Zooming in on the Impact of Collaborative Robot Arms in Manufacturing Workplaces:

A Comparative Case Study

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Abstract

Collaborative robot arms (cobots) are gaining a strong foothold in contemporary manufacturing workplaces. While more information about the cobot's impact becomes available, crucial design, work perception, performance, and strategic implications are systematically overlooked. Following a modern sociotechnical systems design theory (MSTS) perspective, which lies at the heart of workplace innovation literature, we studied if, how, and why the cobot made production units more resilient and strategically relevant. We ran a comparative case study involving 15 Dutch small- and medium-sized manufacturing enterprises (SMEs) and 36 interviewees (managers and operators). The results describe how the cobots are designed as autonomous and rigid mini-robots, handling one or a few high-quantity products in ways that are not inherently more reliable and efficient. Operators interacting with the cobots experience stronger motivational work characteristics, but the cobot's autonomous and stable operation also provokes classic out-of-the-loop problems. Consequently, cobot-equipped production units do not always perform better. Nonetheless, SMEs deem their units strategically relevant since they (indirectly) improve financial flexibility, increase production capacity, streamline future automation projects, and accommodate the resolution of labor scarcity issues. This research creates a pathway for more MSTS and workplace innovation research at the crossroads of human-robot interaction, organisational design, production management, applied psychology, and entrepreneurship. Practical implications are provided and discussed elaborately.

Keywords: Modern sociotechnical systems, workplace innovation, collaborative robots, future of work, comparative case study, small- and medium-sized enterprises, industry 5.0

Introduction

Rising labor shortages (European Labour Authority, 2022), high and diversifying customer demands (Pech et al., 2022), an ageing workforce (European Commission, 2023), and the Industry 5.0 policy agenda (European Commission, 2021) are just four of many external developments requiring manufacturers in Western Europe to produce more and more diverse products with fewer operators. Consequently, manufacturers must continuously increase the resilience of their production units to ensure sufficient output is generated to meet customers' demands (Romero et al., 2021). Increasing production unit resilience is a strategic issue since it affects the manufacturer's maximum production capacity. The ability to satisfy customer demands quickly and effectively is a crucial source of competitive advantage in manufacturing (Daugherty et al., 1992; Sullivan et al., 1999; Alqershi et al., 2020).

Adaptive production technologies that directly interact with and support the operator bear great potential to improve the resilience of labor-intensive production units sustainably. These technologies include pick-to-light systems that guide assembly tasks (Hercog et al., 2022), augmented reality smart glasses that project work instructions (Danielsson et al., 2020), and smart apps connected to the Industrial Internet of Things that enhance more informed decision-making (Muriathinam, 2020). However, the technical complexity of these technologies makes applying and changing them complex, lengthy, and costly activities (Bajic et al., 2020; Stentoft et al., 2021; Sony et al., 2021). This is particularly problematic for small- and medium-sized manufacturing enterprises (SMEs) that, in contrast to large manufacturers, have fewer financial and (specialised) human resources to invest in automation initiatives (Prajogo et al., 2014; Indrawati, 2020; Estensoro et al., 2022). Fortunately, adaptive production technologies are available and highly accessible to SMEs. The collaborative robot arm (cobot) is one of them.

Like a traditional industrial robot, the cobot can be equipped with a broad range of tools and used for many tasks, such as welding, packing, assembling, drilling, inspecting, and machine (un)loading (Bauer et al., 2016; Kadir et al., 2018; El Makrini et al., 2018; Salunkhe et al., 2019; Wolffgramm et al., 2021). However, the cobot is considered easier to use, faster to (re)deploy, safe for direct interaction with operators, and more affordable (Hentout et al., 2019; Sherwani et al., 2020; Javaid et al., 2022). These features are relevant for SMEs since they could increase production unit resilience while demanding limited resources. More specifically, the cobot's reach, payload, and speed require, depending on the application and human-robot interaction, fewer safety-related investments, such as cages and external sensors (Bi et al., 2021). Lower safety-related investment saves on purchasing costs, but also on floor space. Moreover, given the user-friendliness of the cobot's hardware and software (El Zaatari et al., 2019), there is a higher chance that SMEs can swiftly (re)program the cobot without the help of expensive consultants. In other words, the cobot appears to be a promising investment object for SMEs to increase production unit resilience radically. Unfortunately, in line with Cohen et al. (2021), "the cobot literature has been quite blurred when it comes to the justification for the acquisition, installation, and deployment of cobots" (p. 15).

As attested by many literature reviews, considerable scholarly attention has indeed been paid to cobot's interaction with the operator and its impact (e.g., Wang et al., 2019; Cardoso et al., 2021; Gualtierl et al., 2021; Javaid et al., 2022; Liu et al., 2022; Faccio et al., 2023). These impacts could be roughly divided into two categories. The first category concerns the impacts of cobots on human factor outcomes, including physical ergonomics, mental workload, trust, acceptance, and usability (Rücker et al., 2018; Gervasi et al., 2020). The second category encompasses cobot-related impacts on performance outcomes at the production unit level (e.g., productivity, task completion time, error rates, and quality [Matheson et al., 2019]) or at the production system level (e.g., flexibility, reconfigurability, and agility [Faccio et al., 2023]). While the available empirical evidence provides an impression of the cobot's deployment and impact, we note that the current knowledge base fails to describe how the cobot affects production unit resilience and what organisational significance this impact holds. Arguing from a modern sociotechnical systems design theory (MSTS) viewpoint (de Sitter et al., 1997; Kuipers et al., 2020), centrally positioned in workplace innovation literature (Oeij et al., 2023) and concerned with aligning technical and social subsystems for sustainable and robust production, a cobot is a *workplace innovation* that requires more scholarly attention. We provide three reasons.

Firstly, information about the task allocation between the operator and the cobot and their mutual reliance, or interdependence, is limited to a functional approach (i.e., who does what? [Sheridan et al., 1978; Onnasch et al., 2014]). The classification by Bauer et al. (2016) or a familiar buildup is often used to classify the human-cobot interdependence based on whether they share the same workplace and how simultaneously they work on the product (e.g., Segura et al., 2021; Dornelles et al., 2023). Such a classification gives an impression of how the human-cobot production unit is designed, but it leaves out important details about the alignment of the operator's and cobot's capacities (i.e., are the operator and the cobot mutually strengthening each other? [Johnson, 2014; Wolffgramm et al., 2024]). Moreover, there is uncertainty about the product quantities and variations that the operator and the cobot, as a production unit, are supposed to handle (i.e., their functional requirements). It is particularly unclear whether these requirements differ from those of the production unit's 'previous version' (e.g., when the operator still had to execute all tasks manually). The lack of empirical evidence about the human-cobot interdependencies' functional requirements and capacity alignment is problematic since it leads to incomplete descriptions and suboptimal explanations about their impact on human factors and performance outcomes.

Secondly, important aspects of the operator's work perception are systematically understudied. Baltrusch et al. (2022) and Shaba et al. (2024) are the only ones we are aware of who conducted a literature review to clarify the link between cobot deployment and the operator's job quality (i.e., the quality of the working environment related to the operator's well-being). Even though some or neighbouring elements were mentioned, such as autonomy, trust, and awareness, they clearly illustrated that there is no research available that extensively reports the cobot's impact on how the operator perceives its job design (i.e., the contents, methods, and relationships of jobs [Armstrong, 2001]). Moreover, cobot literature overlooks whether the operator shows out-of-the-loop symptoms when working with the cobot (i.e., implications related to the operator's removal from the control loop [Kaber et al., 1997]). These work perception insights are crucial since they both indicate whether the operator can sustain the human-cobot interdependence over time. The quality and continuity of the operator's input have considerable consequences for the performance of the human-cobot production unit and, thus, its resilience.

Thirdly, we noticed a blind spot for the cobot's strategic impact. While some scholars have highlighted the cobot's macroeconomic relevance, none of them have studied it directly (Kadir et al., 2019; Knudsen et al., 2020). Moreover, a recent literature review by Liu et al. (2022) identified 59 future research opportunities in cobot-related studies. None of these studies suggested investigating the cobot's strategic contributions. We find the same in other literature reviews (Matheson et al., 2019; Hentout et al., 2019; Sordan et al., 2021; Baltrusch et al., 2022). Vido et al. (2020) seemed an exception to this as they actively studied the impact of cobots on competitive priorities. Nonetheless, their work was limited to the operational phenomena after all. Thus, as far as we know, no academic effort has yet been directed towards clarifying the cobot's strategic impact. One concept that is likely to be influenced by the resilience of the human-cobot production unit is the SME's strategic flexibility. In line with Brozovic (2018), strategic flexibility is commonly defined as "the degree to which a firm is willing to change its strategy in response to opportunities, threats, and changes in the external environment" (Zahra et al., 2008, pp. 1043-1044).

These three shortcomings concerning the cobot's operational and strategic impact have profound implications for SMEs considering investment in cobot technology, as well as those that have already made such an investment. For SMEs that want to invest in cobot technology, it is unclear whether the design of documented human-cobot interdependencies comes with an acceptable and sustainable alignment between operator and cobot capacities. Moreover, they are uninformed about the outcomes generated by these human-cobot production units, how these outcomes differ from previous production units, and what they contribute to the SME's strategic flexibility. Consequently, SMEs might invest their scarce resources in an asset that cannot meet their operational and/or strategic expectations. For SMEs that have already invested in the cobot technology, there is no exemplary work that allows them to benchmark their cobots' impact extensively. These SMEs might unknowingly accommodate a human-cobot production unit that comes with a much lower impact than expected. To guide their (re)design efforts, both SME types benefit from rich examples of human-cobot production units that, ideally, come with more resilience and a convincing contribution to strategic flexibility. The rising cobot sales

(International Federation of Robotics, 2023) indicates a high market interest in the cobot technology, stressing the societal importance of studying the cobot's operational and strategic impact more extensively.

This research aims to *describe the cobot's (in)direct impact on four areas: the human-cobot interdependencies' functional requirements and task execution, the operator's work perceptions, the production unit's performance, and the SME's strategic flexibility*. To achieve this aim, the following research question has been formulated: *What is the cobot's impact on the design, sustainability, and performance of the production unit, and what do these impacts mean for SME's strategic flexibility?*

Given its broad thematic scope, this research benefits from a multidisciplinary research approach that uniquely combines literature from MSTS, operations management, human-robot interaction, applied psychology, and entrepreneurship. This research has three other remarkable characteristics. Firstly, it occurs at both the operational and strategic levels. Secondly, it simultaneously studies four potential cobot impacts that are systematically overlooked in cobot literature. Thirdly, human-cobot interdependencies are studied from both a task allocation and capacity alignment viewpoint. In addition to the empirical contributions to the existing literature streams, this research directly responds to calls for more MSTS-related research in contemporary work contexts (Parker et al., 2022; Govers et al., 2023; Guest et al., 2022; Oeij et al., 2023). This response is important since it will strengthen the empirical underpinnings of the workplace innovation design theory, making it more observable, convincing, and ready to become the dominant design method.

Theoretical Background

We will theoretically illustrate the four impact areas in consecutive order (i.e., human-cobot interdependence, work perceptions, performance, and strategic flexibility).

Human-Cobot Interdependence

Human-cobot interdependence originates from human-machine interaction literature (Fitts et al., 1951) and later adaptations made by human-robot interaction scholars such as Johnson (2014). We follow Clark's definition (1996), which states that (task) independence occurs when two parties mutually rely upon each other to complete several actions. The production unit's functional requirements strongly dictate the design of the human-cobot interdependence.

Every production unit must meet certain functional requirements (Yasuhara et al., 1980) or, in MSTS terms, requisite variety (Ashby, 1956). These requirements prescribe what products the unit must produce, at what quantity, and against which specifications (e.g., quality standards, just-in-time, and first-time-right). *We expect a human-cobot production unit to face higher functional requirements than the previous version of this production unit* because the cobot can accommodate the fulfilment of increasingly complex functional requirements. As illustrated in the hierarchical task analysis literature (Annett, 2003), specific tasks must be executed to meet these requirements. How these tasks are divided between the operator and the cobot is essential for designing the human-cobot interdependence. Not only do these task allocations direct what the operator and the cobot will do, but they also determine how they will interact with each other and whether their joint efforts will result in superior task execution compared to that of the previous production unit. The latter is, thus, dependent on the *alignment* of operator and cobot capacities.

In line with the classical theory of function allocation by Fitts et al. (1951) and later reconfirmation by De Winter et al. (2014), the operator and the cobot have unique capacities and opposite shortcomings. Norman (2015) found that the operator is generally good at recognising patterns, coping with unexpected situations, and defining high-level goals. However, the operator cannot execute highly repetitive and high-precision tasks or stay alert for long. The latter are the core capacities of the cobot (Djuric et al., 2016; Taesi et al., 2023). The cobot can reliably handle highly repetitive and precise tasks. In line with the irony or fallacy of automation, the cobot's application is as robust as the variation it is programmed for (Bainbridge, 1983; Johnson, 2014; Hancke, 2020). This means that cobot will not function if it must do something unfamiliar (e.g., handling a new product type or resolving an unknown error). In such situations, the cobot requires human flexibility and intelligence to adapt to new variations and remain functional (e.g., by modifying the cobot application, writing a new application, or performing the task manually). The alignment of operator and cobot capacities characterizes the human-cobot interdependence and illustrates the unity between the technical and social subsystems in MSTS (de Sitter et al., 1997).

According to Johnson (2014), two types of task interdependencies illustrate the complementarity between the most capable actor (i.e., the performer) and the assisting actor (i.e., the supporter). The first type concerns hard task interdependencies. These are interdependencies where the performer cannot execute the task without the supporter's assistance (e.g., due to mental and/or physical limitations). The second type captures soft task interdependencies. These interdependencies enable the performer to execute tasks more reliably or efficiently (e.g., by reducing errors or handling time). Recent work by Wolffgramm et al. (2024) built further on Johnson's (2014) taxonomy. They claimed that one task interdependence could be both reliability- and efficiency-enhancing, and they introduced the negative task interdependence (Tjosvold, 1986). This interdependence occurs if the performer receives assistance that does not result in more, better, or faster task execution. Thus, whether the human-cobot interdependence captures mostly hard, soft, or negative task interdependencies depends on how the tasks between the operator and cobot are divided and who is considered the performer and the supporter. Since the operator's capacities are likely higher than those of the cobot, this research considers the operator the performer and the cobot the supporter. Given the optimistic field results (Liu et al., 2022), *we expect that human-cobot interdependencies in manufacturing practice are primarily based on hard and soft task interdependencies*.

Work Perceptions

Quality of working life plays a crucial role in MSTS (de Sitter et al., 1997; Kuipers et al., 2020). Based on the design of the human-cobot interdependence, the operator will obtain new tasks, share some tasks with the cobot, or lose some tasks to the cobot. Two applied psychology literature streams stress that these changes could drastically impact the operator's "subjective experience and perception of work" (i.e., work perceptions [Kobasa et al., 1982, p. 25]).

Work Design Perceptions

The first stream focuses on the operator's work design and captures the "content and organisation of one's work tasks, activities, relationships and responsibilities" (Parker, 2014, p. 662). Earlier work design research has shown that individuals can only sustain their work design if certain quality criteria are met (Hackman et al., 1976). These criteria, also referred to as work design characteristics (Morgeson et al., 2006), relate to the job content (i.e., motivational characteristics), human interaction with internal or external others (i.e., social characteristics), and the environment (i.e., work context characteristics) – since this research focusses on the interdependence between individual operators and a mechanical actor in a specific work setting, we will focus exclusively on the motivational characteristics.

Morgeson et al. (2006) provide the most comprehensive overview of motivational characteristics. They listed 12 characteristics and their definitions. Humphrey et al. (2007) used these motivational characteristics in an effect study and showed how these characteristics contribute to more individual performance and help the operator stay satisfied, healthy, and committed. Two studies have shown that the use of cobots affects motivational characteristics. Berkers et al. (2023) studied cobot applications in logistic warehouses and reported positive and negative developments in the operators' task variety and autonomy. Similar findings were reported by Wolffgramm et al. (2021) for operators in the manufacturing industry. The latter also found that operators' job complexity changed.

We expect human-cobot interdependencies with mostly hard and soft task interdependencies will result in a stronger perception of the motivational characteristics by the operator. In such instances, the cobot provides relevant support to the operator, making it easier for them to cope with work-related demands and creating opportunities to focus on tasks that align with personal working preferences. Opposite outcomes are expected for human-cobot production units with mostly negative task interdependencies.

Operator-Out-of-the-Loop

The second applied psychology literature stream focuses on how technology deployment affects the operator's cognitive alertness or the extent to which the operator is placed out of the control loop (Gouraud et al., 2018). Decades of research on operator-out-of-the-loop situations have been devoted to understanding what happens when the operator shares their task with reliable technological equipment, such as an autopilot (Endsley et al., 1995). Their results showed that if the technology takes over too many or too essential tasks, it will cause alertness problems for the operator (Kaber et al., 1997). On the one hand, the operator's situation awareness will decrease. This means that the operator has problems collecting relevant info about the work system's status, interpreting these data, and predicting the system's future state (Endsley et al., 2000). On the other hand, the operator might rely too much on the cobot's reliability and become complacent towards potential system failures (i.e., automation-induced complacency [Parasuraman et al., 1993]). In either case, if the system fails, it will take the operator longer to notice the malfunction, identify the issue, and resolve it (Onnasch et al., 2014; Agnisarman et al., 2019).

Relying on operator-out-of-the-loop theory, *we expect that human-cobot interdependencies comprising hard and soft task interdependencies come with at least a similar situation awareness compared to the previous production unit and a critical stance* towards the cobot's functioning. We expect this because a human-cobot interdependence with mostly hard and soft task interdependencies does not unnecessarily take over (important) tasks from the operator. The limited takeover will likely minimise situation awareness and automation-induced complacency risks since the operator still plays a considerable role in the task execution process. Ideally, such human-cobot interdependence generates sufficient information about the situation, giving the operator enough time to perceive the cobot's risks and nuance its flawlessness (Simon et al., 2023).

Performance

As mentioned in the Human-Cobot Interdependence subsection, task interdependencies could be hard, soft, or negative. Each type of task interdependence has different consequences for the production unit's task execution. Hard interdependencies will result in more task completion, soft interdependencies in more task reliability and/or efficiency, and negative interdependencies will result in less reliable and/or efficient task execution. Given the link between task reliability and production reliability (He et al., 2018) and between task efficiency and productivity (Vatne et al., 2016), we select production reliability and productivity as the unit performance measures under study. Production reliability is "the probability that a system, component, or part will operate satisfactorily for a specified period of time under specified operating conditions" (Eaton, 2004, p. 1), expressed in the number of rejects. Productivity is defined as the ratio of output to input for a specific production situation" (Rogers, 1998, p. 5), relating to the time needed to handle a series of products.

The design of the human-cobot interdependence and its sustainability likely influence the production unit's performance. Therefore, *we expect that the human-cobot production unit exceeds the production reliability and/or productivity outcomes of the previous production unit if two conditions are met*: 1) the human-cobot interdependence captures *primarily hard and soft interdependencies* and 2) the operator's *work perceptions are acceptable* (i.e., at least similar work design and situation awareness perceptions, and a nuanced automation-induced complacency). Inspired by Alexopoulos et al. (2022) and MSTS notion of designing sociotechnical systems that sustainably meet the requisite variety (Ashby, 1956; de Sitter et al., 1997), we consider a human-cobot production unit increasingly resilient if it 1) processes more functional requirements, 2) has acceptable work perceptions, and 3) achieves higher performance than the previous unit.

Strategic Flexibility

The strategic flexibility concept is deeply rooted in strategic management and entrepreneurship literature. In line with the dynamic capabilities approach, based on the notion that there are organisational "processes that use resources … to match and even create market challenges" (Eisenhardt et al., 2000, p. 1107), strategic flexibility is a process related to the organisation's absorption capacity (Sanchez, 1995; Volberda, 1997; Tu et al., 2006). It is based on the premise that organisations with high strategic flexibility can better and more proactively respond to developments in the external environment, as they have more alternative internal or external courses of action or strategic options to choose from (Sanchez, 1995; Herhausen et al., 2014).

Barringer et al. (1999) specified nine types of such external developments: the emergence of new technology, a shift in economic conditions, the market entry of new competition, a change in government regulation, a shift in customer needs and preferences, a modification in supplier strategies, an unexpected opportunity, an unexpected threat, and a relevant political development. Accurately responding to external developments is an important source of competitive advantage (Hitt et al., 1998; Harrigan, 2017). It improves financial performance (Combe, 2012; Verdú-Jover et al., 2014) and increases organisational adaptability in ways difficult to mimic by others (Zhang, 2005; Nandakumar et al., 2014).

Strategic flexibility holds a close resemblance to the resource-based view (Mahoney et al., 1992), claiming that competitive advantage can be created by acquiring, developing, and deploying unique (combinations) of elements (Connor, 2002). An organisation's strategic flexibility, or the set of strategic options, is determined by the flexibility of available resources and the coordination of these resources. Resources are increasingly flexible when they can be used in alternative ways, at lower costs with less effort, and in a shorter time (Combs et al., 2011). Possessing or having access to flexible resources is necessary, but they must be actively coordinated to become a strategic option (Li et al., 2017). To illustrate, if an SME has a highly flexible cobot but only uses it for one product and cannot redeploy it, then the flexible cobot, as a resource, is not a flexible resource after all. According to Sanchez (1997), such 'coordination flexibility' redefines what the resource will be used for in the new situation, mobilises all prerequisites to make the resource usable for its new purpose, and assures that the organisational structure can absorb the repurposed resource. Higher coordination flexibility allows for a more cost-effective mobilisation of the resource, thus improving strategic flexibility if that the resource is flexible (Yuan et al., 2010; Han et al., 2021).

We expect more resilient human-cobot production units to increase the SME's strategic flexibility more extensively. As mentioned before, such units handle more functional requirements at acceptable work perceptions and similar or even better unit performance. SMEs with resilient human-cobot production units will likely benefit strategically from their operational contribution. Our link between production unit resilience and strategic flexibility is based on the premise that the human-cobot production unit has all the features of a flexible resource (i.e., multifunctional, adjustable and cost-efficient). If the unit is resilient, it is likely to meet the coordination flexibility criteria, resulting in one or more strategic options that increase the SME's strategic flexibility.

Summary

To summarise this theoretical background, our research focuses on investigating whether using a cobot in SME manufacturing: 1) results in the design of human-cobot interdependencies with primarily hard and soft task interdependencies that handle more functional requirements; 2) accommodates acceptable work perceptions; 3) enables higher performance; and 4) provides a substantial contribution to the SME's strategic flexibility.

Method

We adopt a comparative case study approach to richly and more extensively study the cobot's impact in the areas of interest. As defined by Kaarbo et al. (1999), "a comparative case study is the systematic comparison of two or more data points ('cases') obtained through use of the case study method" (p.372) … "with the purpose of examing hypotheses as critically and systematically as possible" (p. 377). As for multiple case studies, comparative case studies produce strong and reliable evidence since they richly illustrate how the phenomena under study behave in different situations (Baxter et al., 2008). According to Gustafsson (2017), such evidence stimulates the creation of a more substantial, and thus convincing, theory. This section specifies the sample, the data collection techniques, and the data analysis procedure.

Sample

The manufacturing sector suits this research. Many cobot applications have been reported in this sector (see Segura et al. [2021] for a comprehensive overview). To enhance the comparability between cases and harmonise the demographic, economic, political, and legal context in which these cases are embedded, we study manufacturing SMEs located in the same country (Stake, 2013). Previous work has shown that Dutch manufacturing SMEs use cobots in their production system (Wolffgramm et al., 2021). Therefore, this method also focuses on these SMEs.

A convenience sampling strategy was applied (Etikan et al., 2016). We started with an internet search to list down manufacturing SMEs with likely a cobot in their production system. In total, 29 manufacturing SMEs were listed. Each SME had to meet three criteria to participate in this study. These criteria were formulated to ensure that the data collection would be based on functional applications, involve informants with sufficient cobot-related experience, and allow a comparison with the previous version of the human-cobot production unit. The first criterion was that the cobot was implemented in the production system – lab and demo applications resulted in immediate exclusion. The second criterion was that the cobot had to be operational for at least six months. The third criterion was that the informants could recall the state of the production unit before the cobot's implementation (i.e., the previous production unit). After verifying the criteria with the SMEs' spokespersons and based on their availability, 15 SMEs participated in this research. Information about the SMEs is embedded in Table 1. The participating SMEs produce a wide variety of (mostly metal) products, employ roughly 7 to 140 employees, and have a functional cobot in their production system for half a year up to six years – most of the studied cobots were Universal Robots type 10.

Since this research spans both operational and strategic levels, we included two types of workers per SME. The first type captures operational workers directly interacting with the cobot, such as machine operators, work organisers, and inspectors (i.e., operators). The second type comprises managerial workers responsible for the SME's operations management and functioning strategically, such as operational directors, manager-owners, and production leaders (i.e., managers).

Table 1: Characteristics of the SME Sample Under Study (Number of Cases = 15)

SME	Core Business	Estimated Number of Employees	Cobot Type	Approximate Cobot Use in Production
A	Producing gears	65	Universal Robot 10	1.5 years
B	Producing ship doors and windows	105	Universal Robot (n/a)	.5 years
C	Producing hinges	22	Universal Robot 10	3.5 years
D	Producing wooden objects	85	Universal Robot 10	2 years
E	Producing electricity cables	130	Universal Robot 10	.5 years
F	Producing metal projects	70	Universal Robot 10	3 years
G	Producing aluminium products	140	Universal Robot 3	4 years

H	Producing plastic products	8	Universal Robot 10	6 years
I	Turning and milling bike axles	7	Techman 12	3 years
J	Assembling electrical components	130	Universal Robot 5	4 years
K	Producing sheet metal products	90	Universal Robot (n/a)	1 year
L	Producing bent pipes	75	Techman (n/a)	1 year
M	Producing metal products	10	Universal Robot 10	1.5 years
N	Producing sheet metal products	25	Universal Robot 10	1 year
O	Producing sheet metal products	100	Universal Robot 10	.5 year

To obtain valid data, both worker types had to be able to reproduce the state of the previous production unit. Operators had to recall how they behaved and perceived their work and needed sufficient working experience with the cobot. Managers had to be capable of reproducing how the previous unit performed and how strategic decisions were taken back then. They also had to be familiar with the human-cobot production unit's current performance and the SME's current strategizing process. The managers from SME B and SME G and one operator from SME B and SME H were not employed in their current function before the cobot was used. These respondents relied on internal information to illustrate the previous production unit and the strategizing process.

Spokespersons were often the managers who were later included in the sample or introduced via a human resource practitioner. The managers introduced us to their operators, who met our sampling criteria. In total, 16 strategic and 20 operational workers participated in this study – two foremen were placed in the manager or operator group depending on their involvement in the SME's strategising process. Most interviewees were male (±91 %), had obtained their highest degree at a community college (±70 %), and had worked between 4 months and 32 years in their current job. The following subsection describes how these individuals participated in the data collection. An overview of the sample characteristics is available upon request.

Data Collection

Since the impact areas and underlying concepts of interest were clear, we conducted semi-structured interviews (Kallio et al., 2016) with managers and their operators. The main advantages of such interviews are that they enable the interviewer to ask specific yet open-ended questions, obtain rich responses, and provide an opportunity to ask follow-up questions (Adams, 2015). The latter is a welcome feature, as it enriches the interviewee's response and allows the researcher to gain a deeper understanding of their thoughts, feelings, and motivations (Lambert et al., 2008). Such richness contributes to understanding the 'why' behind the cobot's impact.

Based on our theoretical framework, we developed two interview protocols. We had to develop two protocols because some of the concepts under study are tied to the experiences of a specific respondent type. To illustrate, it makes no sense to ask strategic workers how their operators' work perceptions have changed, as these are highly personal. Moreover, operational workers are not the ideal informants to answer questions about the cobot's strategic relevance , as they are barely involved in the SME's strategising process. The full protocols, in Dutch and English, are available upon request. Managers were asked about the human-cobot production unit's location, operational use, functional requirements, performance, and strategic relevance. Operators were asked about the production unit's task execution, their perceived change in motivational characteristics and monitoring behaviors, the cobot's shortcomings and their trust in the cobot. A simple conversation tool has been developed to help the operator indicate eventual changes in its motivational characteristics. These characteristics and their definition were printed on separate cards, and a three-column table was laid out. The operator had to position each card in one of three columns (i.e., increased, decreased, or did not change) and explain its placement. This tool is included in the protocol.

The interviews were conducted in Dutch. Interviewees were informed that their data would be processed anonymously. Permission to be recorded was requested prior to the interview. Most interviews were conducted individually (i.e., 18 with operators and 16 with managers). Unfortunately, due to the limited availability of some interviewees, two out of 36 interviews were conducted in pairs. One of them was conducted with two operators in SME K and one with an operator and a manager in SME L. During the interviews, attempts were made to include both interviewees by directing specific questions to both and, especially during the duo interview with both the operator and the manager, critical follow-up questions were asked to minimise socially desirable responding (Frey et al., 1991).

Data Analysis

All interviews were transcribed verbatim and imported into ATLAS.ti (version 22). Given the predetermined concepts, a deductive coding approach was used. Following the six stages of data coding by Fereday et al. (2006), we first developed a code manual with theory-driven (sub)labels, definitions, and descriptions (i.e., coding rules). This manual is available upon request. Secondly, we tested the reliability of the codes by having four graduating bachelor students knowledgeable about the concepts under study apply the code manual to the interview data from multiple SMEs. Thirdly, the students summarised their findings per SME and were able to report specific similarities and differences between the cases. Based on the students' feedback and findings, the first author concluded that the manual was ready to use and that no modifications were necessary. Fourthly, the first author manually applied the pre-tested labels from the code manual to all interview data. A label was attached to a quotation if it met the description. For instance, "Now you also program a little instead of welding all the time" (SME N, Operator 2) was labelled as 'operator tasks' since the text mentioned an operator-related activity. In total, 1508 quotations were coded. The second and third authors have reviewed the quotations. In line with Fereday et al. (2006) and Boyatzis (1998), six labels, different from those in the code manual, surfaced during the data analysis process (i.e., facilitating conditions [62 quotations], external developments [56 quotations], operator capabilities [26 quotations], cobot capacities [17 quotations], job decision latitudes [5 quotations], and ergonomics [5 quotations]). These data-driven labels were added to the code manual. Fifthly, a case description was made for each case. In these descriptions, the concepts under study were expressed using the coded data, making similarities and differences between cases obvious. Sixthly, we created a schematic overview capturing the cases and concepts under study to confirm these patterns and convincingly visualise them. We declared for each concept whether it applied to the case or how it developed. The overview is part of the Results section. The contents of the overview and descriptions were used to verify our expectations. A ranking rule was applied to segment SMEs based on the resilience of their human-cobot production unit. We also illustrate this rule in the Results section.

Results

In this section, six results are presented. Firstly, we describe the design of the human-cobot interdependencies with explicit attention to the production unit's functional requirement and the type of task interdependencies. Secondly, we illustrate the cobot's impact on the operator's work perceptions. Thirdly, we focus on developments in the performance of the production units. Fourthly, we rank the SMEs' human-cobot production units based on their resilient attributes. Fifthly, we reveal the human-cobot production unit's presumed impact on strategic flexibility and how this impact differs per rank. Sixthly, we show an integrated overview of the core insights per case.

Human-Cobot Interdependence Design

Seven cobot applications were encountered. The first, found in SMEs B, F, K, and M-O, concerned welding cobots. These cobots would apply one or more weld seams to a clamped item. The second, found in SMEs A, D, I, and L, were cobots used for loading and unloading industrial machinery by picking and placing items in and out of the machine and communicating with the machine. The third was a cobot used at SME C for picking products, spraying them with a greasy substance, and placing them in a bin. The fourth was a cobot used at SME E for inspecting items by placing them in a testing station and then putting them in a bin corresponding to the test results. The fifth was a cobot used at SME G for drilling (screw) holes in items. The sixth was a cobot used at SME H for packing items in boxes. The seventh and final was a cobot used at SME J for assembly tasks, where a piece of glass was picked and placed with high precision.

We found that the functional requirements of the human-cobot production units barely differed from those of the previous production units. To illustrate, no data indicated that the batch sizes of production units changed. The batch size we encountered ranged from 10 to 4000. In seven SMEs, managers explicitly stated that the cobot was used for handling large batches to earn back the cobot's installation costs and establish a return on investment. One manager stressed it as follows:

> *"It all has to do with the cost price. I can produce unmanned [with the cobot] if batch sizes are higher"*
> *(Manager 1, SME D, manages a production unit equipped with an [un]loading cobot).*

Product variety increased in two cases (i.e., SMEs I and K). Two managers mentioned that the cobot allowed them to accept more client orders, which increased the production unit's product variety. Other cases illustrated that product variation was generally low. In SMEs C, E, G, H, L, and O, the cobot was used for one to three different product types. SME J used the cobot for 40 to 50 nearly identical products. SME M used the cobot for 15 different products. The uniqueness of these products remained unclear. Managers from SMEs C, J, and M explicitly mentioned they used their cobots for repeat products (i.e., products that would be ordered again in the foreseeable future). The reason for SMEs to use the cobot for a limited number of (repeat) products seems to be related to the long time they need to reprogram the cobot and the costs of changing the cobot's physical work environment (e.g., new moulds). To illustrate this, one manager mentioned:

> *"Then I have to fully pre-program the cobot again and different types of drawers are needed. You must constantly ask yourself 'is it worth it, is it worth the investment?'. Particularly in terms of time and the investment to modify the drawers. ... Often, the answer is no"*
>
> *(Manager 1, SME B, manages a production unit equipped with a welding cobot).*

From a task allocation viewpoint, all human-cobot interdependencies under study showed a generic sequence. The operator prepared the workstation by positioning the products to be handled by the cobot in fixed spots and created or selected a pre-programmed cobot application – 15 out of 20 operators mentioned they programmed the cobot. Once programmed, the operator configured the cobot's parameters and started the program. After that, the cobot would execute the same highly repetitive and short-cycled tasks with, depending on the application and the available stock, an uptime ranging from five minutes up to ten hours. In the meantime, the operator was responsible for maintaining the cobot. This included monitoring the cobot and, depending on the application, restocking the cobot, removing handled products, troubleshooting the cobot, cleaning the workstation, and replenishing depleted resources (e.g., welding wire). Next to these cobot maintenance tasks, the operator also checked and finished handled products, prepared new tasks (e.g., moulds), processed (small) batches that the cobot could not handle, or assisted colleagues.

One (direct) hard, 13 soft, and nine negative (set of) task interdependencies were found. The hard interdependence was embedded in SME F and relates to a welding task requiring good eyesight. By executing this task, the cobot enabled welders with reduced eyesight to complete the task and handle the remainder of the product. Most soft interdependencies concentrated on SMEs B, F, J, K, M, and N. According to these operators, the cobot handled products with higher task reliability *and* task efficiency than they could. An operator said:

> *"You cannot keep up with the speed and tightness with the cobot for the whole day. Maybe you will manage for the first two products but you will fall behind. You simply cannot keep up with him [the cobot]"*
> *(Operator 1, SME M, operates a welding cobot).*

The other soft interdependencies were reliability-enhancing. The cobot eliminated mistakes operators made due to reduced attention spans in three cases (i.e., SMEs A, G, and H), handled products in a more constant or less wasteful manner in three other cases (i.e., D, E, O), and proactively signalled mistakes made by the operator in one case (i.e., SME L). Zooming in on the negative interdependencies, we found that all machine (un)loadings had a considerable negative interdependence (i.e., SMEs A, D, I, and L). In these cases, the operators estimated their task efficiency higher than that of the cobot – the cobot was deliberately operated at reduced speed in SME D to increase the application's stability. The human-cobot interdependence in SME C also came with a negative interdependence. There, the cobot did grease products, a high-precision task, at a lower task efficiency than the operator. In SMEs E, G, H, and O, the cobot was not faster than the operator in inspecting, packing, or welding products.

In addition to the aforementioned task interdependencies, we identified a spillover effect. In all SMEs, the cobot took over many tasks from the operator. While these takeovers did not always result in more reliable and/or efficient task executions, they did allow the operator to focus on different tasks and even leave the production unit (e.g., going to another unit, getting coffee, taking a lunch break, or going home). The cobot's assistance enables these opportunities and, thus, could be considered a(n indirect) hard task interdependence. An operator formulated the cobot's assistance as follows:

> *"You must imagine that I am constantly at the machine if the batch size is large. ... That time is wasted, so we let the cobot do it. It is not that we cannot do anything without the cobot, but it is like a tool"*
> *(Operator 1, SME H, operates a packing cobot).*

Work Perceptions

Motivational Characteristics

In total, 17 out of 20 operators declared if and how the cobot changed their motivational characteristics. An overview per case can be found in Table 2. We figured that 13 out of 17 operators reported an overall increase in their motivational characteristics. For them, none of the motivational characteristics deteriorated, while some were perceived as stronger. Three other operators, from SMEs D, E, and J, reported that one of their motivational characteristics decreased since using the cobot – because the remainder of their motivational characteristics stayed the same or even increased, we consider their work perception to be both increased and decreased. One operator from SME O considered ten of its motivational characteristics unchanged, while two had decreased. We marked this operator's work perception as decreased.

This overview also gives a good impression of the presumed developments per case and the motivational characteristics. With nine increased motivational characteristics and zero decreases, operators from SMEs D and N (Operator 2) reported the most extensive increase in their motivational characteristics. In line with the previous paragraph, Operator 2 from SME O reported the poorest development in its motivational characteristics. Specialisation, problem-solving, and job complexity were perceived as stronger by 12 or more operators. Feedback from the job remained largely unchanged.

We uncovered and clustered the operators' reasoning behind each development in their motivational characteristics and placed these in Table 3. The overview shows that some operators perceived greater *autonomy* due to the cobot-related decisions they could make regarding when, if, and how to use the cobot. Other operators reported that working with the cobot did not contribute to their already high level of job autonomy. Operators who were new to cobot programming perceived a higher *skill variety*. Perceptions concerning *task variety* strongly depended on whether the operator received extra, different, or fewer tasks to complete. *Significance* intensified if the operator considered itself capable of making a more internal and/or external impact by using the cobot (e.g., increased customer or employee satisfaction). Operators related *task identity* to the overview created by the cobot. On the one hand, the cobot could contribute to streamlining the production unit and make work processes more transparent. On the other hand, the origins of malfunctions became increasingly difficult to trace, making work less transparent.

Feedback from the job increased *on* the rare occasion when the cobot contributed to the operator's support system and resulted in new insights. *Information processing* increased for some operators who had to process the data streams coming with cobot programming, document the cobot's applications, and manage their cobot-related and parallel tasks. Other operators did not experience this or even perceived less information processing due to the digitalisation and incorporation of information in the cobot software. *Job complexity* increased for operators because of the difficulties coming with (re)programming the cobot, developing a functional application, and managing different work demands. Others considered their work already highly complex. One operator reported lower job complexity since the cobot was used to handle the same product, reducing the job complexity it initially had.

Table 2: Overview of Developments in Motivational Characteristics

	SME																		Total		
Characteristic	A	B	C	D	E	F	G	H	I	J	K[1]	L[1]	M[2]		N[2]		O[2]		Incr.	Unch.	Decr,
Work scheduling autonomy							n/a												7	10	0
Work methods autonomy							n/a												9	8	0
Decision-making autonomy							n/a												8	9	0
Skills variety							n/a												11	6	0
Task variety							n/a												9	7	1
Significance							n/a												9	8	0
Task identity							n/a												7	9	1
Feedback from job							n/a												2	15	0
Information processing							n/a												7	8	2
Job complexity							n/a												12	4	1
Specialisation							n/a												15	2	0
Problem-Solving							n/a												14	3	0

Abbreviations: Incr. (increased perceptions); Unch. (unchanged perceptions); Decr. (decreased perceptions); n/a (data not available)
Legend: Green (perception increased); Blue (perception remained unchanged); Red (perception decreased)
1: Only one out of two operators declared its motivational characteristics
2: Column is split since multiple operators declared their motivational characteristics.

Table 3: Arguments for Developments in Motivational Characteristics

Motivation Characteristic	Increased Because:	Unchanged Because:	Decreased Because:
Work scheduling autonomy	Operator can make choices about working on cobot or parallel tasks	Perceived autonomy was already high	-
Work methods autonomy	Operator can choose between manual execution or cobot use		-
Decision-making autonomy	Operator can make more work-related choices due to the cobot		-
Skills variety	Operator needs more skills to program the cobot	The cobot's ease of use requires no extra skills, or operator is experienced	-
Task variety	Operator considers its job to be subjected to task extension	Operator considers its job to be subjected to task exchange	Operator considers its job to be subjected to task erosion
Significance	The operator's work output increased	The operator's work output caused a limited impact	-
Task identity	Job is more transparent	Job is equally transparent	Job is less transparent
Feedback from job	Cobot becomes an integrated part of the operator's support system	Cobot does not provide feedback	-
Information processing	More data circulates in the production unit	The same amount of data circulates in the production unit	Less data circulates in the production unit
Job complexity	Job becomes more demanding	Job becomes equally demanding	Job becomes more repetitive
Specialisation	Unique capacities are required to program and operate the cobot	Job is already specialised and the cobot is very easy to use	-
Problem-solving	Cobot malfunctions are considered common and complex	Operator is unauthorised to troubleshoot or has experiences	-

Operators perceived more *specialisation* since working with a cobot required advanced and specific skills, especially in programming. Others were already specialised or felt the cobot's ease of use did not require a higher specialisation. *Problem-solving* has increased since the cobot caused considerably more (technical) issues than manual labor. These issues had to be understood and resolved accurately, which gave many operators a greater sense of problem-solving. The operators who did not experience this were either not allowed to solve issues or could rely on their previous work experiences.

Situation Awareness

The results showed that operators' situation awareness either remained unchanged or decreased. These results seem to be related to how the cobot was deployed. In all cases, the cobot was programmed to function autonomously for a longer period. Since the operators' interference would not be required constantly, their physical presence and mental attention shifted from the human-cobot production unit to where their parallel tasks were embedded (e.g., a different production unit). Operators told how they stayed with the cobot when it executed its first tasks and how they would leave the production unit if the cobot executed a sequence of tasks accurately. From that moment, the operator's situation awareness about the human-cobot production unit is based on two occasions. The first is based on visually inspecting the human-cobot production unit to see if it is still functional. The second is an inspection of the unit's output to determine if the unit functioned as intended during the operator's absence. Depending on how operators handled these occasions, their situation awareness either decreased or remained relatively similar to that of the previous production unit.

The operators' situation awareness decreased in nine out of 15 cases (i.e., SMEs A, C-E, and J-N). These operators monitored the cobot less frequently over time. They checked less often if the cobot was still operational and/or inspected its output less extensively over time (e.g., from inspecting all products to inspecting only a selection of production). These monitoring behaviours are caused by the cobot's constant and accurate functioning. One operator mentioned:

> *"I measure one in the morning at 11:00 hours, one at 15:00 hours, and one at 16:30 hours before going home. If everything checks out, then I have full trust … I will absolutely not spend too much time on it [checking the cobot's output]"*
> *(Operator 1, SME L, operates an [un]loading cobot).*

While operators in six other cases (SMEs B, F-I, and O) also frequently left their human-cobot production unit, they regularly checked the cobot's functioning and inspected the same number of products over time. We found three reasons for these behaviours. Firstly, they inspected all the cobot's output as they had to finalize it or follow a company policy on output monitoring. Secondly, the operator stayed nearby or directly saw the cobot to sense cobot-related movements or sounds. Thirdly, operators who could not see the cobot at a distance frequently walked by to monitor its status, especially if the cobot's application was considered unstable (i.e., prone to error).

Automation-Induced Complacency

To determine the operators' automation-induced complacency, we studied their cobot-related assumptions and the nuances that accompanied them. Automation-induced complacency was considered prevalent if the operator did not nuance its cobot-related assumptions (e.g., by stressing the cobot's technical limitations). If such a nuance was provided, then automation-induced complacency was considered 'neutralised' and, therefore, absent.

We encountered two types of complacency-prone assumptions. The first type of assumption is related to the cobot's accuracy, repeatability, and safety. All operators expressed such an assumption at least once. Operators seemed to have these assumptions since they were physically separated from the cobot and needed to rely somewhat on the cobot's functioning. In all cases, the operator assumed that if the cobot executed the first few tasks as intended, its remaining tasks would be handled just as well. The following quotations illustrate two assumptions about the cobot's functioning:

> *"If I let him* [the cobot] *run and I know for sure it runs well, then I can leave him and walk away. I got that trust"*
> (Operator 1, SME B, operates a welding cobot).
>
> *"I must say that the cobot's safety also lowers some consciousness because you rely on the fact that the cobot is safer. It is not a dangerous machine to work with"*
> (Operator 1, SME M, operates a welding cobot).

The second type of assumption relates to the buildup of the cobot's programs. Operators from SMEs B, D, F, I, J, and M mentioned that they relied heavily on the cobot programs they had developed or those developed by others. They assumed that the programs were successfully configured and would control the cobot as intended. One operator expressed this assumption as follows:

> *"I just know from myself, if I configured him [the cobot] right, nothing can go wrong. Simple as that"* (Operator 2, SME J, operates an assembling cobot).

Operators from SMEs D, H, I, and L-O nuanced their cobot assumptions. Most of these nuances are based on previous (technical) experiences with robotics or the cobot itself. Based on these experiences, operators understood which cobot applications were prone to error and what risks the cobot came with, enabling a more critical approach towards the cobot. One of these experienced operators mentioned:

> *"I have seen robots do weird things over time. Very weird things. I always assume that a cobot is the same as a robot, but a mini-sized version"* (Operator 2, SME O, operates a welding cobot).

Performance

Production Reliability

Production reliability developed in multiple directions. All SMEs, except for SMEs C, D, and I, reported increased production reliability. This increase ranged from up to 2% fewer defects and less finetuning to lower energy consumption and less oil waste. Managers attribute these increases to the fact that the cobot has taken over monotonous tasks that the operator could not execute for a prolonged period without wasting resources or causing errors (e.g., identifying mistakes or ensuring all weld seams were applied). SMEs B, G, J, L, and O also mentioned that using the cobot led to increased automation and, thus, standardization of their production system. This resulted in more stable and outlined production processes that are less dependent on the operator.

In contrast to the increase in production reliability, we also encountered various decreases in production reliability. The most visible decrease relates to the operators' situation awareness and automation-induced complacency. In SMEs A, D, E, J, and L-N, operators have, on a structural basis, conducted fewer product inspections since the arrival of the cobot. Consequently, there is a higher chance that mistakes made by the cobot are detected too late or not detected at all by the operator. Having a weaker grip on product quality decreases production reliability. Due to the physical distance between the operator and the cobot, the number of defects increased in SMEs C and G. In the contrary, production reliability remained unchanged for SME I.

Productivity

We found that production unit productivity increased at five SMEs since the introduction of the cobot (i.e., SMEs B, J, K, M, and N). Managers from these SMEs reported that the human-cobot production unit handled products considerably faster than the unit's previous version. To illustrate, the welding cobot in SME B handled products three times faster than the manual production unit did and handling time was reduced by 50% in SME M. Before proceeding, it is important to nuance the productivity increase in SME J. Since their cobot became part of a larger automation solution, the productivity increase cannot be ascribed entirely to the cobot.

Productivity decreased in SMEs A, D, G, I, and L. In these SMEs, the handling time of the human-cobot production unit was longer than that of the previous version of the production unit. Not surprisingly, each of these units' human-cobot interdependencies came with a negative task interdependence. The cobot was also used outside regular working times (e.g., during overtime, evenings, or even nights) to compensate for its slower handling time. Operators would fully prepare the cobot before going home and generate one or more hours' worth of output depending on the cobot's autonomous uptime and the presence of technical issues. These extra machine hours do not increase the human-cobot production unit's productivity. Still, they do harmonize the output of the human-cobot production unit with that of the previous production unit – in the case of SME A, it even led to an increase in output.

Moreover, we did find that the cobots in SMEs A, C, D-G, J, L, and M faced a structural standstill, (further) lowering the human-cobot production units' productivity. In SMEs D, E, J, L, and M, these standstills are caused by the operator noticing the cobot's standstill too late (e.g., due to the physical distance between the cobot and the operator or distraction by the parallel tasks). Moreover, in SMEs F, G, and M, the cobot's structural standstill is caused by the limited number of products it is programmed for. Consequently, the cobot is out of commission until these products are being (re)ordered. The reason(s) behind the structural standstill in SMEs A and C remained unclear. Due to insufficient information, productivity developments could not be established for SMEs H and O.

Resilience Ranking

We ranked the resilience of the human-cobot production units under study based on their design, the operator's change in work perceptions, and the unit's ability to meet or exceed the performance generated by the previous version of this unit. Seven ranks are mentioned in Table 4. Most of the SMEs have a human-cobot production unit with a resilience rank of 3 or 4. This implies that the unit 1) faces similar functional requirements, 2) comes with or without a considerable negative interdependence, 3) was run by operators with a similar, better, or nuanced stance towards at least two out of the three work perceptions under study (i.e., motivational characteristics, situation awareness, and complacency), and 4) achieved similar or higher production reliability and/or productivity. The two SMEs that successfully managed to process more functional requirements achieved the highest ranks. The lower ranks are associated with units that, alongside considerable negative task interdependence, exhibit fewer acceptable work perceptions and/or performance. This ranking will be used in the following subsection to determine whether more resilient units are associated with a greater impact on the SME's strategic flexibility.

Table 4: Resilience Ranking

Rank	Increase in Functional Requirements	Interdependence has no considerable negative task interdependence	Number of Acceptable Work Perceptions	Number of improved Performance Measures	Applies to SME(s)
1	Yes	True	2	0	I
2	Yes	False	1	1	K
3	No	True	2	1 or 2	B, F, M, N
4	No	False	2	1	E, H, L, O
5	No	False	1	1 or 2	A, G, J
6	No	False	2	0	D
7	No	False	1	0	C

Strategic Flexibility

Developments in SMEs' External Context

Except for SME L, all managers gave an impression of the developments taking place in their external context that affected the SME's production system. Five developments were deducted. Most of these developments are related to *increasing customer demands*. Managers from SMEs A, B, E-K, and M reported that customers are becoming more demanding. Customers still require products manufactured in large quantities, and they demand higher product quality and swift delivery. The second external development concerns the *increasing staff shortage*. Managers from SMEs A-E, G-I, and O emphasized that production labor is becoming increasingly scarce and, therefore, difficult to acquire and retain. The third development focuses on *intensifying price competition*. The managers from SMEs D, E, G, H, J, K, and M-O also brought up this development. Those from SMEs D, G, M, and N explicitly referred to increasing price competition with foreign manufacturers in low-wage countries (e.g., Eastern Europe). Three managers from SMEs E, G, and H stressed increased local competition due to the rising reshoring activities (i.e., Dutch manufacturers relocating their foreign production activities to the Netherlands). The fourth development relates to *technical innovation*. Three managers from SMEs F, H, and N stressed the availability of new technological opportunities to replace outdated machinery and further automate their production systems. The fifth development, mentioned by one manager from SME N, captures an *increase in supply chain problems* caused by resource scarcity and geopolitical conflict.

Developments in SMEs' Strategic Flexibility

We could distillate the cobot's presumed contribution to strategic flexibility for all SMEs, but SME L. Al managers presumed that their cobot positively contributed to their SME's strategic flexibility. This contribution enabled the SME to respond more effectively to two or more external developments. Four contributions were deduced from the data.

The first contribution concerned the SME's *response to customer needs*. This contribution was mentioned by managers, except for SME C. The absolute majority stressed that the cobot contributed to their production capacity for one or more of the following three reasons. Firstly, the cobot produces both during and after regular working hours, resulting in increased machine hours and a higher volume of handled products. Secondly, the cobot achieves higher task reliability, resulting in fewer defects. Thirdly, by functioning unmanned, the cobot allowed the operator to focus on other tasks, accommodating additional production capacity. The increased production capacity allowed SMEs to accept more customer orders and meet higher quality standards. In exceptional cases, using the cobot enabled SME J to estimate production capacity more accurately and helped SME M engage in product redesign activities with the client to ensure the cobot could handle the product optimally. One manager explained how the cobot increased their SME's strategic response to client demands as follows:

> "*The core business of this enterprise did not change because of the cobot. ... Only the possibilities within this enterprise changed. Those that allow us to increase the production capacity in particular*"
> (Manager 1, SME H, manages a production unit equipped with a packing cobot)

The second contribution relates to responses to changes in market opportunities. These market opportunities solely concern the availability, attraction, and retention of scarce production labor. Managers from SMEs A-E, G, H, N, and O brought up these responses. In these SMEs, the cobot changed the operators' job demands. We found that SMEs A, C, and D used the cobot to increase their operators' job demands by allocating repetitive tasks to the cobot and occupying the operator with more complex tasks. This would allow the SMEs to leverage their human resources more effectively. SMEs B, E, and N took a different approach. They used the cobot to create a highly automated job with low job demands. A broader group of (very) practically educated workers could do such a job, increasing hiring chances. SMEs C, D, H, and N stated that the cobot contributed to the quality of production labor by reducing the number of repetitive tasks and preventing current and future operators from having to work in shifts and during the night. Finally, SMEs D, F, G, and O mentioned that, by taking over human labor, the cobot decreases their strategic dependability on human resources. One manager illustrated this as follows:

> "*Because you can use it [the cobot], we can keep running the process. Later, if all labor potential dried up here in the Netherlands and in our own enterprise, we would be strategically unable to run the process. In such a case, because of cobot, due to automation, you can continue to operate here in the Netherlands*"
> (Manager 1, SME G, manages a production unit equipped with a drilling cobot).

The third contribution is directed towards the response to new technology. This contribution was expressed by managers from SMEs A-C, E-G, I, J, and O. In these SMEs, the cobot primarily helped to kickstart new automation projects. Managers explained how the SME's implementation and working experience with the cobot resulted in specific insights into the cobot's strengths, weaknesses, and necessities. Moreover, operators encountered the cobot and developed programming and/or gained end-user experiences. These advancements lead to more enthusiasm for automation and new ideas for future automation projects. It also allows the SME to develop more specific (technical) requirements that a future automation project should meet. The cobot-related experiences are presumed to enhance the quality and implementation speed of these projects. Moreover, SMEs A, C, F, G, and N emphasized that the cobot enabled them to expand and innovate their machinery, as well as solve deep-rooted technical problems cost-effectively. These enhancements create better technical conditions for future technology implementations. One manager illustrates how the cobot contributes to the SME's strategic flexibility towards new technology as follows:

> *"You mostly know what you do not want. ... Because of that, you can quickly make a wish list with the things you definitely want and do not want. ... Reach, the angle, the door opening, the products I would like to make ... Based on your wish list, a very select number of solutions [for future automation] remain*" (Manager 1, SME I, manages a production unit equipped with a [un]loading cobot).

The fourth and final contribution relates to how the cobot enabled SMEs to respond better to *changes in economic conditions*. SMEs E, G, J, K, and M-O presumed that the cobot's contribution to their production capacity indirectly increased their financial degrees of freedom. Managers from these SMEs explained that products handled by the cobot had a higher profit margin than those handled entirely by an operator. This difference is caused by the cobot's lower deployment and handling costs. Due to the higher profit margin, SMEs could choose to offer their customers at a lower price or use it to increase their negotiating space. SME N used the higher profit margin to generate additional revenue.

> *"It* [the cobot] *is some sort of a cost reduction. You will either end up with a better price or a better margin"* (Manager 1, SME J, manages a production unit equipped with an assembling cobot).

Resilience Ranking and Strategic Flexibility

Table 5 provides an overview of the strategic flexibility increases per SME. The table is sorted sorts the table ranks and visualizes whether SMEs with a more resilient human-cobot production unit comes with a more extensive increase in strategic flexibility. The overview shows that SMEs N, E, and G reported the most extensive increase (i.e., their strategic response to four out of four developments was presumably enhanced by the human-cobot production unit). SME's B, A, and J reported this for three out of four developments. Consequently, over half of the SMEs only reported improvements in two areas. Moreover, the most extensive increases in strategic flexibility were not reported by ranks 1 and 2 but were all embedded in ranks 3 to 5.

Table 5: Strategic Flexibility Increases per SME, Specified per Resilience Rank

SME	Resilience Rank	More Strategic Flexibility to Respond to:			
Reference	(High = 1; low = 6)	Customer Needs	Market Opportunities	New Technology	Economic Conditions
I	1	✓	-	✓	-
K	2	✓	-	-	✓
B	3	✓	✓	✓	-
F	3	✓	-	✓	-
M	3	✓	-	-	✓
N	3	✓	✓	✓	✓
E	4	✓	✓	✓	✓
H	4	✓	✓	-	-

L	4	n/a[1]	n/a	n/a	n/a
O	4	✓	✓	-	✓
A	5	✓	✓	✓	-
G	5	✓	✓	✓	✓
J	5	✓	-	✓	✓
C	6	-	✓	✓	-
D	6	✓	✓	-	-

1 (n/a) data not available

Overview

Table 6 schematically summarizes the results section. We presented the core results per case and specified these for each of the (sub)concepts under study (e.g., motivational characteristics). To simplify and harmonise the overview, we note per concept how it occurred, whether it was present or absent, or whether it has changed since the use of the cobot. Resilience rankings are also incorporated in the table.

The overview showcases a range of cobot applications that primarily handle the same product quantities and varieties as those managed by the previous version of the production unit. The designs of human-cobot interdependencies encompass a wide range of (indirect) hard and soft task interdependencies, but most of them also exhibit considerable negative task interdependence. The operators' motivational characteristics show few signs of decay. More concerning are the operators' decreases in situation awareness and signs of automation-induced complacency – one and/or the other were present in almost all cases. Regarding performance, the human-cobot production units often had similar or higher production reliability than productivity. Most units had a resilience rank of 3 or 4. Finally, each human-cobot production unit provided at least two distinctive contributions to the SMEs' strategic flexibility. Many of these contributions enabled the SME to better cope with changes in customer demands from a strategic viewpoint.

Discussion

Being the class example of a modern workplace innovation, cobots can potentially contribute to operational and strategic outcomes. This research aimed to describe the cobot's (in)direct impact on four areas: the human-cobot interdependencies' functional requirements and task execution, the operator's work perceptions, the production unit's performance, and the SME's strategic flexibility. A multidisciplinary framework was constructed to guide a comparative case study involving 36 operators and managers from 15 Dutch SMEs. Per case, interview data was gathered at the operational and strategic levels. The rigorous data analysis and systematic comparison of the results allow us to answer the central question of this research: *What is the cobot's impact on* *the design, sustainability, and performance of the production unit, and what do these impacts mean for the SME's strategic flexibility?* In this section, we will answer the research question in light of our expectations, present practical implications, and elaborate on research limitations and opportunities for future research.

General Discussion

Our *first expectation* was that production units equipped with a cobot face higher functional requirements than their previous version (i.e., smaller batch sizes and/or higher product varieties). *This expectation was not met*. We have only encountered two production units handling a higher product variety since the introduction of the cobot. This is the first indication that the human-cobot production units were limitedly resilient and that an important cobot feature (i.e., its reconfigurability [Matheson et al., 2019]) was ignored systematically. This indication was confirmed, as most cobots run on one or a few (similar) cobot programs, stressing that the cobot is primarily used for a limited number of large-quantity and repeat products. Using the cobot in a highly autonomous manner, combined with its limited intuitiveness, comes with high (re)programming efforts that can only be earned back if the batch size is large enough.

Our *second expectation* is that human-cobot interdependencies primarily comprise hard and/or soft task interdependencies. *This expectation was partially met*. We encountered six of these human-cobot interdependencies. Most of them were used for welding purposes. Other human-cobot interdependencies came with a considerable negative task interdependence, which, at first glance, would be a sign of suboptimal design. SMEs seem to take the negative task interdependencies for granted. On the one hand, the soft interdependencies would generate enough task improvement to compensate for the task decay associated with the negative interdependence. On the other hand, these negative interdependencies are tolerated due to the indirect hard interdependencies they come with. The human-cobot interdependence was designed to be both sequential (Thompson, 1967) and autonomous, allowing the operator to execute other tasks outside the production unit. The first signs of such operator decoupling were reported by Wolffgramm et al. (2021). We hoped that manufacturers would have discovered ways to generate value by having operators and cobots interact more interdependently in the meantime. But to no avail. Depending on the number of products that can be stocked, the duration of the cobot's task execution, and the cobot's reliability, its autonomous operation ranges from minutes to hours. This decoupling of operators leads to the ignorance of another important cobot feature (i.e., its capacity to directly interact with the operator [Djuric et al., 2016]).

Table 6: Overview of Core Results per Case and Concept Under Study

SME	Cobot Application	Change in Unit's Functional Requirements		Task Interdependencies in Human-Cobot Interdependence			Change in Work Perceptions			Change in Unit Performance		Resilience Rank	More Strategic Flexibility in Terms of:			
Reference	Core Deployment	Batch Size	Product Variation	Hard	Soft	Negative	Motivational Characteristics	Situation Awareness	Automation Complacency	Production Reliability	Productivity	(High = 1 - low = 6)	CN 1	MO 2	NT 3	EC 4
A	(Un)loading	=	=	✓	✓	✓	↑	↓	✓	↑↓	↓	5	✓	✓	✓	-
B	Welding	=	=	✓	✓	-	↑	=	✓	↑	↑	3	✓	✓	✓	-
C	Greasing	=	=	✓	-	✓	↑	↓	✓	↓	↓	6	-	✓	✓	-
D	(Un)loading	=	n/a	✓	✓	✓	↑↓	↓	-	↓	↓	6	✓	✓	-	-
E	Inspecting	=	=	✓	✓	✓	↑↓	↓	✓	↑↓	↓	4	✓	✓	✓	✓
F	Welding	=	n/a	✓	✓	-	↑	=	✓	↑	↓	3	✓	-	✓	-
G	Drilling	=	=	✓	✓	✓	n/a	=	✓	↑↓	↓	5	✓	✓	✓	✓
H	Packing	=	=	✓	✓	✓	↑	=	-	↑	n/a	4	✓	✓	-	-
I	(Un)loading	=	↑	✓	-	✓	↑	=	-	=	↓	1	✓	-	✓	-
J	Assembling	=	=	✓	✓	-	↑↓	↓	✓	↑↓	↑↓	5	✓	-	✓	✓
K	Welding	=	↑	✓	✓	-	↑	↓	✓	↑	↑	2	✓	-	-	✓
L	(Un)loading	=	=	✓	✓	✓	↑	↓	-	↑↓	↓	4	n/a			
M	Welding	=	=	✓	✓	-	↑	↓	-	↑↓	↑↓	3	✓	-	-	✓
N	Welding	n/a	n/a	✓	✓	-	↑	↓	-	↑↓	↑	3	✓	✓	✓	✓
O	Welding	=	=	✓	✓	✓	↑↓	=	-	↑	n/a	4	✓	✓	-	✓

Legend: (↑) increase; (↓) decrease; (↑↓) both increase and decrease; (=) no development; (✓) applicable; (-) not applicable; (n/a) data not available
1: customer needs; 2: market opportunities; 3: new technology; 4: economic conditions

Our *third expectation* was that operators who run human-cobot interdependencies comprising mostly hard and/or soft interdependencies perceive their motivational characteristics as strong as or stronger than they did before working with the cobot. *This expectation was largely met*. Most of the human-cobot interdependencies without negative task interdependence came with increased motivational characteristics. It is essential to emphasize that such perceptions were also frequently found in human-cobot interdependencies with a negative task interdependence. In contrast to the various warnings for quality of working life decay (Baltrusch et al., 2022; Shaba et al., 2024), most operators perceive their motivational characteristics as strong or stronger since the introduction of the cobot. This was caused by increased work demands, resulting in more perceived specialisation, problem-solving, job complexity, and skill variety. These findings differ from those of Berkers et al. (2023), who reported considerable developments in the operators' task variety and autonomy, and less physically and cognitively demanding working conditions. The developments in job complexity align with those of Kadir et al. (2018) and Wolffgramm et al. (2021). Bragança et al. (2019) and El Zaatari et al. (2019), who rightfully anticipated the developments in perceived skill improvements. While our findings are positive, it is important to remain cautious about too-much-of-a-good-thing effects (Zhou, 2020).

Our *fourth expectation* was that human-cobot interdependencies comprising hard and soft task interdependencies come with at least a similar situation awareness compared to the previous production unit and a critical stance towards the cobot's functioning. *This expectation is not met*. The operators running human-cobot interdependencies with both hard and soft interdependencies consistently reported a decreased situation awareness and/or a complacent tendency towards the cobot. They were not the only ones. In fact, classic operator-out-of-the-loop symptoms were broadly encountered. Operators were removed, or decoupled, from the workstation and, in addition to monitoring the cobot, were provided with new job demands. This led to a physical distance between the operator and the cobot, as well as distraction for the operator. Consequently, according to operator-out-of-the-loop theory, the operator's situation awareness decreased due to poor monitoring behavior (Endsley, 2017). Moreover, the various unnuanced assumptions about the cobot's flawlessness indicate a deep-rooted overreliance on the cobot (Wickens et al., 2015). While we often encounter these thoughts and behaviours amongst operators controlling multiple autonomous (CNC) machines, it is essential to take these signals seriously. Unlike such machines, the unattended cobot is uncaged and has fewer safety measures, increasing the risk of injury to the operator and passersby. Moreover, it evidently results in more defects and downtime.

Our *fifth expectation* was that production units with a human-cobot interdependence comprising mostly hard and soft interdependencies and acceptable work perceptions would establish better production reliability and/or productivity outcomes than the previous version of the production unit. *This expectation was not met.* None of the units met these requirements. This is primarily caused by the operator's poor situation awareness and apparent automation-induced complacency. Moreover, the cobot's lower task efficiency frequently resulted in poor productivity that could only be compensated by running the cobot during and after regular working hours, contrasting productivity increases reported by Realyvásquez-Vargas et al. (2019) and Galin et al., (2020). The performance outcomes also suffered from the operator's out-of-the-loop behaviour. Poor monitoring behaviour increased the chance of cobot-related flaws not being noticed by the operator in time or at all, resulting in more defects in some cases. Productivity outcomes were hindered by structural downtime caused by the operator notifying too late that the cobot had come to a standstill. Similar findings were reported by Kaber et al. (1997). Other examples of structural downtime were related to the cobot's narrow deployment. Due to the limited product variety, the cobot has a high chance of standing still if these products are not in demand.

Our *sixth and final expectation* was that more resilient human-cobot production units to increase the SME's strategic flexibility more extensively. *This expectation is not met*. Based on the resilience ranking we applied, we found that production units with higher rankings came with less extensive increases than units with moderate rankings. On a positive note, the SMEs under study believed that their human-cobot production unit improved their strategic response to external developments, such as high customer demands (Pech et al., 2022) and staff shortages (European Labour Authority, 2022).

The production unit's most prominent contribution relates to how SMEs respond strategically towards customer needs. The cobot's autonomous operation and the decoupled operator increased production capacity, generating strategic opportunities to accept new and/or more advanced customer orders (i.e., its absorption capacity increased [Tu et al., 2006]). Another contribution relates to the SME's strategic dependability on human resources. The human-cobot production unit facilitates job enrichment and job simplification, making the SME a more attractive employer for a specialised or more practical operator population. Moreover, the implementation and working experience with the cobot resulted in collective knowledge about and positive attitudes towards robotisation. These dynamic capabilities (Eisenhardt et al., 2000), combined with the enhanced modernisation of the SME's technical infrastructure, increased its capacity to absorb new (robot) technologies. Finally, in line with the common notion that strategic flexibility results in more financial resources (Combe et al., 2012; Verdú-Jover et al., 2014), the cobot generates more financial degrees of freedom. The SME can use these to offer a more competitive price or reinvest them into their resources and coordination.

From an MSTS viewpoint (de Sitter et al., 1997; Kuipers et al., 2020), the often rigid and misaligned human-cobot interdependencies under study show a minimal increase in requisite variety and unity of technical and social subsystems. Moreover, the operator's quality of working life is demonstrated in order regarding its motivational characteristics, but raises a cause for concern regarding out-of-the-loop behaviour. Finally, the production system's robustness increased clearly, but it was due to the decoupling of the operator instead of a resilient interplay between (wo)man and robot. In summary, most of our expectations were not met or were only met partially. Nonetheless, this research uniquely specified the cobot's impact and placed MSTS, and thus the workplace innovation design theory, in a contemporary and advanced work context, delivering its theoretical contribution to the fullest (Parker et al., 2022; Govers et al., 2023; Guest et al., 2022; Oeij et al., 2023).

Practical Implications

We formulated three practical implications. The first implication relates to the design of human-cobot interdependencies. Rather than prioritizing decoupled human-cobot interdependencies over highly collaborative ones, we argue that both are necessary and recommend a dual strategy. The decoupled human-cobot interdependencies enable the automation of oversimplified and tedious operator tasks, thereby improving the motivational characteristics of the 'mainstream' operator. To prevent operator-out-of-the-loop problems, the human-cobot production unit must be closely monitored. Due to its operational simplicity, this could be done by a highly practical operator or even sheltered workers. In an ideal scenario, such an operator will oversee multiple highly autonomous cobots. This is a good solution for individuals with a physical or mental challenge to participate more prominently in the labor process and a promising avenue to minimize operator-out-of-the-loop waste. Moreover, this approach targets vulnerable worker groups that have been systematically overlooked (Rom et al., 2023).

In addition to more autonomous cobots, developing more interactive forms of human-cobot interdependencies for and with mainstream operators is essential – Alasoini et al. (2023) show that broad employee participation is the backbone of innovative businesses. These applications are highly complex because they must exceed the operator's high mental and physical capacities. Nonetheless, we encourage SMEs to collaborate with researchers in this area and look for lucrative and sustainable solutions. It is essential not to reason from an automation perspective but to follow a capacity-enhancing perspective instead. This way, the operator and its flexibility remain part of the production unit, allowing more task interdependencies across a wider product range (i.e., high-mix, low-volume production).

The second implication concerns the operator's quality of working life. To ensure that the human-cobot production unit remains sustainable, it is crucial to pay close attention to the operator's development in motivational characteristics and its showcasing of operator-out-of-the-loop symptoms. As part of this work, we provide a conversation tool that makes discussing motivational characteristics more convenient. Moreover, we illustrated what a deteriorated situation awareness and an unnuanced overreliance on a cobot entail. Managers can regularly converse with their operators to discuss the latter's work perceptions. Given their work and organisational psychology background, this is also an ideal way for Human resources professionals to immerse themselves in using and optimizing cobot applications. They can advise managers or directly support them when discussing quality of working life matters with the operator.

The third implication concerns the evaluation of the human-cobot production unit. To better understand the cobot's impact, assessing the human-cobot production unit in light of relevant external developments and strategic ambitions is recommended. This research gives an impression of the dimensions that can be used to analyze the human-cobot production unit, how to rank the unit's resilience, and what external developments and strategic impacts to consider. These evaluations can be done both before and after the deployment of the cobot. In both cases, redesign initiatives must be seriously considered if the strategic impact does not meet expectations.

Limitations and Future Research

This research comes with three noteworthy shortcomings. The first and foremost limitation is that this research lacks the quantitative data to estimate the magnitude of the cobot's impact (e.g., uptime, downtime, time to complete, and rejects data). The available data is limited to whether an impact is presumed. Ideally, conducting observations and studying historical performance data leads to more quantified reports about the cobot's impact and a more specific resilience ranking. Since the operator is likely to be decoupled, studying spillover effects outside of the human-cobot production unit is also essential. In addition to its operational impact, the cobot's strategic impact also warrants further attention. We were unable to express these impacts in economic values (e.g., market share and revenue growth). Researching the SME's strategy and strategic decision-making process more explicitly could place the cobot's strategic impact into a better perspective. It is also recommended to study whether the cobot hinders strategic flexibility. These impacts did not surface in this research but were also not studied explicitly.

Secondly, the analysis of the human-cobot interdependencies under study was somewhat simplistic, as the method lacked an in-depth task analysis. We recommend using the interdependence scoring method (Wolffgramm et al., 2024) to better interpret the relevance and ratio of the hard, soft, and negative interdependencies encountered. Thirdly, this research is based on cases involving autonomous cobots. Highly interdependent human-cobot production units might generate very different results, such as out-of-the-loop behaviour. Scholars are encouraged to search for such exceptional cases in, for instance, the social domain (e.g., sheltered workshops). In addition, we strongly endorse more (applied) research into the direction of building, testing, and applying highly interdependent human-cobot production units. An example can be found in Wolffgramm et al. (2025). The cobot technology offers a prosperous avenue for long and impactful collaborations between scholars and manufacturers. Finally, scholars are invited to continue applying MSTS concepts and principles in contemporary manufacturing. These applications contribute to the embeddedness of the workplace innovation design theory and help to identify a wide variety of important antecedents (e.g., learning and development requirements that enable workers to use job decision latitudes constructively [Hammouch, 2025]).

Conclusion

In this comparative case study, we deduced the cobot's impact on the design, sustainability, and performance of production units and described the implications of these impacts for SMEs' strategic flexibility. Being a prime example of a workplace innovation, the cobot's impact is considerable but not necessarily positive by default. The units' design became more rigid due to the substantial removal of the operator. Their sustainability and performance often improved, but these benefits were often suppressed by operator-out-of-the-loop problems and the cobot's technical limitations. The human-cobot production units are presumed to enhance the strategic flexibility of SMEs. The extent of this enhancement seems unrelated to the unit's resilience. Theoretical and practical recommendations at the crossroads of MSTS, workplace innovation and modern manufacturing are provided to quantify and expand the cobot's impact.

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