchers, there is a risk of bias in these interpretations. However, as a team of researchers with diverse backgrounds, and challenged by our reviewers and the editorial team, we have rigorously questioned and refined the interpretations that informed our analysis and discussion.

Third, as a study interested in conceptualising, rather than quantifying, our method has not systematically considered the quality of evidence in the research serving as our sample. "Quality of evidence" has been a topic of discussion in our analysis which we have operationalised as strength of the methodology (see also Supplementary File, Part D). While this approach is less suitable for the generation of hypotheses and predictions, it is, however, fitting the intent of the study, to categorize and conceptualize.

6. Conclusion

Technology, work and organising are deeply entangled, which can render the introduction of novel technologies, such as cobots, to be an uncertain adventure rather than a well-planned change. To facilitate the navigation of these uncertainties, we proposed a holistic conceptual view of the entangled interactions between technology, work, workers and organisation of labour as embedded in their economic and demographic environment. This conceptualisation can serve at the organisational level to better anticipate and manage the complexities of robotisation. Moreover, it may inspire future research that understands robot technology as an entangled part of a complex whole. All these are expected to contribute to the value-creating adoption of robots in manufacturing environments.

7. References

Abdallah, C. and Langley, A. (2014), “The Double Edge of Ambiguity in Strategic Planning”, *Journal of Management Studies*, Vol. 51 No. 2, pp. 235–264, doi: 10.1111/joms.12002.

Acemoglu, D. and Restrepo, P. (2017), *Robots and Jobs: Evidence from US Labor Markets*, Working Paper No. 26738, National Bureau of Economic Research, Inc, Cambridge, MA.

Acemoglu, D. and Restrepo, P. (2018), “The Race between Man and Machine: Implications of Technology for Growth, Factor Shares, and Employment”, *American Economic Review*, Vol. 108 No. 6, pp. 1488–1542, doi: 10.1257/aer.20160696.

Appelbaum, S.H. (1997), “Socio-technical systems theory: an intervention strategy for organizational development”, *Management Decision*, MCB UP Ltd, Vol. 35 No. 6, pp. 452–463, doi: 10.1108/00251749710173823.

Banker, R.D., Bardhan, I.R., Chang, H. and Lin, S. (2006), “Plant Information Systems, Manufacturing Capabilities, and Plant Performance”, *MIS Quarterly*, Management Information Systems Research Center, University of Minnesota, Vol. 30 No. 2, pp. 315–337, doi: 10.2307/25148733.

Bänziger, T., Kunz, A. and Wegener, K. (2020), “Optimizing human–robot task allocation using a simulation tool based on standardized work descriptions”, *Journal of Intelligent Manufacturing*, Vol. 31 No. 7, pp. 1635–1648, doi: 10.1007/s10845-018-1411-1.

Barker, N. and Jewitt, C. (2021), “Filtering Touch: An Ethnography of Dirt, Danger, and Industrial Robots”, *Journal of Contemporary Ethnography*, pp. 3–130, doi: 10.1177/08912416211026724.

Barrett, M., Oborn, E., Orlikowski, W.J. and Yates, J. (2012), “Reconfiguring Boundary Relations: Robotic Innovations in Pharmacy Work”, *Organization Science*, INFORMS, Vol. 23 No. 5, pp. 1448–1466, doi: 10.1287/orsc.1100.0639.

Beer, S. (1966), *Decision and Control: The Meaning of Operational Research and Management Cybernetics*, J. Wiley, Chichester ; New York.

Borjas, G.J. and Freeman, R.B. (2019), *From Immigrants to Robots: The Changing Locus of Substitutes for Workers*, National Bureau of Economic Research, Cambridge, MA, p. 32.

Bragança, S., Costa, E., Castellucci, I. and Arezes, P.M. (2019), “A Brief Overview of the Use of Collaborative Robots in Industry 4.0: Human Role and Safety”, in Arezes, P.M., Baptista, J.S., Barroso, M.P., Carneiro, P., Cordeiro, P., Costa, N., Melo, R.B., et al. (Eds.), *Occupational and Environmental Safety and Health*, Vol. 202, Springer International Publishing, Cham, pp. 641–650, doi: 10.1007/978-3-030-14730-3_68.

Checkland, P. (1983), “O.R. and the systems movement: Mappings and Conflicts”, *Journal of the Operational Research Society*, Vol. 34 No. 8, pp. 661–675.

Checkland, P. (1985), "From Optimizing to Learning: A Development of Systems Thinking for the 1990s", *Journal of the Operational Research Society*, Vol. 36 No. 9, pp. 757–767, doi: 10.1057/jors.1985.141.

Checkland, P. (1999), "Systems Thinking", in Currie, W. and Galliers, B. (Eds.), *Rethinking Management Information Systems: An Interdisciplinary Perspective*, Oxford University Press, New York.

Checkland, P. (2000), "Soft systems methodology: a thirty year retrospective", *Systems Research and Behavioral Science*, Vol. 17 No. S1, pp. S11–S58, doi: 10.1002/1099-1743(200011)17:1+<::AID-SRES374>3.0.CO;2-O.

Checkland, P. (2012), "Four Conditions for Serious Systems Thinking and Action", *Systems Research and Behavioral Science*, Vol. 29 No. 5, pp. 465–469, doi: 10.1002/sres.2158.

Checkland, P. and Poulter, J. (2010), "Soft Systems Methodology", in Reynolds, M. and Holwell, S. (Eds.), *Systems Approaches to Managing Change: A Practical Guide*, Springer London, London, pp. 191–242, doi: 10.1007/978-1-84882-809-4_5.

Chemweno, P., Pintelon, L. and Decre, W. (2020), "Orienting safety assurance with outcomes of hazard analysis and risk assessment: A review of the ISO 15066 standard for collaborative robot systems", *Safety Science*, Vol. 129, p. 104832, doi: 10.1016/j.ssci.2020.104832.

Chin, T., Li, G., Jiao, H., Addo, F. and Jawahar, I.M. (2019), "Career sustainability during manufacturing innovation: A review, a conceptual framework and future research agenda", *Career Development International*, Vol. 24 No. 6, pp. 509–528, doi: 10.1108/CDI-02-2019-0034.

Cho, J. and Kim, J. (2018), "Identifying Factors Reinforcing Robotization: Interactive Forces of Employment, Working Hour and Wage", *Sustainability*, Vol. 10 No. 2, p. 490, doi: 10.3390/su10020490.

Colim, A., Faria, C., Cunha, J., Oliveira, J., Sousa, N. and Rocha, L.A. (2021), "Physical Ergonomic Improvement and Safe Design of an Assembly Workstation through Collaborative Robotics", *Safety*, Vol. 7 No. 1, p. 14, doi: 10.3390/safety7010014.

Coughlan, P. and Coghlan, D. (2002), "Action research for operations management", *International Journal of Operations and Production Management*, Vol. 22 No. 2, pp. 220–240, doi: 10.1108/01443570210417515.

Dauth, W., Findeisen, S., Suedekum, J. and Woessner, N. (2018), *Adjusting to Robots: Worker-Level Evidence*, preprint, Institute Working Paper, n/a, doi: 10.21034/iwp.13.

Dekkers, R. (2017), Applied Systems Theory, 2nd edition ed, Cham, Springer.

Dixon, J., Hong, B. and Wu, L. (2021), "The Robot Revolution: Managerial and Employment Consequences for Firms", *Management Science*, Vol. 67 No. 9, pp. 5586–5605, doi: 10.1287/mnsc.2020.3812.

Dottori, D. (2020), *Robots and Employment: Evidence from Italy*, Banca d'Italia, n/a.

Evans, W. (2020), “How Amazon hid its safety crisis”, *Reveal News*, 29 September.

Farrell, R. and Hooker, C. (2013), “Design, science and wicked problems”, *Design Studies*, Vol. 34 No. 6, pp. 681–705, doi: 10.1016/j.destud.2013.05.001.

Feldman, M.S. and Pentland, B.T. (2003), “Reconceptualizing Organizational Routines as a Source of Flexibility and Change”, *Administrative Science Quarterly*, SAGE Publications Inc, Vol. 48 No. 1, pp. 94–118, doi: 10.2307/3556620.

Ford, M. (2015), *Rise of the Robots: Technology and the Threat of a Jobless Future*, Basic Books, a member of the Perseus Books Group, New York.

Fox, W.M. (1995), “Sociotechnical System Principles and Guidelines: Past and Present”, *The Journal of Applied Behavioral Science*, SAGE Publications Inc, Vol. 31 No. 1, pp. 91–105, doi: 10.1177/0021886395311009.

Gates, D. (2019), “Boeing abandons its failed fuselage robots on the 777X, handing the job back to machinists”, *The Seattle Times*, 13 November, available at: https://www.seattletimes.com/business/boeing-aerospace/boeing-abandons-its-failed-fuselage-robots-on-the-777x-handing-the-job-back-to-machinists/ (accessed 13 February 2023).

Georgiou, I. (2003), “The idea of emergent property”, *Journal of the Operational Research Society*, Taylor & Francis, Vol. 54 No. 3, pp. 239–247, doi: 10.1057/palgrave.jors.2601520.

Gioia, D.A., Corley, K.G. and Hamilton, A.L. (2013), “Seeking Qualitative Rigor in Inductive Research: Notes on the Gioia Methodology”, *Organizational Research Methods*, Vol. 16 No. 1, pp. 15–31, doi: 10.1177/1094428112452151.

Glaser, B.G. and Strauss, A.L. (1970), “Theoretical Sampling”, *Sociological Methods*, Taylor and Francis Group, Routledge.

Gopinath, V. and Johansen, K. (2019), “Understanding situational and mode awareness for safe human-robot collaboration: case studies on assembly applications”, *Production Engineering*, Vol. 13 No. 1, pp. 1–9, doi: 10.1007/s11740-018-0868-2.

IFR. (2022), *World Robotics 2022: Industrial Robots. Statistics, Market Analysis, Forecasts, and Case Studies*, VDMA Services GmbH, Frankfurt.

IFR. (n.d.). “International Federation of Robotics”, *IFR International Federation of Robotics*, available at: https://ifr.org/industrial-robots (accessed 26 August 2022).

Jerman, A., Pejić Bach, M. and Aleksić, A. (2020), “Transformation towards smart factory system: Examining new job profiles and competencies”, *Systems Research and Behavioral Science*, Vol. 37 No. 2, pp. 388–402, doi: 10.1002/sres.2657.

Kannan, K.S.P.N. and Garad, A. (2021), “Competencies of quality professionals in the era of industry 4.0: a case study of electronics manufacturer from Malaysia”, *International Journal of Quality & Reliability Management*, Emerald Group Publishing, Ltd., Bradford, West Yorkshire, Vol. 38 No. 3, pp. 839–871, doi: 10.1108/IJQRM-04-2019-0124.

Kariel, J. (2021), “Job Creators or Job Killers? Heterogeneous Effects of Industrial Robots on UK Employment”, *LABOUR*, Vol. 35 No. 1, pp. 52–78, doi: 10.1111/labr.12192.

Kuz, S., Mertens, A. and Schlick, C.M. (2018), “Anthropomorphic motion control of a gantry robot in assembly cells”, *Theoretical Issues in Ergonomics Science*, Vol. 19 No. 6, pp. 738–751, doi: 10.1080/1463922X.2018.1484528.

Langley, A., Smallman, C., Tsoukas, H. and Van de Ven, A.H. (2013), “Process Studies of Change in Organization and Management: Unveiling Temporality, Activity, and Flow”, *Academy of Management Journal*, Academy of Management, Vol. 56 No. 1, pp. 1–13, doi: 10.5465/amj.2013.4001.

Larsen, M.S.S., Laursen, E.S. and Lassen, A.H. (2023), “Managing Manufacturing Innovation: Four Types of Problems and Matching Innovation Processes." *Proceedings of the Changeable, Agile, Reconfigurable and Virtual Production Conference and the World Mass Customization & Personalization Conference*. Cham: Springer International Publishing, 2023.

Lei, Y.-W. (2022), “Upgrading China through Automation: Manufacturers, Workers and the Techno-Developmental State”, *Work, Employment and Society*, Vol. 36 No. 6, pp. 1078–1096.

Leigh, N.G., Kraft, B. and Lee, H. (2020), “Robots, skill demand and manufacturing in US regional labour markets”, *Cambridge Journal of Regions, Economy and Society*, Vol. 13 No. 1, pp. 77–97, doi: 10.1093/cjres/rsz019.

Li, G., Yuan, C., Kamarthi, S., Moghaddam, M. and Jin, X. (2021), “Data science skills and domain knowledge requirements in the manufacturing industry: A gap analysis”, *Journal of Manufacturing Systems*, Vol. 60, pp. 692–706, doi: 10.1016/j.jmsy.2021.07.007.

Liberati, A., Altman, D.G., Tetzlaff, J., Mulrow, C., Gøtzsche, P.C., Ioannidis, J.P.A., Clarke, M., *et al.* (2009), “The PRISMA Statement for Reporting Systematic Reviews and Meta-Analyses of Studies That Evaluate Health Care Interventions: Explanation and Elaboration”, *PLoS Medicine*, Vol. 6 No. 7, p. e1000100, doi: 10.1371/journal.pmed.1000100.

McMahon, C. (2022), “History of engineering systems design research and practice”, in Maier, A., Oehmen, J. and Vermaas, P.E. (Eds.), *Handbook of Engineering Systems Design*, Springer International Publishing, Cham, doi: 10.1007/978-3-030-81159-4.

McMeel, D. (2021), “Artisan to Automation: Value and Craft in the 21st Century”, *Architecture and Culture*, Vol. 9 No. 4, pp. 674–689, doi: 10.1080/20507828.2021.1919854.

Mingers, J. (2006), *Realising Systems Thinking: Knowledge and Action in Management Science*, Springer, doi: 10.1007/0-387-29841-X.

Moniz, A.B. (2015), “Intuitive interaction between humans and robots in work functions at industrial environments: The role of social robotics”, in Vincent, J., Taipale, S., Sapio, B., Lugano, G. and Fortunati, L. (Eds.), *Social Robots from a Human Perspective*, Springer International Publishing, Cham, pp. 67–75, doi: 10.1007/978-3-319-15672-9.

Morgan, G. (1981), "The Schismatic Metaphor and Its Implications for Organizational Analysis", *Organization Studies*, Vol. 2 No. 1, pp. 23–44, doi: 10.1177/017084068100200103.

Ni, B. and Obashi, A. (2021), "Robotics technology and firm-level employment adjustment in Japan", *Japan and the World Economy*, Vol. 57, p. 101054, doi: 10.1016/j.japwor.2021.101054.

Nof, S.Y. (1999), *Handbook of Industrial Robotics*, John Wiley & Sons.

Parker, S.K. and Grote, G. (2022), "Automation, Algorithms, and Beyond: Why Work Design Matters More Than Ever in a Digital World", *Applied Psychology*, Vol. 71 No. 4, pp. 1171–1204, doi: 10.1111/apps.12241.

Phan, P., Wright, M., and Soo-Hoon Lee. (2017), "Of robots, artificial intelligence, and work", *Academy of Management Perspectives*, Vol. 31 No. 4, pp. 253–255, doi: 10.5465/amp.2017.0199.

Rangraz, M. and Pareto, L. (2021), "Workplace work-integrated learning: supporting industry 4.0 transformation for small manufacturing plants by reskilling staff", *International Journal of Lifelong Education*, Vol. 40 No. 1, pp. 5–22, doi: 10.1080/02601370.2020.1867249.

Rittel, H.W.J. and Webber, M.M. (1973), "Dilemmas in a general theory of planning", *Policy Sciences*, Vol. 4, pp. 155–169.

Romero, D., Stahre, J., Wuest, T., Noran, O., Bernus, P., Fast-Berglund, Å. and Gorecky, D. (2016), "Toward an operator 4.0 typology: A human-centric perspective on the fourth industrial revolution technologies", *CIE46 Proceedings*, presented at the CIE45, Tianjin, China, p. 12.

Stankevičiūtė, Ž., Staniškienė, E. and Ramanauskaitė, J. (2021), "The Impact of Job Insecurity on Employee Happiness at Work: A Case of Robotised Production Line Operators in Furniture Industry in Lithuania", *Sustainability*, Vol. 13 No. 3, p. 1563, doi: 10.3390/su13031563.

Teixeira, J.V.S., Reis, A.M., Mendes, F.B. and Vergara, L.G.L. (2019), "Collaborative Robots", in Arezes, P.M., Baptista, J.S., Barroso, M.P., Carneiro, P., Cordeiro, P., Costa, N., Melo, R.B., et al. (Eds.), *Occupational and Environmental Safety and Health*, Vol. 202, Springer International Publishing, Cham, pp. 791–796, doi: 10.1007/978-3-030-14730-3_83.

Terry, G., Hayfield, N., Clarke, V. and Braun, V. (2017), "Thematic Analysis", in Willig, C. and Rogers, W.S. (Eds.), *The SAGE Handbook of Qualitative Research in Psychology*, Vol. 2, SAGE, pp. 17–37.

Tranfield, D., Denyer, D. and Smart, P. (2003), "Towards a methodology for developing evidence-informed management knowledge by means of systematic review *", *British Journal of Management*, Vol. 14, pp. 207–222, doi: 10.1111/1467-8551.00375.

Trist, E.L. and Bamforth, K.W. (1951), "Some Social and Psychological Consequences of the Longwall Method of Coal-Getting: An Examination of the Psychological Situation and Defences of a Work Group in Relation to the Social Structure and Technological Content of the Work System", *Human Relations*, SAGE Publications Ltd, Vol. 4 No. 1, pp. 3–38, doi: 10.1177/001872675100400101.

Van de Ven, A.H. (2007), *Engaged Scholarship: A Guide for Organizational and Social Research*, Oxford University (2007), ISBN: 9780199226306.

Van der Heijden, K. (2005), *Scenarios: The Art of Strategic Conversation*, John Wiley & Sons.

Venable, J., Pries-Heje, J. and Baskerville, R. (2016), “FEDS: a Framework for Evaluation in Design Science Research”, *European Journal of Information Systems*, Vol. 25 No. 1, pp. 77–89, doi: 10.1057/ejis.2014.36.

Weiss, A., Wortmeier, A.-K. and Kubicek, B. (2021), “Cobots in Industry 4.0: A Roadmap for Future Practice Studies on Human–Robot Collaboration”, *IEEE Transactions on Human-Machine Systems*, Vol. 51 No. 4, pp. 335–345, doi: 10.1109/THMS.2021.3092684.

World Economic Forum. (2018), *The Future of Jobs Report*, CH-1223 Cologny/Geneva, Switzerland.

Zammuto, R.F., Griffith, T.L., Majchrzak, A., Dougherty, D.J. and Faraj, S. (2007), “Information Technology and the Changing Fabric of Organization”, *Organization Science*, , United States, Vol. 18 No. 5, pp. 749-762,881-883.

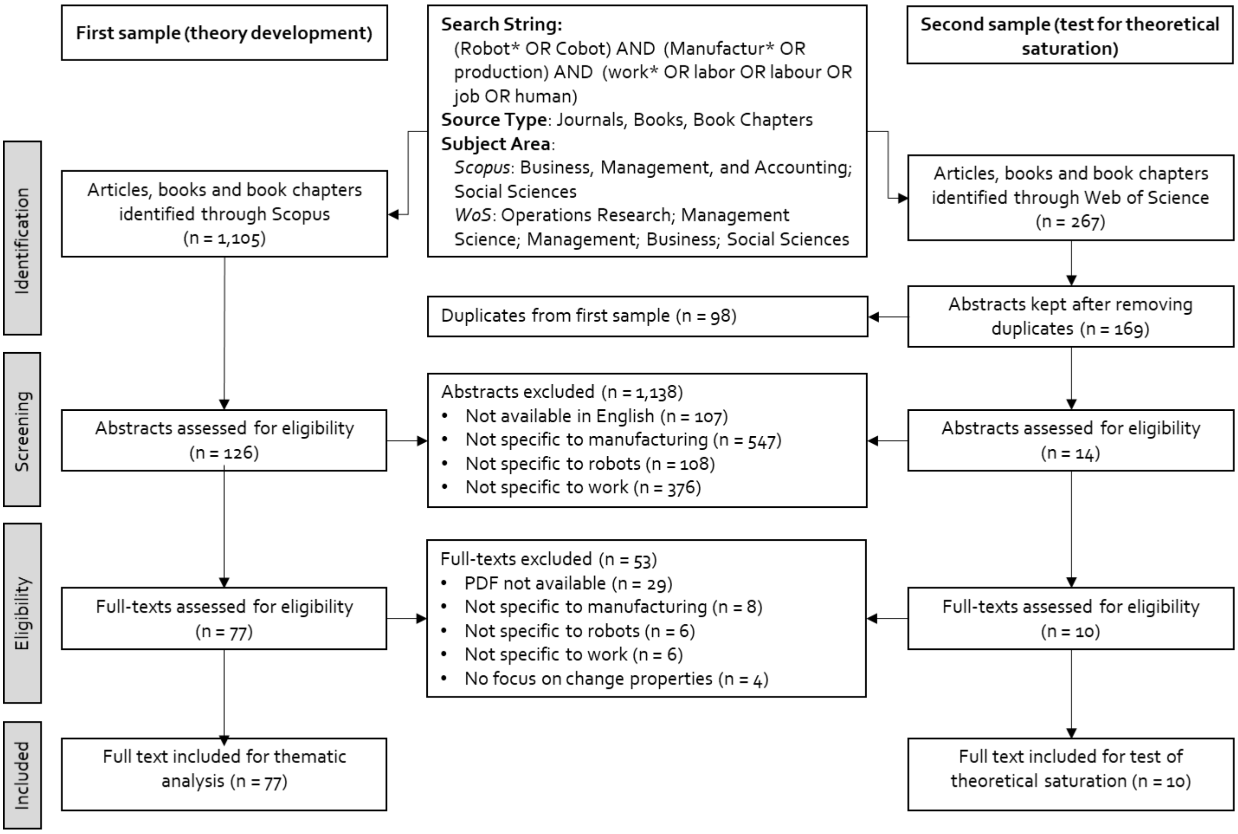
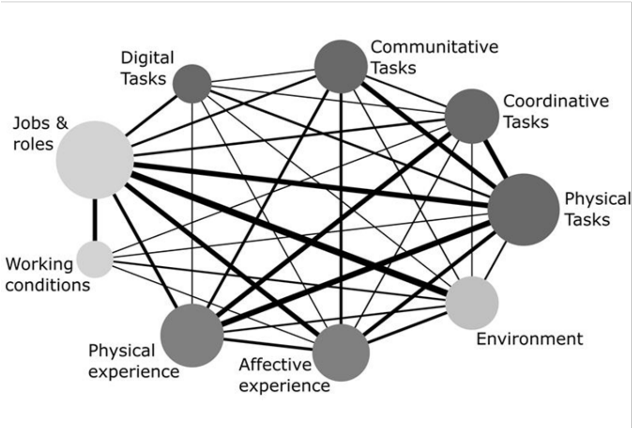


Figure 1. Flow of the structured literature sampling and screening process following the PRISMA statement (Liberati et al.*, 2009).*



	Physical Tasks	Coordinative Tasks	Communicative Tasks	Digital Tasks	Jobs & Roles	Working conditions	Physical experience	Affective experience	Environment
Physical Tasks	33	10	9	5	11	1	12	8	4
Coordinative Tasks	10	20	4	2	5	2	10	3	1
Communicative Tasks	9	4	19	2	5	0	6	6	3
Digital Tasks	5	2	2	10	6	0	2	2	1
Jobs & Roles	11	5	5	6	41	9	7	10	14
Working conditions	1	2	0	0	9	9	0	1	4
Physical experience	12	10	6	2	7	0	27	6	4
Affective experience	8	3	6	2	10	1	6	22	6
Environment	4	1	3	1	14	4	4	6	19

Figure 2. Co-occurrence of themes in the reviewed literature (size of bubble indicates frequency of individual theme and thickness of connecting line indicates frequency of co-occurrence within the same article in the sample; see Supplementary file for underlying data).

Table 1. List of themes, subthemes and variables identified in the literature analysis (The numbers in parentheses refer to the reference in the full list of works reviewed, which is given in Supplementary file, Part C; Variables marked with an asterisk have been added during the test for theoretical saturation.)

	Themes	Sub-themes	Variables of change (within sub-themes; first-order codes)
Work	Physical Tasks	Distribution of manual labour	• Degree of automation [1]–[4] • Degree of interactive collaboration between humans and robots [5]–[14] • Type of robotised physical tasks [13], [15]–[26] • Degree of robotic support/augmentation in execution of human physical work [27] • *Level of abstraction of remaining physical work [28]
		Physical organisation of the workspace	• Degree of physical separation between workers and robots [19], [20], [29]–[33] • Design characteristics of shared workspaces [6], [10], [15], [30], [34], [35]
	Coordinative Tasks	Planning of work	• Approaches to allocating work [2], [17], [36] • Approaches to planning for safety [37]–[41] • Approaches to planning for synergies [9], [10], [23] • Approaches to planning for efficiency [3], [11], [42]
		Flexible reallocation of tasks	• Ability to instruct robot flexibly during collaboration [6], [10], [13], [43]
		Supervision and control of robotic work	• Types of control tasks [25], [44] • *Ethical responsibilities of the planner/workplace designer [45] • *Modes of instructing human/robot collaboration [45]
	Communi-cative Tasks	Instructing the robot	• Mode of (human) communication (language, motions and gestures) [12], [43], [46]–[48] • Intuitiveness of instruction form [24], [49], [50]
		Bidirectional communication between human and robot	• Degree of shared situational understanding between human and robot [5], [6], [8], [10], [14], [29], [30], [48], [50], [51] • Degree of instructions or recommendations given by robots [10], [29], [52] • Modes of bidirectional communication—auditory, text, visual and tactile [5], [13], [53]
	Digital Tasks	System design	• Types of design tasks [54]
		Programming	• Complexity of programming tasks [49] • Types of programming tasks [8], [20], [54], [55] • Quality of programming [41]
		Maintenance	• Type of maintenance tasks [16], [19], [20], [54], [55]
		Data handling	• Complexity of analytical tasks [11], [56]
Orga	Jobs and Roles	Number of jobs	• Level of job replacement or creation [18], [19], [26], [27], [44], [59], [69], [71]–[80]

			• Balance between different job types [8], [44], [54], [59], [74], [81]–[83]
		Types of jobs	• Characteristics of roles and jobs [18], [54], [56], [73], [78], [81], [84], [85] • Level of re-configurability of worker [36] • Level of responsibility [13], [25], [44], [73], [86] • Level of task diversity [60], [73]
		Skill requirements	• Level of technical skill needed to work with robots [22], [35], [49], [52], [55], [56], [72], [80], [85], [86] • Level of physical skill required for certain jobs [87] • Level of cognitive skill required for certain jobs [54], [62], [86] • Level of flexibility and adaptability required [23], [65] • Complexity of skill profile for individual jobs [27], [28], [50] • Efficiency of use of available skills [22]
	Working conditions	Working conditions	• Salary levels [76], [77], [79], [80], [82], [86] • Work hours (duration/time of day) [25], [44], [75] • Work tenure/employment duration [77]
Worker	Physical experience	Physical strain and health risks	• Ergonomics of workplace [17], [30], [34], [35] • Level of musculoskeletal strain [10], [15], [43], [57], [58] • Exposure to health hazards [13], [22], [31], [32]
		Risk of injury	• Number of accidents/fatalities [16], [33], [37], [39]–[42], [59], [60] • Types of accidents [28], [31], [39] • Sources of accidents [33], [38], [50], [51], [61]
	Affective experience	Emotional perception of the workplace	• Perceived safety or (dis)trust in a robotised environment [8], [19], [24], [50], [51], [59], [62]–[64] • Subjective experience of sensory impulses related to robot technology [53] • Workplace satisfaction, motivation and happiness [21], [22], [25], [42], [64]–[68] • Level of stress or cognitive load [13], [51], [63], [66]
		Anticipation of a robotised workspace	• Job loss anxiety [22], [64], [65], [67], [69] • Resistance to change [22], [25] • Attitude towards robotisation [25], [69], [70]
		Experience of relationships at work	• Quality of social relationships at work [50] • Level of interaction with co-workers [4], [66]
Environment	Supply/demand of labour		• Labour supply [21], [52], [80] • Relative power of the worker/worker groups [27], [54], [68]
	Demographics		• Age [24], [43], [87] • Skill level of workforce [27], [76] • Migration background [76] • Gender [73], [76]

	• Industry experience [77]
Labour laws	• Cost of labour [74] • Safety regulations and responsibilities [61] • Strength of labour protection laws and labour unions [22], [27], [59], [72], [75], [80]
Economic conditions	• Trends for outsourcing of labour [74] • Robot friendliness of national policy [69]

Table 2. Examples of patterns of interactions between themes

Communicating Dimensions	***Patterns from the literature on interactions between dimensions***
Technology and Work	• Features of robot technology *change* the distribution of manual labour (physical tasks). • Features of robot technology *create* new possibilities (affordances) for executing work through robot–human collaboration. • Robot technology *creates* specific new tasks (digital, communicative and coordinative) related to working with the technology. • Robot technology *affects* residual physical tasks. • The type of physical task *affects* the choice of robot technology.
Worker and Organisation of Labour	• Particular job/role profiles *influence* workers' identity and perceived self-value. • Reduced human presence in the workplace *affects* social relationships and consequently well-being. • Increased job responsibilities *affect* affective experience (enriching or stressful).
Work and Organisation of Labour	• Shifts in task distribution *change* role and job profiles and skill requirements. • Novel coordinative and communicative tasks *change* physical, cognitive or experiential requirements for specific roles. • Novel coordinative tasks at the worker level *affect the* importance of mid-level management. • New digital tasks *create* new job profiles.
Work and Worker	• The distribution and nature of physical work between humans and robots *affects* the physical experience (accident risks and musculoskeletal strain). • Type and pace of tasks allocated *affect* experienced stress or cognitive load, with an effect on the quality of task execution. • Nature of tasks *affects* the affective experience (satisfaction, self-worth, boredom, etc.).
Technology and Organisation of Work	• Choice of technology *influences* the need for new technically oriented jobs and positions. • Technology replacing manual workers *creates* new responsibilities for managerial/supervising roles. • Choice of technology *influences* skills necessary to do certain jobs (knowledge, physical capabilities, etc.). • Choice of technology *influences* appropriate work organisation to ensure safe and healthy work conditions.
Technology and Worker	• Robots' behaviour and presence *influence* the subjective feeling of safety. • Anticipation of the effects of robot technology on individual work *impact* individual well-being. • Design and choice of technology *affect* physical well-being through (more/less) physical strain.

	• Involvement of employees in technology design *reduces* negative affective experiences.
Environment and Worker	• Perceived or actual shifts in labour market structures and pressures from the labour market *create* affective reactions. • Opportunities in the labour market for particularly skilled workers *affect* their attachment to the current workplace.
Environment and Organisation of Labour	• Labour law *frames* possibilities for the organisation of labour. • The availability (and costs) of adequately skilled workers in the labour market *affects the* need for internal up-skilling efforts. • Degree of robotisation in the industrial sector *affects* working conditions (average pay, etc.).
Environment and Technology	• Market influences or policy *incentivise* the use of specific technologies. • Availability, complexity and costs of technology (and its operation) *influence* the economic viability of specific technologies.
Environment and Work	• Safety regulations and labour law *guide* how work can be executed in a robotised environment. • Cost and availability of labour *influence* the economic viability of the automation of certain tasks and decisions on how to reallocate physical tasks between humans and robots.