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Realising human-robot collaboration in manufacturing? A journey towards industry 5.0 amid organisational paradoxical tensions

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ABSTRACT

Human-robot collaboration is envisioned as a cornerstone of the future ‘ideal’ industry (Industry 5.0)—resilient, sustainable, and human-centred. While this goal has not yet been fully realised, advancements in collaborative robotic technology are expected to accelerate progress. Central to this vision is a workforce equipped with the skills necessary to *collaborate* effectively with robots in ‘ideal’ hybrid teams. Existing literature widely supports this optimistic outlook, suggesting that with the right technological developments, workforce reskilling and upskilling, and the resolution of key ethical and social concerns, human-robot collaboration in manufacturing will eventually become a reality. In this paper, we draw on a one-year field study that engaged with 39 representatives from industry, research, and other key stakeholders in both the technical and human factors of collaborative applications. Using constructive grounded theory and abductive reasoning, we challenge the assumption that the trajectory towards human-robot collaboration is straightforward or can be resolved through a one-time solution. Instead, our results reveal a journey marked by a series of paradoxical tensions, providing a fresh perspective on the complexities and unexpected empirical ‘surprises’ that define the transition towards Industry 5.0. We employ Paradox Theory to examine and elucidate this evolving journey, where paradoxes—such as *automation* vs *augmentation*, *technical efficiency* vs *human wellbeing*, and *exploration* vs *exploitation*—emerge, shift, and are managed in unexpected ways, revealing interdependencies between different types of responses across micro, *meso*, and macro levels of analysis. Extending beyond current theorisations on the implementation of Industry 5.0, our study contributes substantively and theoretically to understanding the evolving socio-technical complexities that shape this transition, highlighting the interplay between technological advancements, organisational dynamics, and workforce adaptation.

1. Introduction

Over the past decade, the manufacturing shop floor has witnessed the widespread deployment of a new kind of industrial robot, commonly referred to as *collaborative robot* or *cobot* (Baltrusch et al., 2022; Dornelles et al., 2023). Their growing adoption is driven by their distinctive characteristics: versatility, programmability for various applications, cost-effectiveness compared to traditional industrial robots, and efficiency in performing repetitive tasks (Silva et al., 2024). According to the International Standardization Organization (ISO), these robots are considered *collaborative* because they are specifically developed to share work environments with human workers without the need for traditional safety barriers (ISO/TS 15066, 2016). This is made possible by their *safe-by-design* features and advanced control mechanisms, such as no sharp edges, pinch points, and force-torque sensitive contact detection (ISO 10218-1, 2025; ISO 10218-2, 2025; Vecellio Segate and Daly, 2023), which significantly minimise the risk of injury or incidents during human-robot interactions (Berx et al., 2023; Simões et al., 2022).

To be clear: *safe-by-design* does not guarantee their safe interaction with human workers. The presence of these safety features ensures compliance with technical standards but does not automatically address the complexities of real-world human-robot interaction, such as dynamic environments, worker variability, or unforeseen safety-related risks. Simply attaching an unsafe tool or process to the robot will make it unsafe. Consequently, the deployment of cobots on the shop floor requires careful evaluation of the tasks they perform, the workspace configuration, and the broader organisational and technological context in which they operate. This shifts the focus from the robot itself

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to its practical application within the work environment. Similarly, being labelled *collaborative* does not inherently make them truly collaborative in practice. Collaboration envisages cobots as central elements of *collaborative systems*—environments where humans and robots work as ideal *hybrid* teammates (Simões et al., 2022). In the literature, this is referred to as *human-robot collaboration*, and it is framed within the core mission of Industry 5.0 (I.5.0) (EC., 2020). I.5.0 emphasises human-centric, sustainable, and resilient manufacturing processes (Huang et al., 2022; Piccarozzi et al., 2024).

Human-robot collaboration in manufacturing is still a vision. For this vision to become a reality, the mainstream literature highlights a range of technical, managerial, organisational, social, and ethical challenges that must be overcome. From a *technical perspective*, collaborative robotic systems must ensure reliability, precise synchronisation, and intuitive interfaces (Berx et al., 2023), as well as advanced levels of responsiveness, intelligence, perception, and contextual, goal-oriented problem-solving capabilities—in other words, they must become *intelligent* (Matheson et al., 2019; Zacharaki et al., 2020). Achieving these attributes remains highly challenging, with some arguing that it would necessitate capabilities approaching artificial general intelligence (Raisch and Krakowski, 2021; Walsh, 2017).

From a *managerial perspective*, the transition towards human-robot collaborative systems remains challenging due to the absence of standardised criteria for assessing return on cobot investments (Silva et al., 2024). Furthermore, the vision of human-robot collaboration may require a reconfiguration of current business models, as managers face complex trade-offs between achieving energy efficiency targets and meeting broader environmental and societal goals. This demands careful alignment of technological progress with principles of sustainability and social responsibility (e.g. (Dhayal et al., 2025; Dhayal et al., 2023). Learning from others can serve as a valuable strategy for navigating the uncertainties inherent in innovation projects, encouraging management to actively pursue collaboration with external stakeholders across the supply chain (Dieste et al., 2022; Moschko et al., 2023). This emphasis on collaboration calls on managers and R&D engineers to adopt a *boundary-spanning* role (Haas, 2015), focused on facilitating knowledge exchange between internal and external stakeholders (Moschko et al., 2023).

From an *organisational perspective*, human-robot collaboration is expected to redefine labour organisation on the shop floor, altering the *social fabric of work* itself (Selenko et al., 2022), and redefining—if not replacing—traditional roles across the workforce (Leitão et al., 2020; Leon, 2023). Concerns arise over the entrenchment of asymmetrical power relations and occupational hierarchies as task boundaries are redefined. Humans may be repositioned as overseers, assistants, or passive monitors—roles differing markedly in autonomy and value (Raisch and Fomina, 2024; Raisch and Krakowski, 2021). Such configurations obscure control, displacement, and empowerment dynamics (Raisch and Fomina, 2024). Without deliberate design of worker roles, smart manufacturing risks deepening deskilling, (Dornelles et al., 2023), generational divides, and socio-technical inequalities (Petrova et al., 2024; Zajko, 2022). Skilling of both the workforce and management is paramount, ensuring that employees can effectively interact with advanced technologies while managers are equipped to drive and support the organisational changes required for successful human-robot collaboration (Oeij et al., 2024).

Socially, workers' trust in robots significantly influences their willingness to engage with and rely on new technological applications (Baltrusch et al., 2022; Bonci et al., 2021; Lewis et al., 2018). Consequently, there may be a strong relationship between trust and the effectiveness of human-robot teams. There remains a lack of empirical evidence regarding the psychological impact of human-robot interaction on the shop floor—an area that demands greater attention and further research (Callari et al., 2024). Critically, workers may experience increased stress, anxiety, and burnout due to the pressure to maintain productivity in an environment where robots set a high benchmark for performance (Callari et al., 2024; Fletcher and Webb, 2017; Lu et al., 2022).

Finally, the *ethical dimensions* of implementing human-robot collaboration raise critical challenges for the human worker as an active agent in the interaction with collaborative systems on the shop floor (Callari et al., 2024). Central to these challenges is the recognition of human character, intentionality, and moral agency in shaping just and meaningful work (Santoni de Sio, 2024). Collaborative configurations must support autonomy and agency (Nyholm, 2020), and nurture a sense of purpose that counteracts potential *power imbalances* between the socio-technical dynamics of human-robot systems (Callari et al., 2024). Ethical concerns also arise around shop-floor data collection: while necessary for robotic systems operation, excessive or opaque data usage may be experienced by workers as a form of surveillance (Callari et al., 2024), erode transparency, and create an *illusion of consent* (Callari et al., 2025). Furthermore, bias in AI can reinforce structural inequalities for marginalised or vulnerable groups (Fletcher et al., 2021). These concerns call for responsible governance that upholds workers' dignity and rights (Callari et al., 2024), and builds trust in human-robot collaborative systems (Winfield and Jirotka, 2018).

Despite acknowledging the significant challenges to implementing human-robot collaboration, this literature often frames it as an unavoidable and transformative cornerstone of future manufacturing. In doing so, it implicitly assumes that organisations can adapt to the capabilities of these technologies, overlooking the uncertainties of transformative innovation processes and the socio-technical complexities of workplace dynamics and broader implementation contexts (Adriaensen et al., 2022). We respond to this underdeveloped area by theorising through the lens of Paradox Theory (Lewis and Smith, 2014; Schad et al., 2016; Schad et al., 2018; Smith and Lewis, 2011). This theory views the decision-making processes surrounding human-robot interaction and collaboration as dynamic and complex, characterised by inherent paradoxes (Schad et al., 2016; Smith and Lewis, 2011). A paradox is defined as "*contradictory yet interrelated elements that exist simultaneously and persist over time*" (Smith and Lewis, 2011, p. 382). Organisations must navigate competing demands, such as balancing innovation with tradition, or technological adaptations, organisational readiness, and workforce capabilities with broader societal considerations (Smith and Lewis, 2011). Paradox Theory reframes these tensions as interdependent, requiring continuous negotiation and critical thinking rather than resolution (Schad et al., 2016).

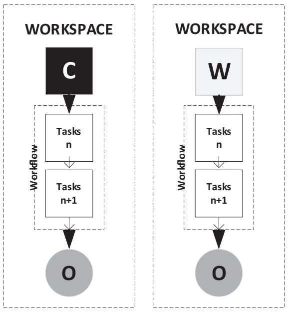
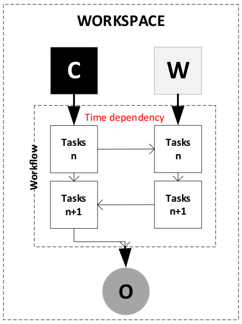
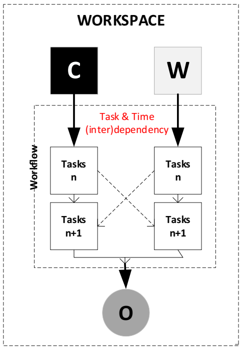
Therefore, this paper addresses the following research question: *What are the perceived organisational tensions*—i.e. *paradoxes—in realising human-robot collaboration?*

To address this research question, we draw on a year-long, in-depth field engagement though interviews with a diverse group of subject-matter experts—including representatives from industry, research, and other key stakeholders— directly involved in or knowledgeable about the implementation of human-robot work configurations in manufacturing organisations. The fieldwork was complemented by an ethnographic investigation conducted on a manufacturing site. Appreciating that geographical context can significantly influence the adoption and readiness of technologies, this research was conducted within the European context, focusing on corporate organisations and stakeholders operating across this region. By situating this study in Europe, we aimed to capture insights into human-robot collaboration that are specific to the region's manufacturing landscape, regulatory frameworks, and socio-economic conditions (Callari et al., 2024). The European context is particularly pertinent given its distinctive regulatory environment, labour laws, and industrial practices. For instance, regulations such as the General Data Protection Regulation (GDPR) and stringent occupational safety standards play a pivotal role in shaping the deployment and integration of collaborative systems (Brassart Olsen, 2020; Vecellio Segate and Daly, 2023). These frameworks not only influence technical implementations but also prioritise worker protections, ensuring that advancements in technology align with ethical and safety considerations.

Methodologically, we employed Constructive Grounded Theory (C-GT) (Charmaz, 2000, 2006, 2017), and abductive reasoning (Timmermans and Tavory, 2012, 2022) to uncover underlying mechanisms, relationships, and explanations, while maintaining a critical stance and a *level of reasonable doubt* throughout the empirical analysis. This exploration considered the rationale driving companies in the deployment of collaborative robots, including their experiences, uncertainties, and long-term vision for integration, highlighting the complexities and adaptations encountered along the way. We examine how paradoxes emerge, evolve, and transform within the daily practices of organising. Using existing typologies of management strategies as sensitising concepts (Putnam et al., 2016; Smith and Lewis, 2011), we identify patterns of responses to these paradoxes.

Our results reveal a journey marked by unexpected empirical 'surprises'. We advance a new model that highlights how paradoxes emerge, and the ways organisations respond to them across multiple levels—micro (e.g., job positions or work processes), *meso* (e.g., entire work organisations), and macro (e.g., relationships with external stakeholders within the task environment). At a *substantive* level, it advances understanding of the decision-making processes underlying the adoption and deployment of collaborative robots, revealing how these are shaped by iterative adaptations, internal experimentation, and growing strategic awareness. Moreover, our results underscore the critical role of human workers in enabling effective interaction with robotic systems on the manufacturing shop floor. These insights lend empirical weight to the notion of human-centricity in I.5.0, moving from abstract speculation to tangible and operational real-world empirical evidence. *Theoretically*, we contribute to the Paradox Theory literature by offering a processual perspective which refutes the notion of paradox

Table 1
Human-robot work configurations in current manufacturing (Legend: C=Cobot; W=Worker; O=Output).

# Configuration	Visual representation	Scenario description	Classification
Configuration-1	a)  **Fig. 1: Configuration-1 (Independent or Coexistence). Source: authors' own work**	Workers and cobots perform distinct tasks for distinct processes in separate locations on the shop floor —— *No task intersection and time dependency,* *No H-R interaction*	***Independent*** (Cesta et al., 2016); ***Coexistence*** (Matheson et al., 2019; Schmidtler and Bengler, 2015)
Configuration-2	b)  **Fig. 2: Configuration-2 (Synchronous). Source: authors' own work.**	One or more workers and one or more cobots perform consecutive tasks, sharing the same workspace —— *Task sequence and dependency* *Time dependency* *Shared workspace but* *No H-R interaction*	***Synchronous*** (Cesta et al., 2016)
Configuration-3	c)  **Fig. 3: Configuration-3 (Simultaneous or Cooperation). Source: authors' own work.**	Both the worker and the cobot work on separate tasks within the same process —— *Task dependency/inter-dependency from both the human and the cobot* *Time (inter)dependency* *Shared workspace*	***Simultaneous*** (Cesta et al., 2016); ***Cooperation*** (Matheson et al., 2019)

as a problem to be solved, and instead position paradoxes as a dynamic condition to be navigated. Moreover, we reveal that *either-or and both-and* strategies are paradoxically interrelated, challenging the dominant view that *both-and* approaches inherently surpass *either-or* strategies.

The remainder of the paper is organised as follows. Section 2 reviews the literature on work configurations involving collaborative robots, the vision of human-robot collaboration, the foundational building blocks of Paradox Theory, and how paradoxical lens can explain the integration of cobots. Section 3 describes the methodology. Section 4 presents the results. Section 5 discusses the results, advancing the study's theoretical model, and critically analysing the substantive and theoretical contributions. Section 6 concludes the paper.

2. Research underpinnings

2.1. *Work configurations involving collaborative robots*

In line with the legacy of Taylor and his seminal work on “Scientific Management” (Taylor, 1911, 1923), the engineering literature frequently analyses human-robot configurations at the micro level, focusing on task complexity, timing, spatial dimensions, and the allocation of tasks and responsibilities. This approach to the organisation of work frames the integration of collaborative robots as a functional and efficiency-driven endeavour. Safety considerations are similarly embedded within this micro-level analysis, emphasising specific dimensions of time and space but often overlooking broader socio-technical or ethical implications. This section seeks to disentangle these distinctions by examining varying degrees of interaction, task dependency, and their safety implications (Table 1), laying the groundwork for the analysis presented in this paper.

In the traditional shop floor configuration, industrial or collaborative robots, which are deemed potentially hazardous due to the nature of their tasks (e.g., handling sharp tools or payloads exceeding specified weight thresholds), operate within safety barriers, separated from human workers (Villani et al., 2018). These barriers are essential for risk mitigation and are guided by international safety standards (Villani et al., 2018). Interaction with these robots is typically facilitated through human-machine interfaces, which provide information on machine status, functionalities, and potential faults (Ardanza et al., 2019; Öztürk et al., 2024).

The first configuration (Table 1.a, Fig. 1) does not inherently involve human-robot interaction. Here, human workers and collaborative robots function independently, carrying out tasks in separate areas and engaging in distinct work processes. Safety-rated systems are active to monitor the robot's workspace and trigger a stop when it detects an unexpected intrusion or potential collision (Magrini et al., 2020). In real-world applications, this often involves tasks such as loading and moving parts, pick-and-place operations, packaging, or palletising. In these scenarios, collaborative robots typically execute low-skill, repetitive actions, complementing human labour without direct interaction (El Zaatari et al., 2019).

The second configuration (Table 1.b, Fig. 2) involves a fixed, coordinated strategy in which one party completes their task, and the other follows in a predetermined sequence, resembling a choreographed routine. This approach is commonly applied in sequential manufacturing processes and assembly operations, such as those in the automotive industry (El Zaatari et al., 2019). In such contexts, collaborative robots are integrated to enhance specific segments of the production process, increasing efficiency and precision while maintaining a clear division of tasks between humans and robots. Safety-monitoring systems and thorough risk assessments are implemented to ensure a safe and secure work environment for human workers in collaborative settings (Arents et al., 2021; Bonci et al., 2021; Gualtieri et al., 2022).

The third configuration (Table 1.c, Fig. 3) represents a more integrated approach, where human workers and collaborative robots operate simultaneously within the same workspace and process but focus on distinct tasks (Matheson et al., 2019). Unlike the second configuration, this one introduces a level of adaptability, suggesting some degree of solution-finding by both parties. This might involve reactive behaviour, where the robot dynamically responds to the human worker's needs, such as providing the correct tool at the right moment (Ajoudani et al., 2018; Dobra and Dhir, 2020). This configuration is commonly observed in those processes where robots handle repetitive or physically demanding tasks, while human workers focus on activities requiring precision, fine motor skills, or decision-making.

2.2. *The vision: Human-robot collaboration*

As integration between humans and collaborative applications deepens, the physical and temporal dimensions of human-robot interaction evolve, reshaping the nature of work towards ‘true’ collaboration as it is encountered in human-human collaborations in the workplace (Gervasi et al., 2020). Human-robot collaboration is envisioned as a process in which human workers and robots work simultaneously towards a common goal, the creation of a solution strategy, contributing their respective strength and capabilities (Matheson et al., 2019; Schmidtler and Bengler, 2015). This often requires on-the-fly adaptation and much more sophisticated interaction, demanding higher levels of robotic intelligence and responsiveness. While there is emerging evidence of such collaboration in fields like medicine—where surgeons and robots jointly perform complex procedures (Bobade and Asutkar, 2024; Weerarathna et al., 2023)—real-world applications in the manufacturing sector remain scarce.

Despite its potential, most research and feasibility studies on human-robot collaboration have been conducted in controlled laboratory settings, to assess the viability of advanced collaboration and addressing the technical barriers and human factors challenges associated with its implementation, as if overcoming these obstacles would pave a straightforward, unimpeded path towards human-robot collaboration. We contest this assumption, as it risks oversimplifying the complexity of the process and neglects the evolving, often unpredictable nature of socio-technical integration, where technological advancements, organisational dynamics, and human factors continuously interact in unexpected ways. Indeed, the challenges of I.5.0 remain complex, and a traditional approach to technological innovation may fall short in explaining the choices and tensions organisations must navigate. In this regard, Paradox Theory can offer a perspective that captures these complexities, providing a framework to understand and address the interdependent tensions inherent in this transformation. This is presented in what follows.

2.3. *Paradox theory: Foundational building blocks*

Paradox Theory offers an alternative analytical lens to conventional approaches, which often conceptualise competing demands within organisations—such as *exploration* versus *exploitation* or *learning* versus *performance* orientations—as *dilemmas* (Lewis and Smith, 2014). Dilemmas describe decision-making processes where one alternative must be chosen from competing but not necessarily incompatible options (Putnam et al., 2016; Smith and Lewis, 2011). Dilemmas are addressed by making trade-offs and selecting the option that align best with contextual conditions (Lewis and Smith, 2014; Schad et al., 2018). In contrast, Paradox Theory portrays competing demands as paradoxical tensions. A paradox refers to “contradictory yet interrelated elements” (Smith and Lewis, 2011, p. 382) that “seem logical when considered in isolation but irrational, inconsistent, and even absurd when appearing simultaneously” (Smith and Lewis, 2011, p. 386).

Building on the earlier work of Lewis (2000) and Luscher and Lewis (2008), Smith and Lewis (2011) identify four types of paradoxes that permeate core activities of organising:

- *Performing paradoxes* (goals): These emerge when an organisation is evaluated by diverse stakeholders, both internal and external, each employing different and often incompatible criteria. This creates persistent tensions, such as those between financial and social goals.
- *Learning paradoxes* (knowledge): These encompass tensions between radical and incremental innovation, exploitation and exploration, and short-term versus long-term orientations.
- *Organising paradoxes* (organisational design): These paradoxes centre on tensions between mechanistic and organic structures, standardisation and mutual adjustment, control and autonomy.
- *Belonging paradoxes* (identity): These involve tensions between self and others, including the interplay between self-expression or distinctiveness and group affiliation.

Paradox Theory is a particularly valuable theoretical lens under contextual conditions characterised by a plurality of goals, change, and resource scarcity, which bring latent paradoxes to the forefront (Lewis and Smith, 2014; Schad et al., 2018; Smith and Lewis, 2011). With regard to how actors respond to paradoxes (Smith and Lewis, 2011; Lewis and Smith, 2014) differentiate between organisational responses that lead to either *vicious* or *virtuous cycles*. Vicious cycles arise from an *either-or* strategy, where individuals or organisations prioritise one pole while minimising or ignoring the other. This limits consideration of alternative options and risks negative outcomes—particularly when organisations prioritise efficiency and seek new solutions closely aligned with existing options, ultimately hindering new knowledge creation.

Conversely, virtuous cycles involve more constructive responses, such as acceptance and resolution strategies. Acceptance means that managers remain open to both competing demands rather than choosing one option over the other (Smith and Lewis, 2011). Acceptance paves the way for resolution strategies, which do not seek to eliminate paradoxes but rather address simultaneously its opposing elements (ibid, p. 386). Resolution strategies include: *spatial separation*, which allocates opposing forces across different organisational units; t*emporal separation*, which involves prioritising one pole at a given time and then switching to the other; *synthesis*, which seeks innovative ways of understanding or interpreting problems that accommodate both opposing poles. Together, acceptance and resolution strategies foster a dynamic equilibrium that supports sustainability by enabling learning, creativity, flexibility, resilience, and unleashing human potential (Smith and Lewis, 2011).

This conceptual framework underpins a small yet rapidly growing body of research on I.5.0 implementation across various sectors, including manufacturing. As noted by Dieste et al. (2022), Paradox Theory provides a valuable alternative to conventional technology-centric analytical approaches, enabling a deeper understanding of the phenomenon. This emerging body of research offers preliminary insights into the paradoxical tensions in human-robot configuration integration and the strategies to address them, although these topics are not yet the primary or exclusive focus of investigation.

2.4. A paradoxical lens to the integration of collaborative robots

Studies using Paradox Theory to explore I.5.0 implementation point to three main specific paradoxes that emerge when integrating collaborative robots into the organisation's actual work activities and operations: the *automation* vs *augmentation* paradox; the *incremental* vs *radical innovation* (i.e. *exploitation* vs *exploration*) paradox; the *technical optimisation* vs *human wellbeing* paradox. Table 2 outlines each type of paradox, detailing the type of decision involved, the inherent opposing elements, and the corresponding management strategy for addressing it.

The *automation* vs *augmentation* paradox influences decisions about how humans should interact with robots in tasks execution (Kabel et al., 2024; Margherita and Braccini, 2024). Often classified as an organising paradox (Dieste et al., 2022; Pacheco and Iwaszczenko, 2024), this tension mirrors the well-known paradox between the standardisation of work tasks and job enrichment, which aims to enhance workers' autonomy and provide greater opportunities for mutual adjustment.

The paradox between *incremental* vs *radical innovation* shapes decisions regarding the nature and pace of change. Referred to as a *learning paradox* (Dieste et al., 2022), it centres on the tension between *exploitation* vs *exploration* (Mishra et al., 2022; Moschko et al., 2023). This tension reflects the contrast and interdependence between a short-term approach—focused on addressing immediate operational needs at the task level—and a long-term approach (Andriopoulos and Lewis, 2008), aimed at exploring the full potential of collaborative applications and optimising the entire manufacturing system (Johansson et al., 2024).

Finally, paradoxes arise when organisations must determine the ultimate goal of collaborative robot integration. Commonly referred to as a *performing paradox*, this tension revolves around the opposition between *technical optimisation*—prioritising efficiency, delivery targets, and quality at the task level—and *human wellbeing*, which focuses and

Table 2
Paradoxes and management strategies for collaborative robots' integration, adapted from (Kabel et al., 2024, p. 1232).

Paradox Type	Decision	Element	Description	Element	Description	**Management strategy**
Automation vs augmentation (organising paradox) [Dieste et al., 2022; Kabel et al., 2024; Margherita and Braccini, 2024; Pacheco and Iwaszczenko, 2024]	Use of robot applications	Automation	Automation implies that robots perform tasks that were previously carried out by a human without human intervention, thereby replacing workers in operational or decision-making activities.	Augmentation	Augmentation occurs when robot applications support workers' activities, increase their autonomy, and elevate the quality of their tasks	**Both-and approach: spatial separation** [Dieste et al., 2022, Kabel et al., 2024, Margherita and Braccini, 2024, Singh et al., 2024]
Incremental vs radical innovation (learning paradox) [Dieste et al., 2022; Johansson et al., 2024; Mishra et al., 2022; Moschko et al., 2023)	Pace and nature of innovation	Incremental innovation	Exploitation of already existing expertise and skills to drive change Task-focused short-term approach	Radical innovation	Exploration of collaborative robot full potential; process-focused long-term approach	**Both-and approach:** *Temporal separation* [Dieste et al., 2022; Pacheco and Iwaszczenko, 2024] *Synthesis* [Johansson et al., 2024]
Technical optimisation vs human wellbeing (performing paradox) [Margherita and Braccini, 2024; Moschko et al., 2023; Pacheco and Iwaszczenko, 2024]	Organisational goals	Technical optimisation	It focuses on efficiency, delivery targets and quality of task completion	Human wellbeing	It takes humans concerns, aspirations and needs on board	**Both-and approach:** *Temporal separation* [Dieste et al., 2022; Pacheco and Iwaszczenko, 2024]; *Synthesis* [Singh et al., 2024]

addresses workers' needs, experiences, motivations, and the development of new skills for future opportunities (Margherita and Braccini, 2024; Moschko et al., 2023; Pacheco and Iwaszczenko, 2024).

Some scholars have also identified management strategies to navigate and respond to paradoxes. In line with foundational studies (Smith and Lewis, 2011), these responses include spatial and temporal separation, as well as synthesis—all revolving around both-and strategies. As illustrated in Table 2, while certain responses align more closely with specific paradoxes, there is no strict one-to-one correspondence between paradox type and response. For instance, Dieste et al. (2022), Kabel et al. (2024), Margherita and Braccini (2024), and Singh et al. (2024) propose strategies such as creating new roles for humans and differentiating responsibilities between robots and humans (spatial separation) to address the *automation* vs *augmentation* paradox. Dieste et al. (2022) and Pacheco and Iwaszczenko (2024) highlight the importance of developing structured training programmes over time (temporal separation) to upskill employees, thereby balancing the *learning paradox* between *incremental* vs *radical innovation*, as well as the *performing paradox* between *technical optimisation* vs *human wellbeing*. Johansson et al. (2024) propose synthesis strategies to address the tension between *incremental* vs *radical innovation*, such as rotating employees across different parts of the organisation. This approach ensures that diverse knowledge perspectives and interests are incorporated when adopting new technologies. Similarly, Singh et al. (2024) advocate for synthesis strategies to reconcile the opposition between *technical optimisation* and ethical concerns (i.e. *human wellbeing*).

Taken together, these studies provide preliminary insights into the complexities organisations face when integrating collaborative robots. However, they are limited in several ways. First, they offer only a partial understanding of the paradoxes that emerge during this process. Many studies lack robust conceptual definitions of paradoxes due to limitations in their methodological approaches. Specifically, studies that classify paradoxes based on—or inspired by—literature reviews of prior research focusing on barriers or challenges in implementing Industry 4.0 (I.4.0) or I.5.0 technologies (e.g., (Dieste et al., 2022; Pacheco and Iwaszczenko, 2024; Singh et al., 2024) often fall short. Critically, the concept of *barrier* typically reflects an organisation's inability to adapt to technological advancements and frames organisational change primarily as an episodic process. Consequently, relying on barrier-focused literature tends to confine conceptual frameworks of paradoxes to a narrow, techno-centric perspective.

Moreover, even in studies that draw on richer qualitative data (Ahlskog et al., 2024; Johansson et al., 2024; Kabel et al., 2024; Margherita and Braccini, 2024; Mishra et al., 2022; Moschko et al., 2023) the presentation of findings often reduces to a mere "*laundry list of paradoxes*" (Andriopoulos and Gotsi, 2017, p. 517). This approach obscures the dynamic interplay between the contradictory yet interdependent elements that makes paradoxes persistent.

Secondly, when exploring management strategies for addressing paradoxes, existing studies often resort to generating lists of best practices. These lists frequently converge on the well-established notion from foundational paradox literature that *both-and* strategies are the most effective approach (Smith and Lewis, 2011), and, therefore, overlook the broader spectrum of possible responses, including *either-or* strategies. Ultimately, this approach contradicts the core of paradox theory by prescribing clear-cut choices that prioritise both-and strategies while downplaying its opposite (Cunha and Putnam, 2019).

In our research, we seek to address these limitations by contributing empirically to a deeper understanding of how paradoxes unfold in practice. In doing so, we explore how they evolve, interact, and shape decision-making in human-robot configuration integration—navigating a landscape of organisational paradoxical tensions. Methodologically, the choice of C-GT and abductive reasoning, as presented in the next section, supports this endeavour by allowing us to move beyond static categorisations of paradoxes. C-GT enables a more process-oriented exploration of how paradoxes materialise, transform, and are managed across different organisational levels—micro, *meso* and macro. Abductive reasoning helps us remain open to emergent and 'unexpected' insights, capturing the complexity and unpredictability inherent in the interplay of paradoxical tensions.

3. Methodology

3.1. Rationale

Key elements of the C-GT method (Charmaz, 2000, 2006, 2017) centre on three interrelated aspects: the construction of *meaning*, the *co-creation of knowledge*, and the *legitimisation of theoretical interpretations* (Charmaz, 2006; Gibson and Hartman, 2014). A critical focus of C-GT is understanding how meaning is constructed through participants' experiences, organisational contexts, and broader socio-technical dynamics (Mills et al., 2006). Here, the emphasis is on how the study's participants have conceptualised their notion of human-robot collaboration within manufacturing environments, with these meanings and narratives further analysed and interpreted by us as researchers (Charmaz, 2000)—thus introducing the second key element.

C-GT emphasises the mutual creation of knowledge that emerges through the interaction between the researcher and the research context (Charmaz, 2006). In this regard, the generated knowledge evolves dynamically as the researchers interact with the participants and interpret their experiences (Schwartz-Shea and Yanow, 2013; J. A. Smith and Fieldsend, 2021). This co-creative process ensures that the results are firmly rooted in the empirical reality of the participants while incorporating the researchers' analytical contributions, situating the research within the historical and situational conditions of its production (Braun and Clarke, 2021; Charmaz, 2000, 2017). In this study, we also sought participants' reflections and comments on emerging insights, fostering a collaborative dialogue that further enriched the grounded knowledge and ensured its alignment with participants' lived experiences (Welch et al., 2022). Patterns identified in each interview were analysed and used to inform subsequent interviews, allowing for the iterative refinement of codes. We shared our interpretation of the gathered inputs from the research participants with them, further elaborating and deepening the investigation of the study phenomenon, yet remaining reflexive about how our background knowledge in systems ergonomics, sociology, automation, and robotics shaped the analysis.

The third key element of C-GT involves legitimising the use of theoretical perspectives and abductive reasoning to construct robust and plausible interpretations of the data. Abduction, as applied here, is a method of inference oriented towards theory building, enabling the identification of theoretically *surprising cases* and the formulation of multiple tentative explanations. It allows to go beyond mere descriptive accounts, uncovering underlying mechanisms, relationships, and explanations while maintaining a *level of reasonable doubt* (Timmermans and Tavory, 2012, 2022). This iterative process of theory building is guided by the interplay between empirical observations (i.e. inductive reasoning) and theoretical frameworks (i.e. deductive reasoning) (Vila-Henninger et al., 2024), ensuring that the resulting interpretations are both empirically grounded and conceptually robust (Charmaz, 2006; Mills et al., 2006).

3.2. Theoretical sampling

The dataset for this study comprised 39 in-depth interviews and a two-hour ethnographic site investigation conducted at an automotive plant in March 2024. The site visit focused on observing the integration of collaborative robots across various work configurations on the shop floor, including workspace arrangements and the organisational and technological contexts in which the robots operate.

The recruitment strategy combined theoretical sampling and snowballing techniques to identify and engage participants with critical expertise and insights into both the technical and human factors of collaborative applications. Theoretical sampling is the iterative approach to data collection, guided by the emerging analysis and the development of theory (Charmaz, 2006, 2017; Mills et al., 2006). It focuses on selecting data sources, such as key subject matter experts, that refine and elaborate theoretical categories as they evolve (Charmaz, 2006). As insights emerged from the early interviews, additional participants, who could address these new areas for exploration, were then contacted and recruited. As such, the sample encompassed subject-matter experts from various sectors, including industry representatives, trade organisations, robot manufacturers, researchers in human factors and engineering, and union representatives to address workforce and labour relations in the context of collaborative robotics (Table 3). This diversity ensured a broad spectrum of perspectives, particularly on the intersection of technological advancements and their implications for labour and workplace dynamics.

Fig. 4 provides an overview of the type of configurations in which cobots (as declared by the participating experts who have reported on the specific applications (*)) are deployed on the shop floor.

3.3. *Theoretical and abductive analysis*

The interviews, conducted between March and December 2024, lasted between one and one and a half hours, depending on the flow of conversation and participants' availability. All interviews were conducted in accordance with ethical guidelines, ensuring informed consent and participant confidentiality [*anonymised*]. Each session was recorded and transcribed verbatim, providing a detailed dataset that served as the foundation for a comprehensive exploration of the study's objective.

The interviews followed a loosely semi-structured format, guided by an initial script that explored high-level topics such as organisational details, automation history, and decisions related to the installation and use of collaborative applications. These broad topics facilitated rich discussions, generating initial broad categories that were revisited with participants, expanded, and further enriched. As the study progressed, ongoing analysis informed subsequent interviews.

Theoretical memo-writing guided the refinement of concepts and areas requiring further exploration. The memos created during this stage were both descriptive—summarising key information and outlining category dimensions—and conceptual, offering interpretative insights and identifying unexpected insights. The first insight was that the implementation of collaborative robots is widely perceived as a learning journey. This perspective remained consistent across industrial participants as the interviews progressed, guiding the focus towards identifying patterns in responses rather than specific feedback to individual industrial or contextual concerns.

Secondly, while initially the participants' responses mainly centred on the technical aspects of robot deployment on the shop floor, factors related to human involvement gradually emerged, demonstrating that the integration of collaborative robots across different work configurations is deeply intertwined with rethinking the role of human expertise. This realisation led to a more refined understanding of workforce skilling, adding nuance and context to discussions on reskilling and upskilling. This led to the uncovering of counterintuitive results—unexpected *surprises* (Tavory and Timmermans, 2014; Vila-Henninger et al., 2024)— such as the organisational effort to balance task optimisation with human task significance that incorporate ethical considerations driving the design towards human-robot collaboration.

To generate the analytical categories that formed the backbone of this study's results, we began with the identification of first-order categories, following a data-driven, iterative approach. These categories were developed through systematic coding of raw data, using in-vivo codes to ensure that the voices of research participants remained central to the analytical process. Data collected from field researchers underwent multiple rounds of coding, improving emerging categories through an iterative process that captured recurring patterns and salient issues within the dataset.

Initially, this descriptive, first-level coding reflected a grounded theory-inspired approach (Gioia et al., 2012). However, as data collection progressed, categories were refined and co-constructed with participating experts and further interpreted by the study's authors. Through this iterative engagement with the data, first-order categories were then aggregated into broader second-order categories, allowing for a structured progression from empirical observations to conceptual insights (Gioia et al., 2012).

This analysis engaged in a theory-building process that challenged existing theoretical assumptions about human-robot collaboration, enabling a critical interrogation of the dynamic interplay between paradoxes and the strategies organisations employ to navigate them (Brandt and Timmermans, 2021; Vila-Henninger et al., 2024). This approach allowed us to identify unexpected tensions and contradictions (Tavory and Timmermans, 2014), leading to the development of a deeper theoretical understanding of organisational paradoxical tensions paving the way towards human-robot collaboration. In doing so, this study moves beyond static categorisations, offering a processual, context-sensitive model that captures the ongoing evolution of tensions, decisions, and organisational responses in human-robot integration (Fig. 5).

Additionally, our analytical strategy incorporated a multi-level perspective, refining the understanding of micro, *meso*, and macro levels as interconnected dimensions within which individual, organisational, and broader system-level factors dynamically interact (Bitektine and Haack, 2014). This perspective was essential in illustrating how paradoxes in human-robot collaboration do not emerge in isolation but rather unfold across levels of organisational decision-making and technological adaptation.

3.4. *Quality criteria*

Trustworthiness criteria—namely, credibility, dependability, confirmability and transferability to support research rigour (Clarke et al., 2023; Denzin and Lincoln, 2017; Loh, 2013)—were applied in this study. *Credibility* refers to the accuracy and plausibility of the research results, ensuring that they authentically represent participants' experiences and perspectives (Charmaz and Bryant, 2011). In this study, we maintained extensive engagement with participants and the research context. This included spending time in the ethnographic field site and conducting multiple in-depth interviews, which allowed for a thorough understanding of the organisational and socio-technical dynamics surrounding collaborative applications. *Dependability* refers to the degree to which the research procedures adhere to constructivist practices (Clarke et al., 2023); detailed memos were kept throughout the research process to document decisions, emerging patterns, and interpretative reflections. These memos served as a tool for reflexivity, helping the researchers critically examine their interpretations and how they shaped the analysis. *Confirmability* ensures that the research results are firmly grounded in the collected data and that this link can be explicitly evidenced (Denzin and Lincoln, 2017). The data collection process included verbatim transcription of all participant interviews, preserving the richness and authenticity of their narratives. The theory generated from this study was grounded in the participants' own words, which were directly integrated into the analysis and theoretical development. Finally, *transferability* assesses the extent to which findings can be applied to other contexts or settings. While C-GT prioritises in-depth understanding of specific contexts, by incorporating a diverse range of participants with varying expertise and perspectives, this study ensured that its results captured a broad spectrum of experiences, enhancing their relevance to other manufacturing environments or socio-technical domains (Sinkovics et al., 2008).

Table 3
Overview of the expertise and knowledge brought by the study's theoretical sample.

'WHO'—contributing expert knowledge				'WHERE'—contextual insights	
#	Job Title	Years of experience	*Professional background* Sector	Type of organisation	No of cobots deployed*
P.01	Engineer	>15	*Industry* Automotive	Large (>500 employees) or Multinational organisations	100+
P.02	Innovation & Tools Manager	5–10	*Industry* Automotive	Large (>500 employees) or Multinational organisations	11–30
P.03	Senior Research Engineer	5–10	*Industry, Academia, Consultancy* Multisectoral/Manufacturing	Research & Industry organisation	1–10
P.04	Service and Solutions Manager	>15	*Industry, Consultancy* Automotive, Education, Engineering	(Cobot manufacturer) SME	N/A
P.05	Technical Services Manager	10–15	*Industry* Engineering	(Cobot manufacturer) Large (>500 employees) or Multinational organisations	N/A
P.06	Senior Technical Experimental officer	5–10	*Industry, Academia* Multisectoral	Academia, Engineering	1–10
P.07	Chief Automation Officer	>15	*Consultancy* Automotive, Construction, Education, Engineering, Textile	Research & Industry organisation	1–10
P.08	Factory Automation Manager	<5	*Industry* Engineering	Large (>500 employees) or Multinational organisations	31–50
P.09	Head of Manufacturing	>15	*Industry* Multisectoral	Large (>500 employees) or Multinational organisations	1–10
P.10	CEO	>15	*Industry* Multisectoral	SMEs Association	N/A
P.11	HO Actuators and End Effectors	>15	*Industry* Multisectoral	Large (>500 employees) or Multinational organisations	100+
P.12	System Integrator Sales Manager	>15	*Industry* Automotive, Education, Engineering, Transport	(Cobot manufacturer) SME	N/A
P.13	Assistant Professor	5–10	*Education* Engineering	Large (>500 employees) or Multinational organisations	1–10
P.14	Business Development Manager	>15	*Industry* Automotive, Chemical, Construction, Education, Health services, Engineering, Oil and gas production and refining, Transport	(Cobot manufacturer) SME	N/A
P.15	Senior Specialist | Manufacturing Automation & Robotics	>15	*Industry* Multisectoral	Large (>500 employees) or Multinational organisations	1–10
P.16	CEO	10–15	*Industry* Automotive, Construction	(Human-robot collaboration software) SME	N/A
P.17	Technical Specialist | Robotics	>15	*Industry* Engineering	Large (>500 employees) or Multinational organisations	0
P.18	Technology Advisor	>15	*Industry, Consultancy* Multisectoral	SMEs Association	N/A
P.19	Manufacturing Engineer | Automation & Integrated Systems	>15	*Industry, Consultancy* Automotive, Chemical, Construction, Engineering	Large (>500 employees) or Multinational organisations	1–10
P.20	Business Level Technology Specialist	10–15	*Industry* Transport	Large (>500 employees) or Multinational organisations	11–30
P.21	Manufacturing Research Engineer | IIoT	5–10	*Industry* Multisectoral	Large (>500 employees) or Multinational organisations	1–10
P.22	Manufacturing Development Engineer	5–10	*Industry* Multisectoral	Large (>500 employees) or Multinational organisations	1–10
P.23	Additive & Joining Repair Specialist	>15	*Industry* Transport	Large (>500 employees) or Multinational organisations	1–10
P.24	Junior Manager	<5	*Industry* Engineering	Large (>500 employees) or Multinational organisations	1–10
P.25	Manufacturing Engineer | Automation	>15	*Industry* Transport	Large (>500 employees) or Multinational organisations	1–10
P.26	Manufacturing Technician	<5	*Industry* Engineering	SME	1–10
P.27	Manufacturing Development Engineer	5–10	*Industry* Multisectoral	Large (>500 employees) or Multinational organisations	1–10
P.28	Engineering and Technology	<5	*Industry* Transport	Large (>500 employees) or Multinational organisations	1–10
P.29	UK Business Development Manager	>15	*Industry* Automotive, Chemical Education, Health services, Engineering, Textile	(Cobot manufacturer) Large (>500 employees) or Multinational organisations	N/A
P.30	Robotics, Automation & Quality Manager	5–10	*Industry* Multisectoral	SME	1–10
P.31	Full Professor of Automation and Robotics	>15	*Industry, Academia* Education	Large (>500 employees) or Multinational organisations	1–10

(*continued on next page*)

Table 3 (*continued*)

'WHO'—contributing expert knowledge				'WHERE'—contextual insights	
#	Job Title	Years of experience	*Professional background* Sector	Type of organisation	No of cobots deployed*
P.32	Senior Lecturer in Human Factors	>15	*Industry, Academia* Education	Large (>500 employees) or Multinational organisations	1–10
P.33	HM Principal Specialist Inspector	>15	*Industry* Multisectoral	(H&S auditing and inspection) Large (>500 employees) or Multinational organisations	N/A
P.34	Head of Science and Technology	>15	*Industry* Food	Large (>500 employees) or Multinational organisations	0
P.35	Technical Consultant	>15	*Industry, Consultancy* Automotive	SME	1–10
P.36	Senior Manufacturing Engineer	>15	*Industry* Engineering	Large (>500 employees) or Multinational organisations	1–10
P.37	Senior Lecturer AI & Robotics	>15	*Industry, Academia, Consultancy* Education	Large (>500 employees) or Multinational organisations	1–10
P.38	Principal Manufacturing Engineer	>15	*Industry* Engineering	Large (>500 employees) or Multinational organisations	1–10
P.39	Trade Union Official	>15	*Industry* Automotive, Construction, Engineering, Public service, Transport	(Trade Union Association) Large (>500 employees) or Multinational organisations	N/A

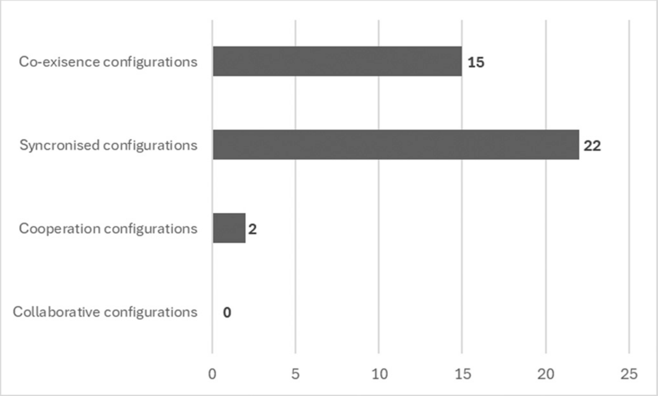


Fig. 4. Work configurations currently designed for cobot deployment.

4. Results

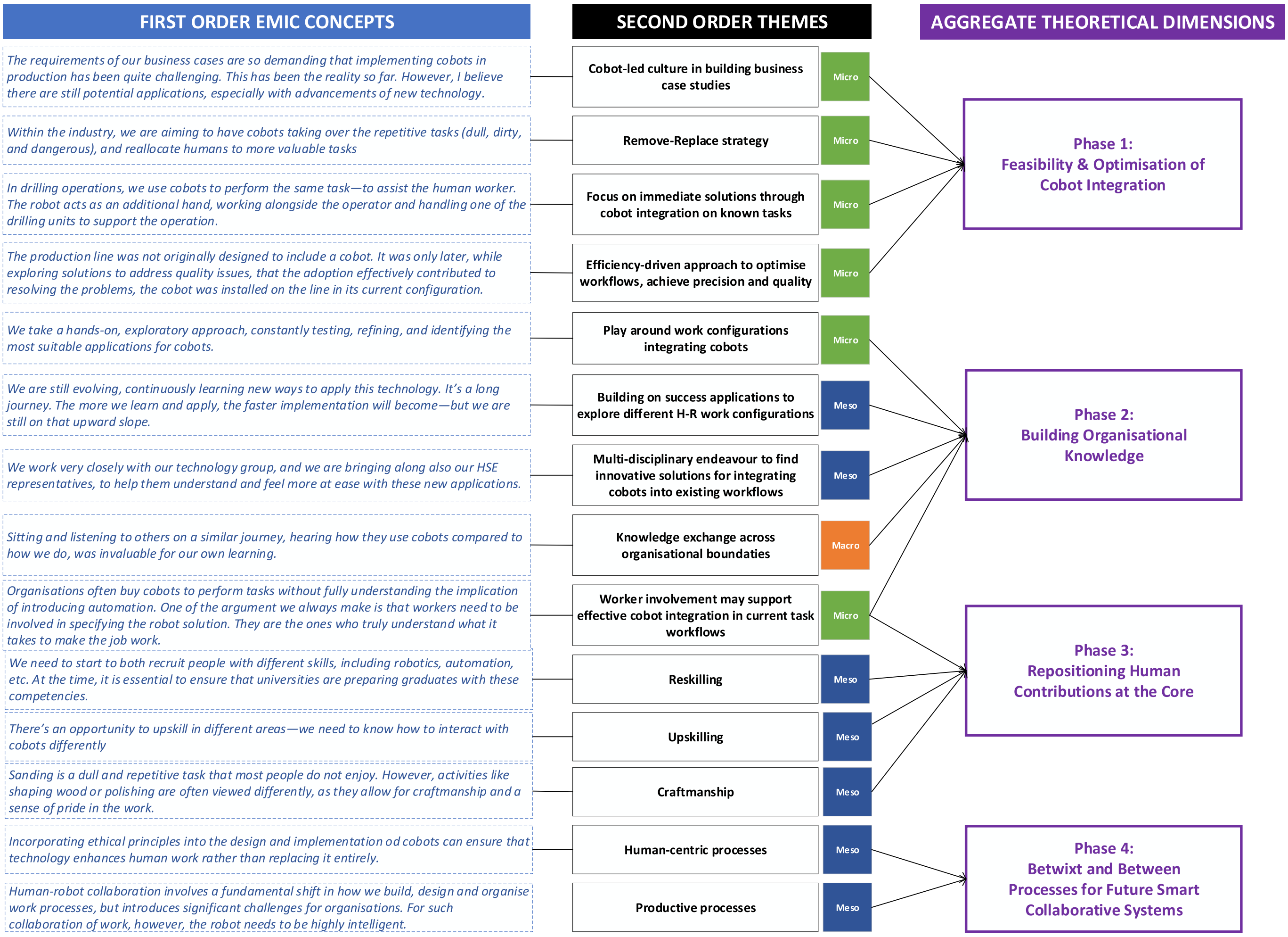
4.1. Phase 1: Feasibility & optimisation of collaborative robot integration

As collaborative robots have only been actively implemented in industry for a relatively short time (in Europe, in the last ten years (Patil et al., 2023)), a recurring pattern among the cobot manufacturer participants highlights the discrepancy between expectations and the practical realities of cobot implementations. Organisations often approach automation with preconceived notions about the adaptability and seamless integration of collaborative robots, yet real-world deployments reveal limitations that require adjustments in practice. As one participant noted, "*the terminology and conceptual framing of robotic applications carry significant weight, continuing to shape how organisations perceive their utility and risks*" *[P.04, Service and Solutions Manager, Cobot manufacturer]*). Cobot manufacturer participants (e.g. *[P.05]*, *[P.14]*, and *[P.29]*) consistently acknowledged that companies may initially overestimate what collaborative robots can achieve, expecting 'true collaboration' without fully grasping the complexities of task allocation, system integration, and operational constraints. Such misalignment can lead to underutilisation or even abandonment of robotic solutions when they fail to meet inflated expectations. However, as organisations gain experience with collaborative robots and develop a more nuanced understanding of their capabilities, this expectation-reality divide appears to be narrowing.

In our research dataset, both SMEs and Large organisations seem to still be adapting to this new paradigm, which is contingent on developing a robust business case that evaluates technical feasibility, workflow compatibility, and broader operational and business implications. Some industry representative reflected that, during this initial exploration phase, the majority of business cases ultimately have proved ineffective, leading to the decision to forgo cobot integration.

> "*When I receive a request—whether it's for an inspection system, a new drilling process, or a solution to improve an existing process—we conduct a study and develop a business case. There are many factors to consider in this process. In aerospace, the two main challenges are size—since collaborative robots are relatively small compared to aerospace components—and precision, which demands far greater accuracy than what many robotic systems currently offer. The level of accuracy required in aerospace is significantly higher than in many other industries. As a baseline, our systems must achieve an accuracy of at least 0.5 millimetres. This is just the minimum requirement, and there is always a need for further improvement. Achieving this level of precision also requires accounting for a complex chain of error propagation and tolerance variations across all systems. After investing tens of millions in time, materials, and effort to make this happen, we had nothing. Yet today, four years later, we finally have one.*" [P.11, HO Actuators and End Effectors, Large organisation]

Key barriers primarily may revolve around the specific task or workflow's technical feasibility but also extend to challenges such as securing budget allocations, demonstrating a clear return on investment (ROI), and ensuring alignment with organisational safety policies and risk management frameworks. Notably, organisations remain hesitant to adopt collaborative tasks due to the complexities of complying with evolving safety standards. A major challenge is not the cost of purchasing collaborative applications alone—though costs can rise significantly with the addition of custom end-effectors or modifications compared to standard implementations—but rather what surrounds the actual implementation on the shop floor. Beyond the cost of the machine, companies must invest in sensors, risk assessments, and certification processes to ensure that its integration meets safety standards. For instance, if a collaborative robot is equipped with a sharp end-effector, the safety certification of the robot does not cover this addition, as it introduces new safety risks, requiring a complete new risk assessment and certification of the new system adding complexity and cost (as it was noted by the H&S inspector *[P.33, HM Principal Specialist Inspector]*, and the academics experts specialising in safety considerations in human-robot interaction—e.g. *[P.13]* and *[P.37]*). Additionally, organisations must have the necessary expertise to design tasks appropriately and



FIRST ORDER EMIC CONCEPTS	SECOND ORDER THEMES	
The requirements of our business cases are so demanding that implementing cobots in production has been quite challenging. This has been the reality so far. However, I believe there are still potential applications, especially with advancements of new technology.	Cobot-led culture in building business case studies	Micro
Within the industry, we are aiming to have cobots taking over the repetitive tasks (dull, dirty, and dangerous), and reallocate humans to more valuable tasks	Remove-Replace strategy	Micro
In drilling operations, we use cobots to perform the same task—to assist the human worker. The robot acts as an additional hand, working alongside the operator and handling one of the drilling units to support the operation.	Focus on immediate solutions through cobot integration on known tasks	Micro
The production line was not originally designed to include a cobot. It was only later, while exploring solutions to address quality issues, that the adoption effectively contributed to resolving the problems, the cobot was installed on the line in its current configuration.	Efficiency-driven approach to optimise workflows, achieve precision and quality	Micro
We take a hands-on, exploratory approach, constantly testing, refining, and identifying the most suitable applications for cobots.	Play around work configurations integrating cobots	Micro
We are still evolving, continuously learning new ways to apply this technology. It's a long journey. The more we learn and apply, the faster implementation will become—but we are still on that upward slope.	Building on success applications to explore different H-R work configurations	Meso
We work very closely with our technology group, and we are bringing along also our HSE representatives, to help them understand and feel more at ease with these new applications.	Multi-disciplinary endeavour to find innovative solutions for integrating cobots into existing workflows	Meso
Sitting and listening to others on a similar journey, hearing how they use cobots compared to how we do, was invaluable for our own learning.	Knowledge exchange across organisational boundaties	Macro
Organisations often buy cobots to perform tasks without fully understanding the implication of introducing automation. One of the argument we always make is that workers need to be involved in specifying the robot solution. They are the ones who truly understand what it takes to make the job work.	Worker involvement may support effective cobot integration in current task workflows	Micro
We need to start to both recruit people with different skills, including robotics, automation, etc. At the time, it is essential to ensure that universities are preparing graduates with these competencies.	Reskilling	Meso
There's an opportunity to upskill in different areas—we need to know how to interact with cobots differently	Upskilling	Meso
Sanding is a dull and repetitive task that most people do not enjoy. However, activities like shaping wood or polishing are often viewed differently, as they allow for craftmanship and a sense of pride in the work.	Craftmanship	Meso
Incorporating ethical principles into the design and implementation od cobots can ensure that technology enhances human work rather than replacing it entirely.	Human-centric processes	Meso
Human-robot collaboration involves a fundamental shift in how we build, design and organise work processes, but introduces significant challenges for organisations. For such collaboration of work, however, the robot needs to be highly intelligent.	Productive processes	Meso

Fig. 5. Data structure.

ensure that the integration of collaborative robots aligns with both operational efficiency and workplace safety. Moreover, the complexity of physical space allocation to accommodate hybrid work environments presents an additional challenge (e.g. *[P.08]* and *[P.11]*), highlighting the need for a paradigm shift in industrial design practices to enable meaningful adoption, rather than merely retrofitting collaborative robots into existing setups that may not fully support their intended capability.

> *I see human-robot phenomenon as developing. The field still requires significant progress in process maturity, safety integration, and operational readiness before it becomes widely adopted.* [P.37, Senior Lecturer AI & Robotics, Academia/School of Engineering]

Rather than pursuing radical redesigns of production reconfigurations, organisations initially tend to adopt conservative integration patterns, incorporating collaborative robots into existing workflows and configurations (as witnessed by *[P.03]* and *[P.07]*; and further discussed with industry representatives, such as: *[P.22]* and *[P.27]*). When first integrated, the deployment of collaborative applications within participating organisations typically follows a *remove-replace* strategy, wherein collaborative robots are introduced to perform known tasks previously performed by human workers. In these early stages, organisations prioritise *simpler applications* that can be redesigned to accommodate robotic capabilities, focusing on immediate solutions that align with existing processes. This efficiency-driven mindset ensures that tasks that are straightforward to automate are addressed first, optimising workflows and minimising disruption.

> *"As automation continues to advance, we are likely to tackle the simpler applications first—those that can be redesigned to suit robots. Once those are addressed, we'll begin to move into more complex applications that require both human and robotic contributions."* [P.07, Chief Automation Officer, Research & Industry organisations]

This approach is driven by immediate concerns such as *efficiency and production quality*, aiming to achieve greater precision and consistency in defined processes. Cobot tasks may also include those that *pose ergonomic risks for workers*, such as repetitive or physically demanding activities. In this phase, technology is conceived as a practical tool to optimise rather than reconfiguring workflows involving human and robots in shared tasks.

> *"The first robot we introduced was primarily brought in as a health and safety measure. We had a process where we dipped our units into a molten pool of solder, which was entirely done by hand. The repeatability and quality of that process were always bearing down on the operator. We saw an opportunity to automate this, which we did, and it has been very successful. Essentially, we've removed the operator from that equation."* [P.36, Senior Manufacturing Engineer, Large organisation]

As one participant noted *[P.11, HO Actuators and End Effectors, Large organisation]*, in their company, the adoption of collaborative robots in drilling operations has been driven primarily by ergonomic concerns rather than improvements in speed or task quality. Drilling tasks often involve kneeling, drilling overhead, or lifting heavy drilling units. While these conditions may not present immediate issues, they can lead to long-term musculoskeletal strain, particularly after years or even decades of repetitive work. However, the difficulty in quantifying these ergonomic challenges may contribute to reluctance in adopting collaborative robots, especially among workers who fear job displacement. Additionally, "*the benefits of improved ergonomics are not easily measurable in business cases*", making it still challenging to justify such investments *[P.10, CEO, SMEs Association]*.

4.2. Phase 2: Building organisational knowledge

After the initial implementation of collaborative robots, organisations appear to experiment with different applications and robot configurations, gradually refining their use—as attested by *[P.01]*, *[P.07]*, *[P.15]*, *[P.30]*, *[P.35]*, *[P.36]*, and *[P.38]*. Over time, this process evolves into a *learning journey*, where companies continuously adapt and explore new ways of cobot integration into their operations—to describe this process, the term "*play around*" was suggested by some industry representatives, highlighting the importance of a hands-on, exploratory mindset in testing, refining, and identifying suitable applications for collaborative robots.

> *"We had a manager at the time that managed to get some budget to buy cobot. And we just **played with it** for a while. And that's when we start seeing, we started seeing what we could use it for."* [P.38, Principal Manufacturing Engineer, Large organisation]

During the interviews with industry representatives, a pattern emerged: early positive outcomes serve as a catalyst for gradual refinement, encouraging companies to expand and optimise their integration strategies over time—with specific examples provided by *[P.35]*, *[P.36]*, and *[P.38]*. Critically, this phase focuses on building organisational knowledge by systematically testing use cases to develop confidence in the capabilities of cobots, and expand their applications to new workflows and processes—*[P.10]* and *[P.14]*. This progression consistently shows a gradual shift from basic coexistence, where robots function independently of human workers, towards more integrated cooperation, which requires higher levels of adaptability and technical precision.

> *"We've replaced a person with a collaborative robot for an existing operation, learning from the process along the way. Now, we're looking ahead—working with the technology team to design systems with features that enable automation and the use of collaborative robots from the outset. I believe we're on the cusp of that shift. The past three to four years have allowed us to build the knowledge needed to inform and shape these designs."* [P.38, Principal Manufacturing Engineer, Large organisation]

Although many interviewees stated that these efforts often remain still experimental—for instance, multinational companies, in particular, have dedicated R&D departments focused on testing and evaluating new cobot applications, such as indicated by *[P.21]* or *[P.25]*—and require iterative adjustments to align with production constraints, operational goals, and safety considerations, they play a crucial role in refining the path towards human-robot collaboration configurations. Critically, successfully integrating collaborative robots demands a deep understanding of existing operations, coupled with the ability to analyse and restructure workflows to align with the capabilities and limitations of current robotic applications. These continuous adaptations pave the way for innovation, unlocking the broader potential for deeper collaborative configurations.

Indeed, many replies indicate that the transition towards more advanced human-robot interaction is not just a technical challenge—it is a multidisciplinary effort that involves research, development, and cross-functional expertise. While the literature often highlights technical barriers, such as the limitations of robotic capabilities, these challenges exist but are only part of the equation. It was highlighted multiple times that engineering teams, safety representatives, and technology specialists must work together to refine safe, efficient, and practical robotic applications.

> *"As we introduce more collaborative systems, we are learning that technical feasibility alone does not determine success. It requires a combined effort from research, production, and health and safety teams to ensure a seamless transition."* [P.36, Senior Manufacturing Engineer, Large organisation]

Furthermore, the industry representatives underscored the critical role of peer learning in the journey towards effective cobot adoption (e.g. *[P.11]*, *[P.15]*, *[P.23]*, *[P.28]*, *[P.34]*, *[P.35]*, *[P.36]*, *[P.38]*). For many participants, in industry events and discussions with other practitioners were instrumental in identifying new applications, addressing challenges, and exchanging insights on robotic deployment. Exposure to different implementations offer fresh perspectives on best practices, allowing participants to benchmark progress, learn from others' successes and setbacks, and problem-solving strategies. As one participant highlighted, hearing how others approached similar challenges was an "*eye-opener*" that emphasised the importance of building on existing knowledge within the broader industry community:

> *"The key takeaway for me from attending that event was listening to others who are on a similar path—seeing how they use it compared to how we do. That was invaluable for our own learning. It really highlighted that I need to get out more, attend more events like this, and talk to others about their experiences. Until now, I've only seen what we're doing here. You can watch things on TV or YouTube, but you rarely get the chance to have real conversations with people who are actually working with it. That, for me, was **a real eye-opener**."* [P.38, Principal Manufacturing Engineer, Large organisation]

However, challenges persist in knowledge-sharing across the industry, especially in situations where organisations have developed robotic solutions internally but were unwilling to document or share their findings for broader industry benefit.

4.3. Phase 3: Repositioning human contribution at the core

Beyond technical expertise, academic experts e.g. *[P.32, Senior Lecturer in Human Factors, Academia]* and *[P.37, Senior Lecturer AI & Robotics, Academia]* highlighted how worker participation plays a fundamental role in shaping trust, acceptance, and the perceived value of automation within the company. Without their meaningful involvement, automation initiatives may fail to align with real-world operational needs, creating barriers to both efficiency and adoption. To this end, workers should be involved in the effective design and deployment of human-robot work configurations. Indeed, it was highlighted that many workers "*possess unique, tacit knowledge about their tasks, including contextual nuances and operational challenges that may not be immediately apparent to engineers or system designers*" *[P.39, Trade Union Official, Large organisation]*.

However, based on discussions with industry representatives, it appears that worker participation in automation design remains inconsistent across organisations. While some companies indicate that they engage employees in process reconfiguration suggestions (as commented by *[P.01, Engineer, Large organisation]* and *[P.02, Innovation & Tools Manager, Large organisation]*), others seem to confine their involvement to post-implementation adjustments. Despite this, as automation continues to advance, human involvement becomes indispensable due to robots' inherent limitations in versatility, adaptability, and sensory capabilities (among others: *[P.08]*, *[P.15]*, and *[P.39]*).

Across the dataset, responses converged in indicating that deeper integration of collaborative robots in manufacturing increases task interdependence between humans and robots, highlighting a growing need for workforce capability development to support collaboration and adaptability. *Reskilling* becomes essential to align workers' skills with evolving technologies. Participants noted that this shift demands continuous development, particularly as technology adoption accelerates (*[P.01]*, *[P.02]*, *[P.04]*, *[P.07]*, *[P.15]*, *[P.16]*, *[P.20]*, *[P.32]*, *[P.36]*, *[P.39]*), emphasising the need for workers to adapt to more digitalised roles and troubleshoot robot malfunctions or errors in real time.

> "*Interacting with collaborative systems may require operators to learn new tasks that are not directly related to manufacturing but instead focus on controlling and managing the robot. This introduces a new digital dimension to the operator's work.*" [P.01, Engineer, Large organisation]

Beyond reskilling, the continued integration of collaborative robots necessitates *upskilling strategies* that extend beyond technical and digital proficiency, equipping workers to engage meaningfully with these applications (*[P.01]*, *[P.02]*, *[P.32]*, *[P.36]*, *[P.38]*). Industry participants stressed that upskilling involves a deeper understanding of robotic principles, functionalities, and their contextual relevance within production systems. Workers must be able—beyond troubleshooting skills—to anticipate and respond to system changes, ensuring reliability, efficiency, and consistency in manufacturing processes (*[P.35]*, *[P.36]*, and *[P.38]*). This evolution in upskilling requirements expands the scope of manufacturing roles, requiring operators to combine technical expertise with critical thinking and problem-solving skills—both essential for managing complex human-robot environments and driving efficient, innovative solutions.

> *"We need worker to first understand their own operations and then be upskilled to comprehend how the collaborative robot functions, including its limitations and requirements. Upskilling isn't just about programming; it's about gaining a deep consideration of the system within the context of existing processes to ensure consistent and reliable operation. This level of understanding is crucial. For instance, if something changes—such as a tweak made by someone—recognising and addressing such adjustments requires an understanding of both the robotic application and the manufacturing process."* [P.38, Principal Manufacturing Engineer, Large organisation]

The shift from reskilling to upskilling opens the possibility for organisations to reevaluate workers' roles—i.e. empowering skilled workers *to take an active role in governing and overseeing processes*, positioning them as key agents in managing, adapting, and optimising tasks within production workflows (*[P.02]*, *[P.07]*, *[P.32]*, *[P.35]*, *[P.36]*, and *[P.38]*). Contrary to common assumptions, as automation continues to reshape the manufacturing shop floor, it appears to act as an 'amplifier' of workers as knowledge contributors, reinforcing the need for human oversight and elevating skilled workers to the role of strategic *orchestrators* in an increasingly technology-driven future. In this capacity, worker expertise ensures the effective integration of advanced technologies into production processes (*[P.01]*, *[P.10]*, *[P.11]*, *[P.18]*, *[P.32]*, *[P.36]*, *[P.38]*, and *[P.39]*). Furthermore, participants highlighted high-value tasks, such as bespoke customisation in high-end automotive manufacturing, as examples where quality and precision will continue to depend on human expertise.

In this context, the concept of *craftsmanship*, once central to pre-industrial economies, was advanced (directly referred to by *[P.01]*, *[P.02]*, *[P.04]*, *[P.35]*, *[P.38]*, and *[P.39]*) to articulate the distinctive value of human involvement in these processes. Craftsmanship, as defined in the participants' contributions, thrives on individual expertise—i.e. the application of specialised knowledge, skill, and care in producing work of high quality and personalisation where human role remains indispensable. For example, robotic-assisted assembly lines enable precision tasks, while humans retain control over customisation and final adjustments. Hybrid systems, where repetitive or physically demanding tasks are allocated to robots while humans focus on complex, adaptive roles, can indeed provide a viable pathway forward.

> "*Human intervention provides added value that a robot cannot replicate. This type of attention and care, rooted in the operators' expertise and training, imbues the product with an identity that goes beyond mere functionality. Moreover, highly advanced automation is often associated with mass production. It is hard to imagine a robot crafting 20 Ferraris with the same level of attention that a human team dedicates to producing just 5 vehicles. Artisan craftsmanship, perceived quality, and the story a brand represents are elements that cannot be automated.*" [P.02, Innovation & Tools Manager, Large organisation]

4.4. Phase 4: Betwixt and between processes for future smart collaborative systems

Advancements in technology and the aspiration to deploy *smart-er* robotic systems are not without *ethical and social implications.* Concerns about the "*potential for labour stratification*" (*[P.02]*, *[P.32]*, and *[P.39]*) were raised, especially where lower-value, repetitive roles are relegated to less skilled or vulnerable workers. This division risks creating inequities in how the benefits of automation are distributed across the workforce. Organisations operating in low-cost labour markets, for example, may prioritise cost efficiency over meaningful work, "*perpetuating exploitative practices that undermine worker dignity*" *[P.39, Trade Union Official, Large organisation]*. Some participants from large organisations (e.g. *[P.02]* and *[P.17]*) argued that companies with long-standing histories and structured management practices are better equipped to address this dualism thoughtfully. Such organisations face both the challenge and the opportunity to embrace a more ethical pathway by fostering work environments that are dignified and sustainable, ensuring the equitable distribution of automation's benefits across the workforce.

> "*Another critical factor to consider is labour cost. When labour is inexpensive and flexible—meaning organisations are not constrained by rigid contracts—they may lack the incentive to optimise processes. In such contexts, hiring and firing workers on demand becomes an attractive option. Labour can adapt to existing processes, even in disorganised or inefficient conditions, as long as it remains cost-effective. Efficiency may not be a priority under these circumstances, as organisations can sustain themselves despite the inefficiencies.*" [P.31, Full Professor of Automation and Robotics, Academia]

Inclusive training approaches that account for diverse learning needs are critical to ensuring that all workers—irrespective of age, experience, or background—can adapt to new technologies and thrive in transformed roles. As one participant noted, the challenge for organisations is not merely to respond to technological trends but to do so thoughtfully, ensuring long-term sustainability and innovation. This requires investments in training, process adaptation, and worker engagement, recognising that the integration of collaborative systems is a moral and cultural endeavour (*[P.01]*, *[P.03]*, *[P.04]*, *[P.06]*, *[P.09]*, *[P.13]*, *[P.15]*, *[P.20]*, *[P.31]*, and *[P.37]*). Challenges exist due to variability in worker motivation and baseline skills. While some employees are open and eager to learn, others face significant difficulties due to lack of interest or foundational skills (*[P.01]*, *[P.02]*, *[P.07]*, and *[P.32]*). Age and experience are significant factors (*[P.01]*, *[P.32]*), influencing the ease or difficulty of adaptation to new technologies.

To this end, participants suggested considering the importance of broader implications of the evolving socio-technical complexities of the workplace, encompassing factors such as "*the emotional, psychological, and cultural dimensions of work*" *[P.03, Senior Research Engineer, Research & Industry organisation]*. This includes addressing mental demands, work stressors, and the availability of workplace resources, all of which are integral to fostering a sustainable and effective human-robot integration on the shop floor. Crucially, as emerged in the co-meaningful interaction between the participants and the authors during the interview, this necessitates a framework of ethical organisational governance—the establishment of principles, frameworks, and accountability mechanisms that prioritise fairness, transparency, and worker wellbeing while fostering the responsible and sustainable adoption of automation. For example, integrating smart robotic systems raises questions about accountability, data reliability, and the potential for surveillance in manufacturing environments.

Another aspect of human-centric governance is ensuring that *meaningful work* is preserved by empowering workers to take on roles and responsibilities aligned with their expertise (as suggested by *[P.07]*, *[P.20]*, *[P.39]*). While repetitive, undesirable tasks are naturally suited for automation, other tasks provide workers with a sense of ownership, purpose, and expertise, positively impacting the psychological and social aspects of the workplace. An example from food illustrates this dynamic: although placing slices of ham on sandwiches may seem a repetitive task suited for automation, some workers take pride in arranging it aesthetically, viewing it as more than a mechanical process (as discussed during the interview with *[P.34, Head of Science and Technology, Large organisation]*. If automation focuses solely on eliminating tasks deemed unproductive, it risks reducing workers' roles to something less engaging and detached from their sense of contribution. Yet it was frequently highlighted that even seemingly simple tasks can hold intrinsic value, reinforcing a sense of fulfilment and meaningfulness.

> *"Take welders, for example. Welding is a skilled job, as are painting or decorating cakes. When considering welding, you'd ideally allocate skilled welders to tasks that require their expertise. For repetitive tasks, like producing 300 identical pieces, it makes more sense to deploy robots. This approach aligns with the principle of automating the "three Ds"—dull, dirty, and dangerous tasks—while reserving skilled human workers for roles where their abilities shine."* [P.07, Chief Automation Officer, Research & Industry organisation]

In this regard, it was highlighted that establishing clear policies and regulations that align with workforce concerns presents a potential avenue for gaining union support. Industry participants acknowledged that structured policies—particularly those ensuring fair treatment and job security—could serve as a bridge between technological advancement and worker advocacy, ultimately facilitating a more balanced and inclusive approach to automation.

From a technical standpoint, participants widely agreed that 'real' human-robot collaboration remains unattainable unless current technological limitations are addressed (e.g. *[P.03]*, *[P.04]*, *[P.06]*, *[P.07]*, *[P.29]*, *[P.31]*, *[P.37]*). Present-day collaborative robots lack the ability to reason, adapt, and predict human behaviour in real time, significantly constraining their role in dynamic, shared work environments. True collaboration requires cognitive and smart robotic systems capable of autonomous decision-making, situational awareness, and seamless interaction with human counterparts. Participants noted that advances in AI-driven robotics, particularly in machine learning, perception, and adaptive control, are seen as essential to bridging this gap (e.g. *[P.03]*, *[P.04]*, *[P.06]*, *[P.07]*, *[P.29]*, *[P.31]*, *[P.37]*). Future smart robotic systems must integrate context-aware intelligence, real-time learning capabilities, and enhanced sensory perception to enable proactive rather than reactive interactions. These systems must not only process environmental data but also anticipate human actions, adjust to unstructured environments, and engage in fluid task coordination with human workers.

> *Having that foresight, that technology is there and it's starting to become more affordable as well. Gives me that hope that it will come there.* [P.04, Service and Solutions Manager, SME]

However, participants highlighted a significant divide between technological advancements in academia and their real-world industrial application (e.g. *[P.03]*, *[P.04]*, and *[P.07]*). While research in cognitive robotics and human-robot interaction has made notable strides in laboratory settings, many of these innovations remain difficult to scale, costly to implement, or insufficiently tested in real-world manufacturing environments. It was pointed out that the transition from experimental AI-driven robotic systems to practical, deployable solutions in industry remains slow due to challenges in standardisation, safety certification, and the need for robust, fail-safe architectures that can operate reliably on the shop floor (*[P.04]*, *[P.16]*, and *[P.29]*). Moreover, the high costs associated with developing and deploying truly autonomous collaborative robots present a major barrier. It was frequently highlighted that particularly small and medium-sized enterprises (SMEs) often lack the resources to invest in cutting-edge AI-driven automation. Participants stressed the need for gradual, phased integration strategies, where improvements in robotic intelligence and adaptability are incrementally introduced while maintaining cost-effectiveness and operational feasibility.

Reflecting on the meaning of collaboration from a production perspective, a few participants suggested that achieving full human-robot collaboration requires strategic deployment and organisational adaptation to create systems where humans and robots complement each other's strengths rather than simply coexist. While synchronised configurations are well-suited for workflows that involve task substitution, true collaboration demands that both human and robotic agents deeply understand each other's roles. Collaboration at this level is less about integrating robots into existing processes and more about co-designing processes that inherently leverage their respective strengths. In other words, from a labour design perspective, this will necessitate a fundamental shift in rethinking traditional process structures—i.e. how work processes are built, designed, and organised.

> *Take, for example, the disassembly of EV batteries—a complex process involving multiple complex steps like removing lids, disentangling wires, unbolting components, and extracting battery cells. This kind of task requires close human-robot collaboration because of its complexity and the need for precision at every step. In such scenarios, the robot must understand what the human is doing and adjust its actions accordingly, while the human remains aware of the robot's tasks and intentions. This is not a sequential or synchronised relationship; it's a cooperative, or even collaborative effort where the human and robot work together within the same space and time, sharing the same goal. [...] For such collaboration to work, the robot needs to be highly intelligent. It must understand its environment, the human worker, and the task at hand. This involves integrating three key elements: human factors, robot factors, and environmental factors. The robot must navigate these elements effectively, making it a subset of all these considerations.* [P.03, Senior Research Engineer, Research & Industry organisation]

Others suggested that the focus should not be on enforcing collaboration for its own sake but rather on identifying tasks that inherently require shared agency and mutual adaptability. This approach calls for fostering a culture of trust and innovation, and advancing technology to bridge existing gaps in robot capabilities to enable meaningful human-robot interaction. Achieving this level of collaboration poses significant challenges for organisations:

> *Engineering principles often prioritise simplification, breaking down complex processes into manageable steps before automation. This approach aligns with Taylorism, which enhances productivity by reducing the skill required for individual tasks. Collaboration, by nature, introduces complexity, making it counterintuitive from an engineering perspective unless the task necessitates it. The challenge lies in identifying tasks where collaboration is indispensable rather than designing tasks to force collaboration.* [P.31, Full Professor of Automation and Robotics, Academia]

Finally, while key drivers for the increasing integration of collaborative systems—such as labour shortages, productivity enhancement, and addressing skill gaps—are recognised, industry participants do not yet perceive human-robot collaborative configurations as the ultimate goal or endpoint, but rather as a gradual process of technological and organisational adaptation. Looking across the different inputs, the maturity of an organisation in understanding and optimising its processes plays a crucial role in unlocking the full potential of collaborative robotics. It was predicted that as automation costs decline and technical capabilities expand, more organisations may begin to recognise the internal need and opportunity to explore advanced human-robot configurations, moving beyond basic automation towards deeper collaboration.

> *From a business perspective, this raises critical questions: Will changing the process add value? Will it generate more revenue? Can the investment in such changes yield the right return? And most importantly, if the current process is working fine, is it even necessary to change it? These questions are central to whether companies decide to adopt synchronised, cooperative or more collaborative workflows.* [P.16, CEO, SME]

5. Discussion

This paper aimed to explore the paradoxical organisational tensions that shape the deployment of collaborative applications in manufacturing, particularly in work configurations that advance towards human-robot collaboration, where human workers and robotic systems are expected to function as hybrid teams within the future I.5.0 paradigm. In what follows, we present the theoretical model that emerged from the study's empirical investigation (Section 5.1), and discuss the substantive and theoretical contributions to the literature on cobot integration in industrial settings (Section 5.2).

5.1. Study's theoretical model

In line with previous studies adopting Paradox Theory to investigate the transition towards I.5.0 (see, for example, (Dieste et al., 2022; Johansson et al., 2024; Margherita and Braccini, 2024)), we found that the integration of human-robot collaborative systems is characterised by three key paradoxes: the *performing paradox*, which emerges from the tension between *technical optimisation* vs *human wellbeing*; the *learning paradox*, which unfolds between *incremental* vs *radical innovation*— or, in other words, between *exploitation* vs *exploration*; and the *organising paradox*, where organisations must navigate the relationship between *automation* vs *augmentation* in everyday work processes. However, in our study, we challenge a central tenet in the literature which suggests that organisations experiencing a smooth transition tend to adopt a paradox mindset from the outset (Johansson et al., 2024; Moschko et al., 2023; Smith and Lewis, 2011). This means that organisations are able to recognise the paradoxical nature of competing demands and to adopt

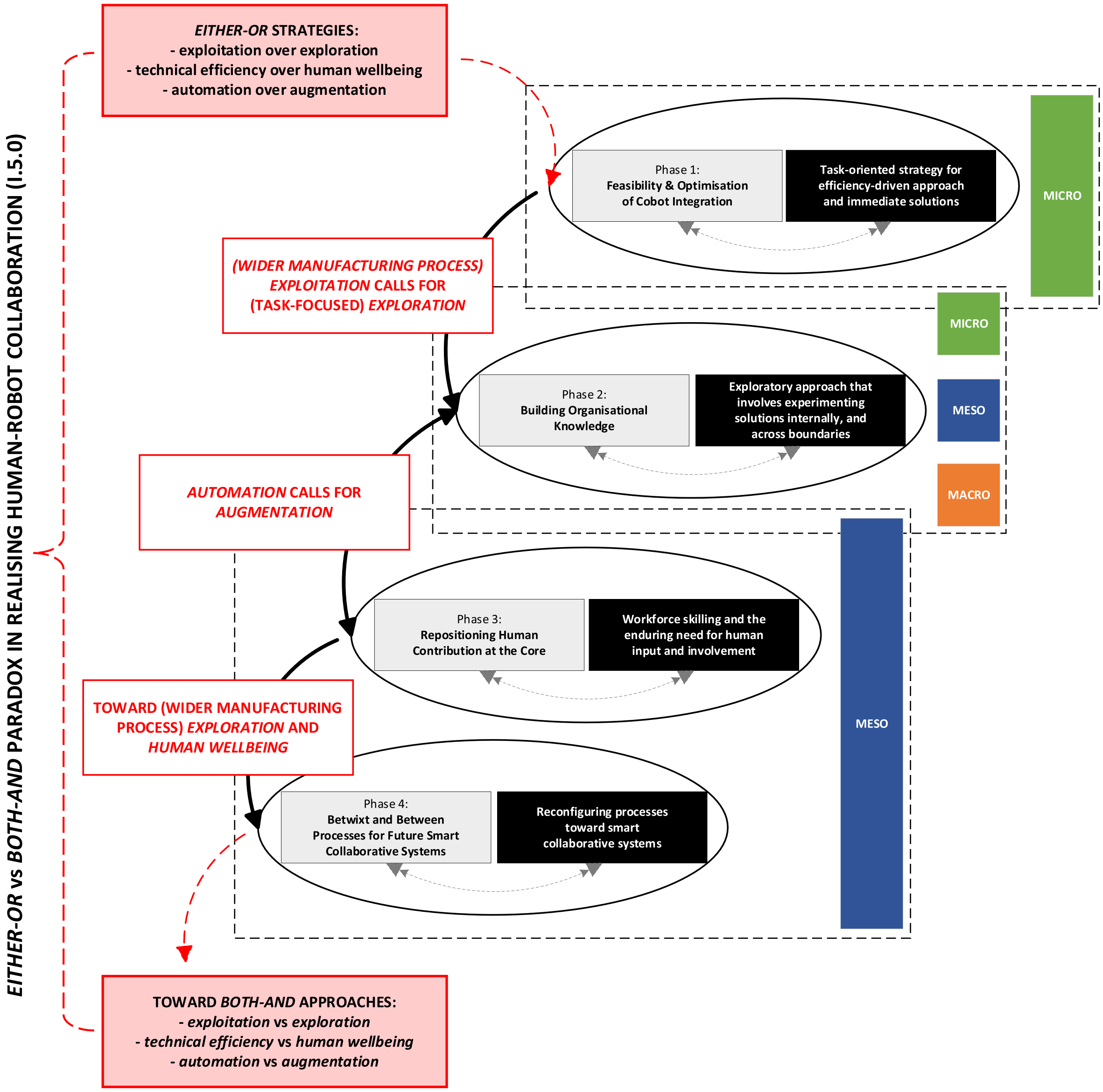


Fig. 6. Theoretical model of the theoretical contribution to Paradox Theory to explore I.5.0 implementation.

both-and strategies from the early stages. Our results show a different counterintuitive trajectory, as illustrated in our theoretical model (Fig. 6).

Based on insights from discussions with our subject-matter experts, particularly industry representatives, in the initial stages of decision to cobot adoption and actual integration, organisations seem not to acknowledge the paradoxical tensions between *exploitation* vs *exploration* (learning paradox), *technical efficiency* vs *human wellbeing* (performing paradox), and *automation* vs *augmentation* (organising paradox). Indeed, they embrace *either-or* strategies for cobot integration, prioritising immediate *technical optimisation* over *human wellbeing, exploitation* over *exploration, automation* at the expense of *augmentation.* Their efforts to optimise broader manufacturing processes (*exploitation*) seem to trigger the *exploration* of solutions to cobot task replacement in specific workflows (*automation*). This suggests the emergence of the learning paradox—i.e. (wider manufacturing process) exploitation vs (task-focused) exploration). To this end, responses from industry representatives provide substantial evidence that organisations seek to navigate the learning paradox by establishing R&D departments or engaging multidisciplinary teams at the organisational level—in line with Johansson et al.'s work (2024). Furthermore, as they deepen their engagement with collaborative robotics technology, they increasingly extend their learning efforts beyond organisational boundaries, fostering cross-industry peer-learning practices and knowledge exchange. This result offers a counterpoint to prior studies which assume that organisations prioritising wider manufacturing process exploitation tend to minimise cross-border collaborations (Moschko et al., 2023).

With time, organisations gradually develop a deeper understanding of the actual potential of collaborative robots in real-world contexts, as well as their technological limitations. Organisations that have been implementing collaborative robots for several years appear to be gradually exploring work configurations that demand greater levels of task interdependency, moving beyond basic automation towards more integrated human-robot interaction. What appears initially as a straightforward process of task replacement (*automation*) seems to call for a more complex reconfiguration of productive workflows and operators' role (*augmentation*) (Raisch and Krakowski, 2021). This suggests the emergence of the organising paradox, which coincides with a growing focus on skilling issues.

The advanced stage of this journey reveals that efficiency and worker expertise are not mutually exclusive but can, in fact, be mutually reinforcing, particularly within the evolving landscape of I.5.0—illustrating the *technical efficiency* vs. *human wellbeing* paradox. This is indeed a counterintuitive insight: rather than diminishing the role of human workers (as reported by (Margherita and Braccini, 2024)), efficiency-driven automation actually increases the need for human involvement. Additionally, all organisations involved in this study initially tend to focus on exploiting existing knowledge to optimise current manufacturing processes, but over time, they begin to shift towards exploring new approaches, innovations, and reconfigurations—highlighting the *exploitation* vs. *exploration* paradox.

Counterintuitively, our theoretical model highlights the paradoxical relationship between *either-or* strategies and *both-and* approaches. Our analysis challenges the widespread assumption in existing Paradox Theory studies on I.5.0 that *both-and* approaches surpass *either-or* strategies (see, for example, (Dieste et al., 2022; Johansson et al., 2024; Pacheco and Iwaszczenko, 2024), and as summarised in Table 2 Section 2.4). Specifically, as Fig. 6 shows, *either-or* strategies emerge at the micro level, setting in motion opposing yet complementary responses that unfold across micro, *meso*, and macro levels of analysis.

Unlike prior research that portrays paradoxes and their management as static—often due to a limited process perspective (Cunha and Putnam, 2019)—our analysis reveals a dynamic, multi-level process in which tensions emerging at one level catalyse strategic shifts and adaptive responses at others. This lens moves beyond both technocentric approaches to cobot adoption and the views of paradoxes as problems to be solved (e.g. (Dieste et al., 2022)), offering instead a conceptualisation of paradoxes as inherent and evolving tensions that organisations must continuously navigate, adapt to, and strategically balance over time. This is an open-ended journey.

5.2. *Substantive and theoretical contributions*

This study offers the following substantive and theoretical contributions (Table 4).

First, we advance existing theoretical perspectives on decision-making in cobot adoption. Some authors (e.g., (Silva et al., 2024)) propose frameworks for cobot integration, treating it as a matter of fit between the new technology and the existing system (*either-or* decision-making strategies). While this perspective offers a structured lens for evaluating adoption, it overlooks the complexity of the implementation process, particularly the evolving dynamics towards more advanced work configurations over time. In contrast, other scholars (e.g., (Moschko et al., 2023)) emphasise the complexity of implementation by adopting a paradox perspective, arguing that an overemphasis on exploitation can actually hinder the full realisation of a new technology's innovative potential. Our study builds on and bridges these perspectives, offering new theoretical insights to the decision-making in cobot adoption and deployment. Specifically, we argue that the decision to adopt collaborative robots is initially driven by *exploitation*, with organisations leveraging their existing technical and production systems, following feasibility studies that reflect their specific operational context. However, while these studies provide a structured foundation for adoption, they cannot fully anticipate the real-world complexities that arise post-deployment. To navigate these complexities, organisations build knowledge both within and across boundaries (at micro, meso macro levels), developing expertise that is context-specific to their intended use of collaborative robots. This ongoing learning process allows them to address newer emerging and unforeseen issues, by refining their integration strategies over time. Therefore, we contend that this process is inherently dynamic, actively shaping both technological and organisational change. This requires an analytical shift—one that moves away from static decision-making frameworks (Silva et al., 2024) towards a continuous, evolving approach to both cobot adoption and deployment.

Second, we offer a fresh perspective on the role of the future factory workforce and the skills essential to sustaining it. Mainstream literature discussing the transition from I.4.0 towards I.5.0 often frames workforce skilling as a gap to be addressed (Rikala et al., 2024), reinforcing a technocentric approach that views skills development as a reactive measure (e.g. (Leesakul et al., 2022; Leitão et al., 2020; Leon, 2023)). This gap becomes salient at the initial stage of technology adoption and implementation, often presenting itself as a barrier that organisations must overcome. Our results, instead, provide a more nuanced understanding of workforce skilling configurations that acknowledges the evolving relationship between work, smart technology, and human capabilities, throughout this journey. The skills configuration encompasses reskilling, upskilling, and craftsmanship that actively shape and are shaped by the integration of collaborative robotics, reinforcing the co-evolution of human expertise and automation in the future of manufacturing. Reskilling, in line with the literature, is about providing workers with digital skills to effectively interact with robotic application (Leesakul et al., 2022; Li, 2024). However, we firmly contest the mainstream narrative that cobots will take over repetitive and boring tasks, leaving humans to focus on more ‘creative’ work (e.g. (Dornelles et al., 2023; Horvat et al., 2025; Leon, 2023)). Drawing from our empirical insights, we argue that the evolving technological landscape of I.5.0 upskilling is key. This regard equipping workers with a broader comprehension of robotic principles, functionalities, and their contextual relevance within production systems. This shift in upskilling broadens manufacturing roles, requiring operators to integrate technical proficiency with critical thinking and problem-solving—essential for

Table 4
Study's contributions.

#	Substantive contribution	Empirical Results	Key Literature	Theoretical contribution
1	Decision making process for cobot adoption and deployment.	▪ Initial feasibility evaluation through studies focusing on context-specific needs ▪ Knowledge building process at micro, meso, and macro levels of analysis	Cobot adoption: e.g. structured frameworks emphasising exploitation (*Either-or* strategies) (Silva et al., 2024) Cobot deployment: paradoxical lens downplaying the role of exploitation (Moschko et al., 2023)	**_Exploitation_ vs _exploration paradox:_** *exploitation* at the level of adoption (micro level) calls for *exploration* at the level of deployment (micro, meso, macro)
2	Key role of upskilling and craftmanship to sustain the transition towards human-robot collaboration, beside reskilling and craftmanship considerations—substantiating the, until now, abstract notion of human-centricity in I.5.0.	▪ Workers' Skill considerations: reskilling (e.g. troubleshooting cobot failures) and upskilling (overseeing processes) ▪ Craftmanship	Technocentric lens to workforce skilling (e.g. (Leesakul et al., 2022; Leitão et al., 2020; Leon, 2023)) Mainstream narrative that robots will take over repetitive and boring tasks, leaving humans to focus on more “*creative*” work (e.g. (Leon, 2023))	In line with the extant Paradox Theory literature: **_Automation_ vs _augmentation paradox:_** *automation* calls for a more specialised and central role of the human workforce (*augmentation*)
3	Relationship between I.4.0 and I.5.0—I.5.0 builds and extends upon I.4.0.	▪ I.5.0 ‘paradoxically’ builds on I.4.0	I.4.0 and I.5.0 are presented as alternative paradigms (Pacheco and Iwaszczenko, 2024)	From techno-centric explanations (such as barrier-oriented analysis) towards paradoxical explanation—i.e. **_exploitation_ vs _exploration_, _technical efficiency_ vs _human wellbeing_,** and **_automation_ vs _augmentation_**
4	How and when paradoxes emerge, unfold, and transform along the journey towards I.5.0.	▪ Unexpected empirical surprises—such as *either-or* vs *both-and* paradox	“*Laundry list of paradoxes*” (Andriopoulos and Gotsi, 2017, p. 517) –see Section 2.3.	**Temporal and process-oriented perspective** on paradoxes and management strategies

navigating complex human-robot work environments—while their expertise sustains safety by minimising errors, preventing accidents, and transferring critical knowledge to less experienced colleagues (e.g. (Jung and Yang, 2025)). Finally, the notion of craftmanship emerges as an emphasis to individual expertise, where specialised knowledge, skill, and precision are applied to produce high-quality, personalised work. In this context, the human role remains essential, as upskilling and craftsmanship reflect the judgment, adaptability, and attention to detail that automation alone cannot replicate. This provides empirical evidence for the, until now, abstract notion of human-centricity in I.5.0, demonstrating that human involvement is not diminished but rather amplified in shaping, enhancing, and adding value to work transformation as automation and collaborative robotic systems become more prevalent. Workforce skilling is integral to the organisations' learning process.

Third, this leads to two additional contributions. On one hand, we offer a substantive contribution to the relationship between I.4.0—which prioritises efficiency, automation, and technical optimisation (Klingenberg et al., 2022)—and I.5.0, which emphasises resilience, sustainability, and human-centricity (He and Chand, 2024; Troisi et al., 2024). Our results challenge the dominant view in the literature that frames I.4.0 and I.5.0 as distinct and alternative paradigms (see for example, (Javaid and Haleem, 2020; Pacheco and Iwaszczenko, 2024; Xu et al., 2021)), while aligning with emerging but still minority research streams that argue I.5.0 builds upon I.4.0 (Piccarozzi et al., 2024). Our study provides further empirical evidence supporting this perspective by drawing attention to the paradoxical nature of the relationship between these two paradigms. On the other hand, from a theoretical perspective, we advocate for an analytical shift away from barrier-oriented analyses (e.g. (Dieste et al., 2022)) that focus on technical limitations, risks, and challenges associated with human-robot collaboration. Instead, we propose adopting a paradoxical lens that better captures the co-implication of key tensions such as *exploitation* vs. *exploration*, *technical efficiency* vs. *human wellbeing*, and *automation* vs. *augmentation*.

Fourth and finally, we introduce a process-oriented perspective that conceptualises paradox management as a pattern of inconsistent, yet interdependent decisions unfolding over time. Organisations initially frame the competing demands (*automation* vs *augmentation*, *exploration* vs *exploitation*, *technical optimisation* vs *human wellbeing*) permeating key decisions in human-robot configuration integration—such as the use of robot applications, pace and nature of innovation, organisational goals (see Table 2)—as dilemmas, which they address with an *either-or* approach. However, choosing one alternative unintentionally and unexpectedly brings its opposite to the fore, fuelling the emergence of paradoxes. In response, organisations flexibly shift their efforts between opposing demands and across analytical levels, resulting in new decisions that may appear inconsistent with earlier ones. Over time, these decisions aggregate into a pattern of *both-and* strategies of temporal separation.

Ultimately, our contribution to Paradox Theory unfolds in three directions. First, it offers a counterpoint to the widespread assumption that effective paradox management requires the paradox to become salient (i.e. visible and consciously recognised)—either due to external environmental conditions (i.e. plurality, scarcity, and change) or the managers' ability to adopt paradoxical cognitions that recognise and juxtapose contradictory demands (Smith and Lewis, 2011). We show instead that paradoxes may emerge as an unexpected consequence of deliberate *either-or* decisions, eventually transforming into unrecognised conditions that prompt organisations to adopt *both-and* strategies. Second, by unveiling these dynamics, our study complicates existing understanding of *either-or* and *both-and* strategies revealing that the two are paradoxically interrelated, with *either-or* choices often laying the groundwork for the emergence of *both-and* responses. Third, our study contributes to a more dynamic understanding of paradoxes and paradox management—as opposite to “*laundry list of paradoxes*” (Andriopoulos and Gotsi, 2017, p. 517) and prescriptive lists of best management strategies.

6. Final remarks

With this study, and through the lens of Paradox Theory, we have critically examined how paradoxes—such as *automation* vs *augmentation*, *technical efficiency* vs *human wellbeing*, and exploitation vs *exploration* —emerge, shift, and are managed in unexpected ways, revealing interdependencies between different types of responses across micro, *meso*, and macro levels of analysis. Additionally, we provide empirical evidence of the tensions towards I.5.0. This requires more than human-centricity—it also demands the integration of advanced smart robotics and the reconfiguration of production workflows and processes. However, this transition remains an open question as industry experts still struggle to envision it. Undoubtably, in the future, embodied AI and smart machines will further redefine work processes and the boundaries of human-smart robotic systems. Alternative configurations remain largely distant from the established repertoire of solutions, where Tayloristic principles continue to dominate current manufacturing landscapes. To move forward, organisations must leverage the complementarities between human agents—particularly their domain knowledge—and the opportunities offered by AI-enabled technologies that can unlock possibilities through hybrid problem-solving approaches (Raisch and Fomina, 2024).

6.1. Potential implications for organisations pursuing human-robot collaborative systems towards I.5.0

This section would traditionally outline a set of practical recommendations for organisations pursuing human-robot collaborative systems as part of their transition to I.5.0. However, doing so would directly contradict the core results of our study and the theoretical model we have developed, which frames this transition as an open-ended journey navigated amid contextually embedded contradictions. As argued earlier, paradoxes are not universal problems to be resolved but dynamic, situated tensions that organisations must continuously interpret and rebalance in context.

In line with Cunha and Putnam (2019), rather than offering a set of solutions, we suggest for a shift towards reflection-in-action (e.g. (Luscher and Lewis, 2008)). Prescriptive and decontextualised recommendations risk stripping paradoxes of their situated complexity, obscuring the iterative, contingent, and emergent nature of how organisations actually engage with tensions in practice. Instead, we propose that the most meaningful way for research to support organisations in coping with I.5.0 complexity is by enabling them to cultivate reflexive organisational learning—a practice grounded in responsiveness to local tensions, temporal rhythms, and emergent contradictions. Supporting organisations in this journey means enabling them to learn through paradox, rather than bypass it through simplified frameworks.

6.2. Key directions for future research

First, while this study has adopted a multi-sectoral perspective, capturing diverse organisational experiences with cobot adoption and its organisational implications, future research should focus on sector-specific dynamics. A mono-sectoral approach would allow for a deeper understanding of industry-specific challenges, as sectors such as logistics may exhibit distinct organisational tensions, resistance points, and drivers compared to others. This approach would provide more granular insights into how different industries navigate the complexities of digital transformation while addressing human-centric considerations.

Second, although this study adopts a European perspective, it acknowledges that focusing on specific countries with more advanced stages of technological adoption could reveal different patterns in the perception of dilemmas, paradoxes, and organisational responses. Differences in policy frameworks, labour market structures, and cultural attitudes towards innovation may shape how organisations experience and manage these challenges. Comparative studies across countries at different adoption stages would offer valuable insights into these contextual factors and their impact on organisational decision-making.

Third, the model developed in this study reflects the trajectory of organisations that have already adopted, or have decided to adopt, collaborative technologies. While our study includes perspectives from SMEs, the majority of participants were from multinational companies with established management practices, openness to innovation, and existing technological infrastructures. These boundary conditions are essential when considering human-centric implications, as they may not fully capture the experiences of smaller or less structured organisations. Future research should further investigate how different organisational profiles—including startups, SMEs, and companies with lower levels of digital readiness—engage with and respond to these technological transitions.

Data statement

Due to the sensitive nature of the participants' responses reflecting the organisational choices and cobot implementation strategies, participants were assured raw data would remain confidential and would not be shared.

CRediT authorship contribution statement

Tiziana C. Callari: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ylenia Curzi:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **Niels Lohse:** Writing – review & editing, Supervision, Funding acquisition.

Data availability

The data that has been used is confidential.

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