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Fostering Industry 5.0: an evidence-based framework to sustainable and human-centered technological transitions

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ABSTRACT

This study aims to identify conditions that promote work sustainability after technological transition processess in an industrial context, and understand the possibilities of operators' involvement in these. Two use-cases in a manufacturing company were part of the study with the project development team, HR, team leaders and the workers who will interact with the new technologies. Following a work activity-oriented approach, the results demonstrated that there is still progress to be made to move towards a human-centered approach (e.g., consideration for workers and their work activity; organizational support to skills development). However, conditions that favor a renewed work activity within the technological transitions aligned with the I5.0 paradigm were also found and taken into account into an evidence-based framework of guidelines for sustainable work conditions. This framework considers an organizational, collective, and individual level of guidelines aimed to support companies' stakeholders in the design and implementation of human-centered technological transitions. This study contributes to fostering the I5.0 transition, seeking sustainable conditions for workers and their work possibilities.

1. Introduction

1.1. *Understanding socio-technical dynamics in technological transitions in I4.0 and I5.0*

Technological transformations are increasingly embedded in industrial contexts. While technology is expected to improve quality of life of people (Chen and Chan, 2011), its introduction can also pose challenges for workers and the fulfilment. Due to technical transformations of production systems, first with Industry 4.0 (I4.0) and, more recently, with Industry 5.0 (I5.0), technological transitions have been widely considered in workplaces and has attracted significant attention within the Ergonomics/Human Factors (E/HF) community (e.g., Trstenjak et al., 2025; Reiman et al., 2021). Research highlights the need to address challenges related to the design of more sustainable, healthy, and resilient work systems (Trstenjak et al., 2025; Reiman et al., 2021). Briggs et al. (1998) describe a technological transition as either a radical change in workplace involving discontinuous events, non-linear shifts leading to new sociotechnical models (Geels, 2004; Holscher et al., 2018); or incremental changes, involving accumulated smaller modifications that gradually reshape systems while enhancing quality of products and services (Mulder et al., 1999). Regardless of the type of change, the socio-technical dynamics implied is conditioned by the well-known techno-centric approach in I4.0 (e.g., Barcellini, 2022; Compan et al., 2022; Cunha et al., 2022; Neumann et al., 2021; Enang et al., 2023; Velasco et al., 2022), somehow neglecting the principles of social justice and sustainability (Directorate-General for Research and Innovation, 2021).

1.2. *Workers' participation in technological transitions*

In this regard, studies have shown that workers are not often involved in transition processes, specifically in the design of technologies (Barcellini et al., 2021; Bellantuono et al., 2021). Their participation is almost always limited to training, expecting that this will be enough to guarantee the desired technological acceptability (Barcellini, 2022). However, a possible lack of technology flexibility associated with this non-participated process may undermine workers' trust in the technology (Sadrfaridpour et al., 2016). More recent research further highlights the workers' perception of not being trusted by technology – specifically, when AI is perceived as distrusting humans or when it issues inappropriate alerts and takes over actions without explanation (Xie

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et al., 2025).

This absence or scarcity of workers' involvement during the design and implementation stages of a new technology often leads to a non-participatory and non-collaborative technological transition. In this context, not only is system performance negatively affected, but also workers' well-being (Kadir and Broberg, 2020), since the transition fails to address their actual needs for performing work with quality (Bellantuono et al., 2021). Additionally, such systems may pose risks to workers' health, safety, and overall professional development, as well as negatively impact their actual work (Barcellini, 2022).

1.3. Links between technological transitions and work sustainability

In contrast to the I4.0 approach, the emerging I5.0 paradigm emphasizes ecological and social sustainability while adopting a human-centered perspective that values the role of workers in technological transitions, ensuring their occupational health and safety (OHS), and fostering opportunities for skills development (Directorate-General for Research and Innovation, 2021; European Commission, 2021; Mourtzis et al., 2022). Developing sustainable systems requires therefore balancing economic, social, and environmental objectives, aligning them with sustainable development goals and the digital transformation process (Bolis et al., 2025; Thatcher et al., 2019) while simultaneously generating value for stakeholders (Leal Filho et al., 2023).

The notion of sustainable transitions (Geels, 2004; Köhler et al., 2019) highlights these dynamics. According to Markard et al. (2012), "sustainability transitions are long-term, multi-dimensional, and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption" (p. 956). These "sustainable transitions" are complex and can be facilitated by an E/HF approach (Kadir and Broberg, 2021), where the participation of workers and other stakeholders actively contribute to the design and implementation process of successful transitions (Broberg et al., 2011).

Additionally, it is necessary to position sustainability from the work activity's point of view (Docherty et al., 2002), enabling a focus on prioritizing workers and their working conditions (Gollac et al., 2008). Thus, debating the real possibilities of designing sustainable work systems includes the consideration of working conditions and their evolution with new I5.0 technologies, and to what extent they provide opportunities for workers' learning and development, for the use of their previous know-how and for constructing meanings of their activity (Vendramin et al., 2012; Volkoff and Gaudart, 2015). This work sustainability perspective integrates multiple dimensions: bio-compatibility, which considers the functional properties of the human organism and its evolution, and can be compromised, for example, by the impact of physical demands; ergo-compatibility, concerning the development and durability of individual and collective work strategies, and can be compromised by time pressures; and social-compatibility, reflecting the family and social sphere, that can be compromised by the lack of professional prospects and misalignment between work schedules and personal life (Gollac et al., 2008; Volkoff and Molinié, 2013; Barcellini et al., 2024). In this field, the articulation of the E/HF, OHS dimensions and operational leeway is fundamental to promote this sustainability (Gollac et al., 2008).

1.4. Aims and research questions of the study

Considering the importance of E/HF approach and the assumed perspective of work sustainability, in the design and implementation of new systems, it is important to reflect on how workers have been, are or can be included in these processes (Broberg et al., 2011; Hall-Andersen and Broberg, 2014; Thatcher, 2024), acknowledging that workers' needs is a key factor for the success of technological transitions (Thatcher, 2024).

While these understandings guide the study to inform and support stakeholders during technological transition processes, the literature still reveals a gap regarding workplace examples on how to prioritize workers' participation, recognize their experience, foster possibilities for developing skills and for preserving their health.

Thus, the aim of the study was to identify conditions that promote work sustainability in technological transition process in an industrial context, and understand the role assumed by workers, based on the reconstruction of two use-cases carried out by a manufacturing company: use-case 1 – a pallet tracking system and a software to support product verification and labelling by operators; use-case 2 – introduction of a vehicle with digitalized delivery system and a tool to support operators work). To this end, three research questions were defined: 1) How were the workers involved throughout the process of designing and implementing technological systems in their respective use-cases? 2) What is the perception of workers about the impact that the introduced technology/technological transition had on their work?; 3) What kind of work sustainability conditions can be identified to support a human-centered technological transition process?

2. Method

2.1. Context of the study and participants

The study was carried out in the context of two use-cases developed by a big supplier of technology and services company from the industrial sector in Portugal with an international base. Both use-cases were driven by the need to optimize resources and processes leading to technological changes (creation of digital twins, involving work digitalization and automation processes in the context of Industrial Internet of Things) designed and conducted by digitalization and industrial engineering teams which led to changes in the ways of performing the work and in working conditions. Details regarding the use-cases and analyzed work activities are provided in the results section.

Regarding the participants of the study, we considered company's stakeholders and workers whose work was impacted in each use-case. The company's stakeholders were the Project Manager (PM) responsible for the technology development team in the use-cases (seniority 10 years in company) and actively involved in the technological design and implementation of the use-cases; and one member of the Human Resources team (HR) (4 years in company) who was present in the meetings about the research study.

The workers involved in each use-case were the primary users of the technology and the team leaders (TL). Table 1 provides details on these participants and their characterization.

2.2. Data collection and analysis

This study was developed to seek an in-depth understanding of the technological transitions in both use-cases of the company, focusing on the workers' point of view and on the impact on their work. Following a work activity-oriented approach to ergonomics and work psychology, qualitative and participatory methodologies (Barcellini et al., 2014; Daniellou, 2005; Delgoulet and Santos, 2022; Garrigou et al., 1995) were used to understand workers' perceptions regarding the changes they felt in the organization and performance of their work, their health and the possibility of developing skills. In addition, information collected from key stakeholders made it possible to reconstruct the technological transition processes in each use-case, thus enabling retrospective understanding of the process from its design phase and identifying when and how workers were considered.

Data collection was adjusted to the specificities of each use-case and the respective work activity. Analyses of micro-demographic data and documents related to functions and technological transitions were carried out; meetings were held with project manager (PM), team leaders (TL), and member of the HR team; observations of the LO work activity were conducted; and interviews with workers were performed -

Table 1
Characterization of the workers and team leaders of use-case 1 and use-case 2.

Use-case 1			Use-case 2		
Participants	Age	Seniority	Participants	Age	Seniority
10 Logistics operators (LO1; warehouse)	Ages between 26 and 57 years old ($M = 40$)	Between 1 and 26 years	4 Logistics operators (LO2) (warehouse)	Between 20 and 57 years old ($M = 37$)	Between 1,5 and 17 years
1 Team Leader	data not collected	data not collected	2 Team Leaders	data not collected	data not collected

particularly in use-case 2, where direct observation of work activity was limited due to the difficulty in observing all moments of a work activity that is carried out in mobility (along the routes involving vehicle driving). Finally, data were restituted to workers and key interlocutors.

During the data collection period, use-case 1 was already in the use phase (i.e. the technology was already stable in the workplace and in use by the LO1); and use-case 2 was followed during the implementation phase (i.e. the technology was in the testing phase, in which LO2 were already carrying out their work using it) and the use phase. The study was conducted according to the procedure explained in Fig. 1.

After separately analysing the different types of data collected (e.g., meeting verbalisations, interviews, work activity data), data triangulation was applied. The analysis was structured around major categories, including employee involvement (when and how), the role of stakeholders, and the impacts of the transition process on working conditions, learning and skills development, and health. Further details regarding the duration and frequency of the activities performed, as well as the data analysis procedures, are provided in Appendix A.1. (supplementary material). The data collected supported the identification of work sustainability conditions, which will be presented in the form of a framework in the discussion.

Drawing on the analysis of the different data, the results section integrates and cross-references the findings from both use-cases to address the study's objective and research questions.

3. Results

3.1. Work activity after technological transition processes: a continued work autonomy vs. a work limited to following instructions

The results on work activity of LO1 and LO2 are based on the data collected in meetings with the PM and in the observations with workers and are presented according to the specific technological transition of each use-case designed and implemented by the company: pallet tracking systems in use-case 1; vehicle with digitalized delivery system in use-case 2.

The use-case 1 corresponded to the introduction of a *pallet tracking system* in the warehouse. A technology with the goal of "*enabling the reorganization of the warehouse, making it more reliable and agile, ensuring product traceability*" (PM) was developed. The warehouse work process is divided into three parts: unloading goods and recording software; labelling the products; and storage. The developed technologies involved integrating a sensor for identification, creating a pallet ID and, consequently, developing software to support product verification and labelling. Two workstations, where the different LO1 work, interact with these technologies in distinct ways. Workstation 2 (product verification and labelling) interacts directly with the software and experiences the imposed work pace derived from the sensor's registration of the palette at Workstation 1. In this case, work activity still allows for a degree of autonomy, enabling workers to manage and control their work.

The use-case 2 involved replacing a conventional and consolidated vehicle for delivery of materials in cyclical route systems with a vehicle equipped with digitalized delivery system, with the aim of "*guaranteeing timely supply to the production line, optimizing the resources used*" (PM). To this end, a software was developed for use by the LO2 on personal digital assistant (PDA) devices. This software, powered by a route optimization algorithm for delivering raw materials to production, began to guide their work: the LO2 receive the route to be taken to deliver the products in the production lines via the PDA, and must follow the instructions on the device (e.g. which wagons to hitch to the vehicle, which route to take), recording each step completed in the PDA. Once the route has been completed, the PDA generates new instructions for workers about the next route, creating a continuous workflow. This reveals that work activity, in this case, is constrained and restricted mainly to following instructions from the tool (e.g. when to start a route, which route to take and how), without the possibility of anticipation.

3.2. Reconstruction of both technological transition processes: from late participation of workers in the process to an absence of their involvement

The reconstruction of the technological transition processes of the two use-cases was based on the meetings with PM and TL. It was

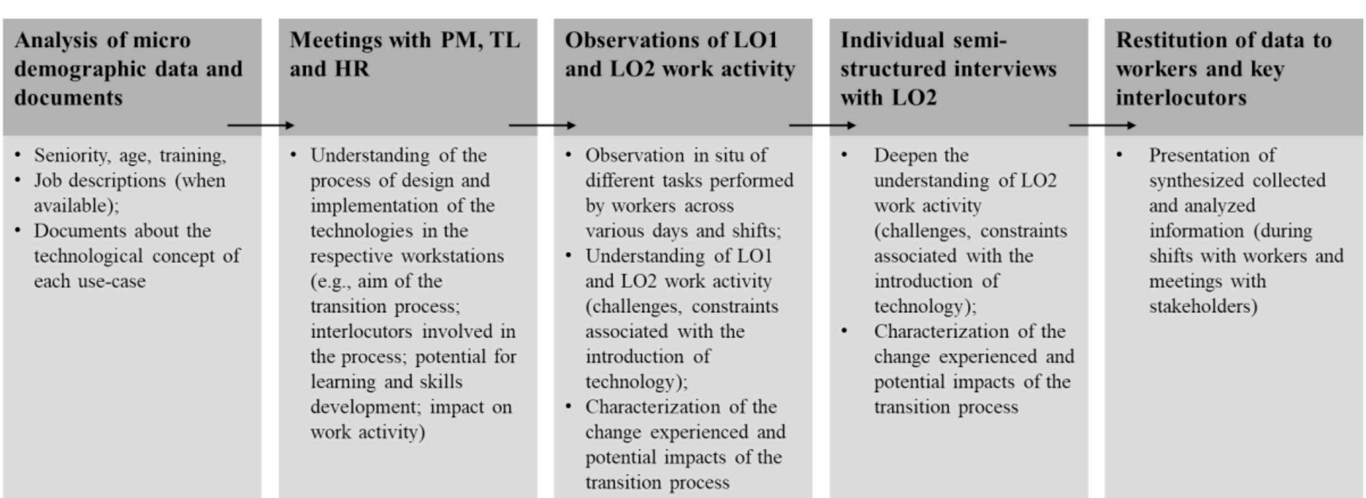

Fig. 1. Procedure for the study conducted, considering the type of activities carried out and details associated with its implementation.

identified key milestones related to the implementation of the technology (including design phase) and the involvement of interlocutors (i.e., different types of employees), considering: i) decision-making in the design phase and implementation of the technology; and ii) interlocutors involved throughout the process (with opportunity to make suggestions; and/or users of the technologies and tools introduced). Figs. 2 and 3 show this reconstruction for each use-case.

In use-case 1, the technological transition process began in 2018 and has now been completed. Four years passed until the implementation phase of the pallet tracking system in the warehouse. It was only during the implementation phase that the operators on different shifts were accompanied to explain the new operating procedures, in coordination with the digitalization team. Operators were also involved through the possibility of submitting contributions for improving the introduced system. These contributions were analyzed in meetings with the TL, in conjunction with the digitalization team, and, whenever justified, were taken into account: "*The inputs* [for improvement] *were always from the operators*" (TL). Although the operators were only involved in the implementation phase, their opinion was valued and encouraged, particularly by the TL that was well aware of the activity carried out by the operators and the challenges they had to face in their work.

Also, there was a notable involvement of a logistics operator who accompanied the design process. Due to his expertise, this operator joined the project development team, providing real knowledge of working in the warehouse, and contributing to the technology design process.

Regarding the decision-making process on the technology to be implemented and the subsequent design and implementation process, data collected from meetings with PM and TL indicate that strategic company discussions focused mainly on technical issues aiming to improve systems and optimize resources. Consequently, concerns regarding the work process following the technological transition were only addressed indirectly.

In use-case 2, the transition process started in 2021, with three years having elapsed until the implementation phase. It was only after this phase, that is, from the use-phase that operators began their interaction with the technology while carrying out their work. However, the data does not clarify whether they were asked to suggest improvements, leaving it unclear whether operators were solely users of the new technology or had the opportunity to participate actively in the process. Communication about the introduction of the new process was conducted by the TL during shift change meetings: "*for months we took advantage of the shift change to talk about the project. So it wouldn't fall apart overnight*" (TL1). Team leaders also participated in the design of the new system, trying to ensure that the warehouse operations were aligned with the best practices recognized as future trends in logistics. Additionally, members of the digitalization team accompanied work shifts during the technology implementation phase to address technical difficulties encountered by operators and resolve issues.

With regard to the decision-making process on the technology to be implemented, and the subsequent design and implementation process, the data is identical to that of use-case 1. The existing strategic meetings regarding the technology to implement focused primarily on technical issues, aiming to improve systems and optimize resources, with the belief that the new technology would contribute to improving people's health and the way they carry out their work: "*the idea is that people won't have so many worries, won't be so tired … (…) people will work with less suffering and it will be easier to train an operator now (…) it will make it easier for new workers, to have a system that does the work for them*" (TL).

The reconstruction of each use-case shows that in both cases workers were not involved in the design phase of the technological transitions. From the PM's point of view, in addition to a reference to a lack of understanding of the proper way to involve workers (e.g. how, when, which operators), this absence is related: i) to the fact that their involvement occurs indirectly, through the involvement of their operational leadership: *"in the design phase, the leaders of the project only receive clear feedback from the operators in prototyping. Until then, it's filtered by the operational leader who says it can be one way or another. It's only in the prototype that we adapt and the operators are already taken into account and adjustments are made.";* ii) to a 'comfort' factor associated with the design process on the part of those responsible for the process and by the leadership: *"the process was through observing things, and we realized (…) it's more comfortable* [for those leading the process] *to create a theoretical perception. It's still the path of resistance, although I don't agree (…) the test phase is when the possibility of making adjustments arises [with input from operators]"* (PM). This aspect is recognized by the PM as an area for improvement in future technological transition processes: *"(…) this is a clear point for improvement"* (PM); iii) uncertainty about how to involve employees and consider their work – *I don't know how to involve workers … and also*, which employees can participate?" (PM).

The data related with the design and implementation of the processes also revealed that these were not supported by the company's HR team. The meetings with the HR member pointed out an absence of training initiatives and the monitoring of the process with workers from the use-cases in terms of their skills or possible needs of reconstructing their professional paths, further underscoring that these transitions have not been thought, for example, in terms of skills development. Despite this, the PM acknowledges the added value that active involvement of this department could bring to the technological process.

Given the lack of possibilities for worker involvement in the decision-making and technology design phases and the limited involvement of workers in the implementation process, and understanding that the process is situated in an I4.0, it is important to analyze the impacts of these limited or absent forms of involvement. This analysis supports the identification of elements that could be considered conditions of sustainability for workers and their work activity to be taken into account in future technological transition processes.

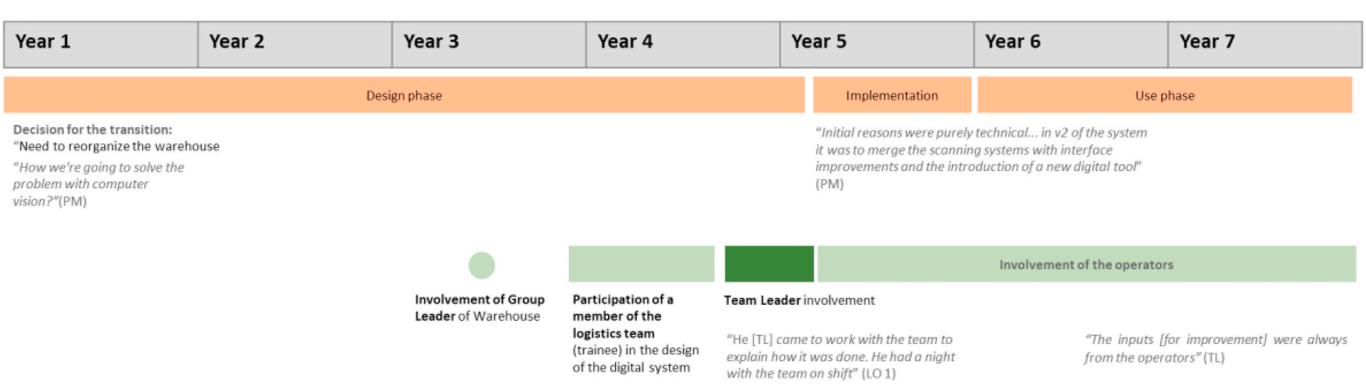

Fig. 2. Reconstruction of the use-case 1 process, considering design, implementation and use-phase and the interlocutors involved.

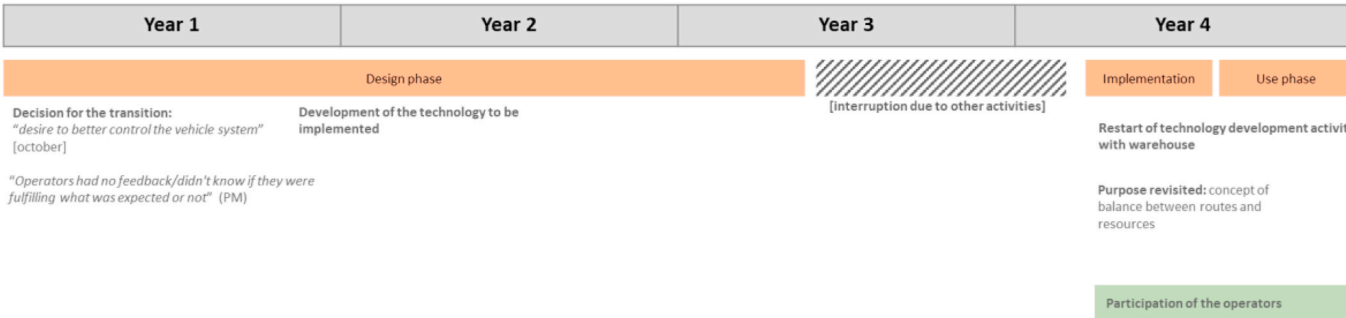

Fig. 3. Reconstruction of the use-case 2 process, considering design, implementation and use-phase and the actors involved.

3.3. *Impact of the technological transitions: individual and collective impacts*

The results regarding on workers' perceptions, complemented by those of TL, indicate differing positions among workers depending on the use-cases. These were organized into four categories (Fig. 4) to provide an understanding of the dimensions associated with work sustainability in transition processes. Fig. 4 presents the main results for each category, considering impacts at individual and collective levels (teams and interaction with leaders).

The results from the verbalizations collected during observations and from the semi-structured interviews illustrate varying perceptions depending on the impact of the new technology on the work of LO1 and LO2. Impacts at the individual level are particularly notable in terms of recognition of the importance of the technological transition and its effects on health. Impacts at the collective level are particularly notable with respect to working conditions and skills development.

In use-case 1, the LO1 expressed that they recognized the transition's importance in improving how they carry out their work, the fact that the process of digitalization of their work has ensured continuity in the management and control over their activity, supported by their leadership, and the possibility to continue mobilizing knowledge and learning on a daily basis. In contrast, in use-case 2, LO2 expressed that the new technologies led to a situation of control both of the operators and their work, with impacts for their health, and with difficulties in mobilizing knowledge and skills.

Regarding the role of work collectives, while they were reinforced with LO1, for LO2 this level was weakened in terms of the process of carrying out the work, but still played an important role in facilitating the learning of the new work situation.

The overall elements identified also reflect the consequences of the technological process conducted (previously reconstructed) and

	Logistics operators 1 [use-case1]	Logistics operators 2 [use-case 2]
Recognition of the importance of the technological transition	- **Recognition of the importance of the technological transition:** "*People recognized the difficulty of the conference process... there was a lot of receptivity.*" (TL) - **Perception that the system is useful for carrying out the work** (makes it easier, is suitable, reduces the possibility of errors): "*the work goes faster if the system is working well...*" (LO1 -2) - **No feeling of job loss threat**: "*the activity [of the workers] continues to exist*". (TL)	- **Understanding of the need behind the introduction of the digitalized delivery system, but lack of recognition of the importance of the technological transition**: "*in the digitalization process we weren't listened to, and I think we should have been. we often have more insight into things (…) and I don't really understand the advantage of this change, because it takes us longer to do things" (LO2-1)* - **Acceptance of the PDA tool:** "*I understand that the PDA allows to control the routes…" (LO2-1)*
Impact on working conditions	- **Activity not thwarted by technology and supported by leadership, guaranteeing some autonomy**: "*the guideline is to leave it alone when an order doesn't have data, but what we do is call the buyer or leave a message*"(LO1-1) - **Reinforcement of a working collective** by valuing, through leadership and project management, contributions related to improving the system and by helping colleagues (e.g. recovering errors; clarifying doubts, supporting colleagues' work).	- **Perception of increased activity prescription and reduced autonomy**: "*before, each one of us took its own route; we already knew what we were going to do next. we always did it autonomously (...) now we don't have much autonomy anymore*" (LO2-1); "*the program is already done according to the lines and routes; we put the wagons m in the order that the PAD tells us when we arrive*" *(LO2-4)* - **Perception of activity controlled by technology, associated with reduced possibilities for anticipation and flexibility in carrying out the work:** "*if the system tells me to take wagon X and Y, that's what I take. The PDA says everything we need to know*" (LO2-2); "*each person has their own work pace and there are times when we feel very controlled by the system (...) the only thing that impacts me more is being controlled by a system"* (LO2-3); "*now I can't control things in my job"* (LO2-1); "*I don't know the number of routes, but I know I'm going to do a lot of them"* (LO2-2); "*We can't do things the way we used to; we used to have more flexibility"* (LO2-1) - **Quantitative and qualitative underload**: "*It's not a challenging job - it's either this or this. There's not much work to do.*" (LO2-2) - **Redefining and weakening of collectives**: "*I'm frustrated. The leader says 'you can't do favors', but I can't. I have to do favors. I get mad If I don't help.*" (LO2-1); "*with the other system, we'd get 5/10 minutes to help inside*" (LO2-2)
Impact on health	- **Generalized fatigue**: "*I just feel tired at the end of the day... but I was like that before*" (LO1-2)	- **Generalized fatigue, and reports of musculoskeletal pain**: "*now the work is more tiring because we're here, it gives us a finished product, associated with the diversity of the route...*" (LO2-1); "*I have more pain in my legs. the work doesn't pay off, and we get more tired*" (LO2-2); - **Perceived feeling of greater frustration with work**: "*I feel less exhausted, but more frustrated*" (LO2-3)
Impact on skills development	- **Mobilization of previous knowledge and the possibility of learning new things:** "*I'm not always doing the same thing. Every day new things come up, situations in which I have to help my colleagues, every day I have to solve something.*" (LO1-2) - **Recognition by the leadership**: "*My people don't even know what skills they have when interacting with the system*" (TL) - **Learning about interacting with the software mainly from colleagues,** but also from leaders and the development team (lack of formal learning moments)	- **Difficulty in mobilizing previous skills, namely associated with working strategies for managing and solving problems**: "*now we can't use the strategies we used to*" (LO2-1); "*we can't do things the way we used to"* (LO2-4) - **Learning about interacting with the new digitalized delivery system mainly with work colleagues**, but also with leaders and the development team (lack of formal learning moments)

individual level   collective level

Fig. 4. Workers' perception in use-case 1 and 2 of the impact of technology (individual and collective level) on different dimensions of their work, health and skills development.

reinforce the need for greater support and coordinated action at an organisational level, given the criticality of the aspects presented in terms of skill development, health, working conditions and the (im) possibility of continuing to perform their work activity.

4. Discussion

4.1. Human-centered transitions as a necessary progress to support the development of the work activity

4.1.1. Linking empirical findings to existing literature

The findings reveal that the workers' involvement in the design, implementation, and use phases of technological transitions, as well as the impacts (tendentially more positive in the use-case 1 and more negative in the use-case 2) on their working conditions, health, and skills development in both cases, varied considerably, highlighting also the role of E/HF in shaping these processes (Research Questions 1 and 2). In use-case 1, with the LO1, the technological transition process corresponded to an incremental change (Briggs et al., 1998), in which the new system and consideration of workers' opinion and experience (from the implementation phase onwards), enabled continuity in how work was carried out, maintaining autonomy and a sense of work control, supported by both by technology and leadership. This provides an original example to complement the literature and reinforce the importance of E/HF, which generally reports a lack of consideration of workers and their work activity and confines participation to training initiatives (e.g., Barcellini, 2022) or lack of empirical analysis in human factors (Lam and Chan, 2024). In use-case 2, with the LO2, more aligned with examples found in previous studies (e.g., Enang et al., 2023; Velasco et al., 2022), the transition appeared to be a non-linear change, characterized by a perception of increased control and prescription in operators' work activity, and decreased flexibility imposed by the introduced technology. Although perceptions differ in each use-case, in both the reconfiguration of the technical working conditions led to a renewed work activity with implications for workers' health, which were particularly concerning and immediate for the LO2. This may be due to the absence of protective factors in their renewed work activity that also serve as enablers of work sustainability aligned with the perspective of a bio, ergo and social-compatibility (Gollac et al., 2008), such as a strong collective, opportunities to exercise control over their own work, and possibilities for continuous learning or skills development.

Moreover, studies show that trust in new technologies is related to system complexity (Khasawneh et al., 2019) and tends to increase when workers believe they can adapt the technology to meet their specific needs (Sadrfaridpour et al., 2016). In the use-case 2, due to the lack of recognition of the technology's importance and the rigidity of the new system, which limits operators' control, this trust doesn't seem to be established. The alignment of workers' perceptions with the recognition of the technology's importance for performing their work can also affect technological use (Chen and Chan, 2011), and the extent of workers' involvement throughout the transition process. Regarding this latter point, the findings corroborate previous studies indicating that workers' participation in design phases is often limited, occasional, or absent (e.g., Bellantuono et al., 2021), highlighting missed opportunities for E/HF integration. Furthermore, operators' work, particularly work-as-done (Hollnagel, 2018), was not considered in the overall objectives of the transitions, which may also contribute to the way the transition unfolds and to its perceived impacts.

4.1.2. Insights for the development of work sustainability conditions

The study conducted reveals a reality still strongly associated with I4.0 principles, highlighting concrete examples of organizational elements that can facilitate or hinder work activity and its impacts on workers, providing insights for identifying work sustainability conditions (Research Question 3) that inform the framework to be presented. First, the lack of workers' participation appears to be linked to the representations and, consequently, to the conceptual references for action of development teams and strategic leaders. There seems to be a lack of awareness of the added value of operators' contributions during these transitions, as well as concerns about the interference they may have in the process and uncertainty about how and when to involve workers. This risk could contribute to the perpetuation of certain I4.0 implementation patterns. Second, the findings on the role of operational leaders and their position regarding the relationship between technology and people's work suggest that recognition of employees' knowledge and the work carried out by them can be a differentiating element in fostering their involvement and reinforcing the value of their role. Third, the lack of involvement from the company's HR team in the technological transition process (a department that, by the nature of its activity, should assume responsibilities related to training and employee development) seems to perpetuate a disconnection between the role of these stakeholders and the workers and their activity. It also indicates that learning and development of workers and reflections about workers' professional paths within technological transitions may occur without an intentional and planned organizational support. These contributions complement studies highlighting the undervaluation of workers and their knowledge at work (Pereira et al., 2023) and the role of workers during the introduction of new technologies (e.g., Barcellini et al., 2021; Broberg et al., 2011).

The impacts identified and the lack of organizational support underscore the need for a human-centered perspective to support workers and the possibilities of developing their work in a sustainable way, and the need for strategic, decision-making level support during technological transitions. Also, the PM perception regarding the difficulty of how and when to involve workers emphasizes the need for designing elements to guide this involvement, whether from the perspective of stakeholders managing people and their health (e.g., the support and conditions created for training and development, for health preservation) or the stakeholders responsible for digitalization processes (e.g. the type of software or tools introduced).

That said, how can sustainable transitions be reflected? How can technological transitions be developed considering workers and their work?

4.2. Incorporating work sustainability conditions in technological transition processes: guidelines from an organizational to an individual level

4.2.1. An evidence-based and human-centered framework development

Based on the data collected, a framework of guidelines on work sustainability conditions to enhance sustainable and human-centered technological transition processes was developed. This framework is intended to support practitioners and key stakeholders responsible for decision-making in the design and implementation of technologies. The aim is to contribute to an evidence-based transition approach aligned with I5.0 principles (Coelho, 2023; Directorate-General for Research and Innovation, 2021; Leng et al., 2022), which focus on people, their work, possibilities for skills development, reflection of their professional paths, and on health preservation.

With this purpose as background, the framework considered both the results highlighting that the specificities of work activity was not considered in the design and implementation processes, and those identifying protective factors and enables that support uninterrupted work activity, preserve working conditions, and foster skills development and health. The design process of the framework involved mapping the main empirical findings to the guideline categories (individual, collective, and organizational impact) and the stakeholders responsible for reflecting on and implementing the guidelines – elements that could be transversal to different technological transitions. Appendix A.2. (supplementary material) provides a detailed representation of this process.

4.2.2. Framework structure and practical implications

The framework is structured on three levels of guidelines, targeted at stakeholders with decision-making power to act in the workplace, placing work activity at its core (see Fig. 5). The framework highlights the importance of involving stakeholders such as HR, digitalization teams, managers or team leaders in the design and implementation of new technologies, and supports the identification of actions they can consider throughout these processes, taking into account the workers and work activity that will be impacted by a technological transition.

This framework positions work activity as the starting point for both the change itself and for discussions about the purpose of the changes, since it is through work activity that production and quality standards can be achieved. It also assumes that the challenges of work activity will inform and impact sequentially and interactively (represented by the uni- and bidirectional arrows, respectively): i) at the organizational level (in the process of designing and implementing new technologies – digitalization teams; and in the monitoring of the process – e.g., HR, HSO); ii) and at the collective and individual level (within teams and among operators who will be affected by the technological transitions).

The framework also links guidelines to specific stakeholders responsible. The designation of responsibility and the type of actions required to meet the guidelines must be discussed in each workplace, as they depend on the type of transition (with a greater or lesser degree of disruption to the work activity carried out and the production process) and the organization of the company's departments and teams. The work sustainability guidelines should also be understood as a dynamic process, that renews itself, with a temporal dimension. That is, the introduction of these sustainability conditions also impacts the altered/renewed work activity, fostering new ways of performing the work activity, maintaining or reinforcing the meaning attributed to work activity, and enabling the development of skills and strategies for regulating work activity. Additionally, this renewed work activity serves as the starting point for future transitions, thus repeating this process.

Applying the framework from the decision-making phase of introducing a new technology enables the integration of I5.0-aligned dimensions and actions into technological roadmaps and project planning, focusing on workers and the possibility of developing their work activities in a healthy manner with opportunities for development, ultimately contributing to the achievement of work that complies with quality and productivity standards.

5. Conclusion

The study conducted aimed to identify work sustainability conditions to support technological transition processes in industrial contexts. From a human-centered point of view, the study has several strengths, notably the originality of combining a work activity–oriented ergonomic approach with an Industry 5.0 perspective, the diversity of company stakeholders' viewpoints, and the practical relevance of the evidence-based framework. The results revealed facilitators and barriers related to the recognition of the importance of the technological transition process, working conditions, health, and skills development of workers, demonstrating that, although progress is still needed to achieve a fully human-centered approach, certain conditions appear to support a renewed work activity within technological transitions aligned with the I5.0 paradigm. It is expected that the proposed framework could be a valuable contribution and a tool for practitioners and decision-makers, promoting a participatory ergonomics perspective, particularly as technological transitions become increasingly frequent in workplaces. However, since the study was conducted during ongoing technological transition projects, it has limitations related to the data collection process and the timing associated with the maturity of use-cases. The research team's access to the field and contact with workers was limited, and the results correspond to different levels of technological maturity across the use-cases, which should be considered when interpreting the findings.

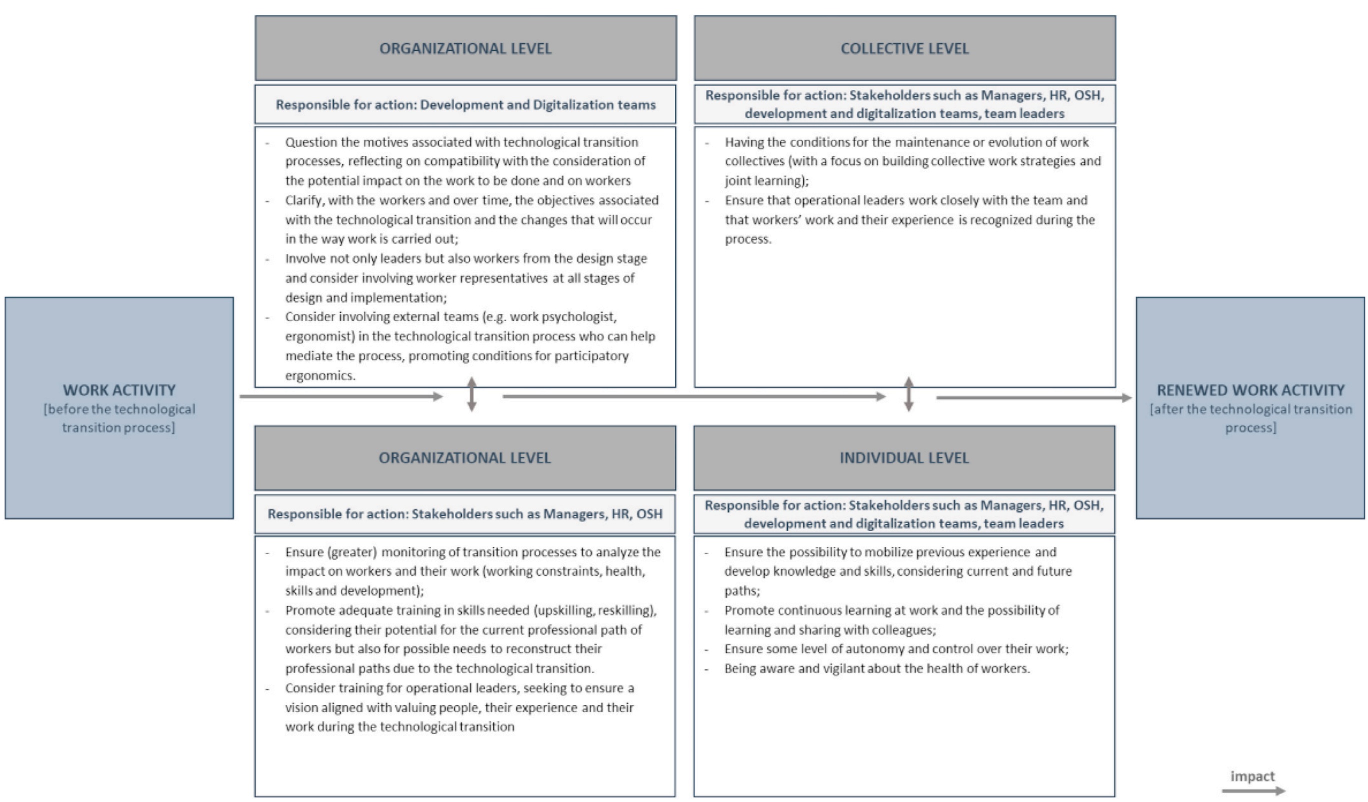

Fig. 5. Framework of individual, collective and organizational level guidelines for sustainable work conditions to support stakeholders in work activity-oriented and human-centered technological transition processes.

The originality of the study lies in the identification of an evidence-based framework of guidelines to promote work sustainability in technological transitions, from the point of view of workers and their work. The ultimate goal is to foster the I5.0 transition, seeking a sustainable transition for workers and their work possibilities.

CRediT authorship contribution statement

Cláudia Pereira: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mariana Magalhães:** Writing – review & editing, Writing – original draft. **Paula Lopes:** Writing – review & editing, Writing – original draft. **Daniel Silva:** Writing – review & editing, Formal analysis. **Marta Santos:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ergon.2025.103833.

Data availability

The data that has been used is confidential.

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