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RESEARCH ARTICLE

A method to improve workers' well-being toward human-centered connected factories

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Abstract

One of the most actual and consistent drivers for the industry is sustainability, which includes three main pillars: environment, economics, and society. While numerous methods for environmental and economic sustainability assessment have been proposed, social sustainability assessment is still lacking in structured methods and tools, although human has always played a key role. Moreover, technological development is pushing the industrial world toward a new paradigm, the "Industry 4.0," which embeds topics such as data digitalization, cyber-physical systems, and machine learning. It entails significant changes in human resources management, without reducing their importance. Humans were part of the manufacturing system from the first industrial revolution, and no automation or digitalization can be possible without humans. The industry can no longer underestimate the reasonable application of human factors and ergonomics principles to the workplace. For this purpose, the paper provides a novel transdisciplinary engineering method to measure and promote social sustainability on production sites. It exploits Internet of Things technology to support the (re)design of manufacturing processes and plants toward human-centered connected factories. To improve the workers' well-being has positive effects on their health, satisfaction, and performance. The method has been implemented in a real industrial case study within the footwear industry. The sole finishing process has been analyzed from different perspectives to solve ergonomics-related problems and implement effective improvement strategies.

Keywords: social sustainability; manufacturing ergonomics; human factors; Industry 4.0; human-centered connected factories

1. Introduction

Although the fourth industrial revolution is evolving at an exponential pace—transforming entire systems of production, management, and governance—sustainability continues to play a pivotal role. In general, independently of the driver, sustainable manufacturing should create great value for a company (Badurdeen & Jawahir, 2017). It is often driven by cost factors (Asiedu & Gu, 1996; Garbie, 2015), but the ISO 26000 (2010) introduced the topic of social responsibility as the willingness of an organization to incorporate social and environmental considerations in its decision-making. Besides the environmental contributions, Industry 4.0 holds a great opportunity for realizing sustainable industrial value creation on all three sustainability dimensions: economic, environmental, and social (Stock & Seliger, 2016). Industry 4.0 can be viewed as an integrated, adapted, optimized,

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service-oriented, and interoperable manufacturing process enabled by algorithms, big data, and high technologies (Lu, 2017). The integration of Internet of Things (IoT) inside the production process supports and facilitates new procedures and modalities to monitor, manage, realize, and optimize the same production process as well as its automation. The cooperation among connected objects allows having a real-time framework of data, predicting the process behavior, and promptly reacting. Discrete event simulation tools are other emerging technologies that are playing an important role in transforming the traditional factory, supporting design activities (Laurindo, Peixoto, & de Assis Rangel, 2019). However, Industry 4.0 is not just about machines or equipment. It should also focus on humans, creating an adequate, safe, sustainable, and attractive work environment. The sole focus on technology will result in non-sustainable systems with negative outcomes. Special attention should also be paid to physical and non-physical influencers to implement interventions that can induce positive change and minimize negative behavior for all stakeholders (Genaidy, Huston, Dionysiou, & Karwowski, 2017). Indeed, Industry 4.0 is changing how to produce goods and consequently the role of the operator, which is increasingly called to manage and supervise production systems. It allows enhancing the level of flexibility and adaptability that humans have. For example, Ceruti, Marzocca, Liverani, and Bil (2019) demonstrated how the implementation of Industry 4.0 technologies in the aeronautical maintenance allowed reducing the operators' workload and improving the task performance concurrently. Any repetitive, forceful, and dangerous task becomes a perfect candidate for robotic manufacturing, especially if it takes place in a hostile environment. It means a revolution of work-related risks that have to be investigated according to a holistic perspective (from musculoskeletal disorders to stress) and a human-centered approach. On the other hand, Industry 4.0 presents an opportunity for organizations to develop more intelligent workspaces that allow monitoring and improving working conditions. Through the rapid development of IoT devices, it will be possible to monitor the workers' psychophysical status and promptly intervene for improving their well-being.

In this context, this paper proposes a framework for measuring and promoting social sustainability in the factories of the future. The remainder of the manuscript is organized as follows. Section 2 proposes a clear state of the art on sustainable manufacturing in the Industry 4.0 context. Particular attention is paid to human factors and the relative methods and tools aimed at improving working conditions. Section 3 describes the transdisciplinary engineering method for human-centered connected factories. The method aims to assess workers' well-being, identify work-related risks, and define proper improvement strategies. Section 4 describes the method implementation in a real plant of an Italian sole producer. In Section 5, the results relied on the case studied are presented and discussed. Finally, the main findings, concluding remarks, and future works are reported.

2. Research Background

Garetti and Taisch (2012) recognized the "manufacturing" as the main pillar of the civilized lifestyle. It will be strongly affected by the sustainability issues playing an important role in establishing a sustainable way ahead. Rödger, Bey, and Alting (2016) proposed a holistic framework to integrate sustainability thinking into manufacturing. The idea is to merge the life-cycle perspectives with product and production to optimize the latter in the early design stages. Moldavska and Welo (2017) proposed an interesting literature review of this topic. Although the definitions of sustainable manufacturing remain inconclusive within the research community, some elements are commonly considered. One of them is the employees' domain.

In the past decades, several models of the factory planning process have been developed (Hawer, Sager, Braun, & Reinhart, 2017); however, the human perspective is lacking. From the literature review by Otto and Battaïa (2017), what emerged is the importance of adapting the ergonomics estimation methods to the needs of preventive planning. Few papers analyze the workers' experience to support human-centered product–process design. Peruzzini, Grandi, and Pellicciari (2018) are addressing this issue by defining a reference model to monitor the human stress and comfort to be used to support the requirements definition of industrial systems, considering product and process features in an integrated way. Gregori, Papetti, Pandolfi, Peruzzini, and Germani (2017) dealt with the acquisition of social data in a production plant. They proposed a tool (social decision matrix) that lets the designers consider the workers' conditions and performances during the design and development process of a new production system. Machine design and practices based on a preventive knowledge-based approach would be helpful when a regulation or a standard, which sets forth the principles and the methodologies to address hazards and risks in the design processes, is in force. Designers should apply the international standards about "safety machinery" and "ergonomics" focusing both on performance and human aspects. Therefore, a transdisciplinary approach is required to adopt a holistic vision and obtain effective benefits. Several competencies should be involved, such as production managers, ergonomists, health and safety executive, designers, data analyst, psychologist, and operations researchers.

The main aspects to be faced by social innovation include the following: preventive occupational health and safety, human-centered design of work, employee participation, and work–life balance. Human-focused best practices needed to be defined and implemented to solve existing criticalities from an ergonomics perspective and to increase the operators' well-being. Monitoring key parameters and consequently adapting tasks, workstations, tools, and equipment to fit the worker help in reducing physical work-related disorders and mental stress. IoT and data are key enablers of social innovation. However, there is the need to increase the level of trust that humans have toward their future co-workers such as connected devices, autonomous devices, and software (Siemieniuch, Sinclair, & Henshaw, 2015). All these concepts aim to preserve or build up human capital. It is known that the quality of life and the quality of production are both dependent on the working environment (Jokl, 1982), which influences workers' health, safety, and performance. Evidence from the literature demonstrates that ergonomics has benefits in terms of shareholder value, productivity, and comfort, highlighting how participatory approaches contribute to the success (Vink, Koningsveld, & Molenbroek, 2006). Although the importance of both operational performance and employee well-being for organizational success is intuitive, organizations often perceive a conflict between them (Hoffmeister, Gibbons, Schwatka, & Rosecrance, 2015). Zink (2014) considers sustainability as a chance to include the concept of ergonomics or human factors in a worldwide relevant topic and proposes a global framework for designing sustainable work systems. Ergonomics is not just related to machinery but can be extended to the entire organization every time the design production process involves human factors. It is the science of designing user interaction with equipment and workplaces considering several aspects: physical, cognitive, and organizational. Physical ergonomics concerns with the study of the relation between anthropometric, physiological, and biomechanical characteristics, as well as the dynamic or static parameters of physical effort at work. The most significant features include safety and health risk factors such as working postures, materials handling, repetitive movements, which are possible causes of work-related musculoskeletal disorders (Karwowski, 2006). Cognitive ergonomics involves psychological processes such as awareness, human information elaboration, and movement response, as it concerns human interacting with other system components. Some important topics include workload, decision-making, perception, attention, motor response, skill, memory, and learning as these may relate to human-centered design. According to the EN ISO 10075-1 (2017), mental stress is the effect of all conditions with a mental impact on an operator, i.e. either cognitive (e.g. information to be processed) or emotional (e.g. potentially aversive consequences of work activities). Organizational ergonomics is based on interdisciplinary work, which affects the social, cognitive, relational, and physical aspects of the working environment. In this field, methodological studies and suitable tools for the prevention, assessment, and evaluation of emerging psychosocial diseases (i.e. stress, mobbing, and burn out) are involved. The issues that may affect the ergonomics of the organizational structure are related to the work organization in terms of shifts, working time, and breaks.

According to this holistic vision, May et al. (2015) proposed a new human-centric factory model providing a taxonomy of the aspects to be considered in designing these worker-centric factories of the future. Mengoni, Matteucci, and Raponi (2017) defined a multipath methodology to effectively support the measurement of the ergonomic quality of the worker in his workspace. Lamb and Kwok (2016) studied the indoor environmental quality considering noise, light, and thermal as comfort factors. Yoon, Ko, and Jung (2016) suggested a job rotation schedule to prevent exposure to high workloads successively on the same body region. Romero, Wuest, Stahre, and Gorecky (2017) explored the role of the social operator 4.0 in the context of smart and social factory environments, where humans, machines, and software systems will cooperate (socialize) in real time to support manufacturing and services operations. They presented a high-level social factory architecture based on an adaptive, collaborative, and intelligent multi-agent system. Also, Song and Moon (2016) focused the discussion on new technologies. They discussed the benefit of cyber manufacturing systems and their role in future development. The smart factory paradigm requires operators to be more flexible and to acquire new capabilities. For this aim, companies are increasingly relying on smart training systems based on virtual reality and augmented reality simulation. Longo, Nicoletti, and Padovano (2017) proposed an intelligent personal digital assistant to provide quick and effective support to operators about tasks/procedures/equipment.

One of the widespread issues about the ergonomics methods implementation is the absence and poor quality of the required data (Otto & Battaïa, 2017). IoT-enabled manufacturing, successfully implemented with many industrial cases, highlights real-time data for production decision models and smart manufacturing objects modeling. Most of the IoT applications were focused on the monitoring domain dealt with remote sensing of physical and environmental parameters (Talavera et al., 2017). However, intelligent manufacturing and cloud manufacturing are still in the research or proof-of-concept stage and have a limited number of real-life cases (Zhong, Xu, Klotz, & Stephen, 2017). Moreover, they mainly refer to resources, production, and logistics and rarely focus on monitoring operators' daily tasks to improve their working conditions and well-being, which is the aim of this work. To resolve these issues, the paper proposes a transdisciplinary engineering method to promote social sustainability on production sites by providing the basis for the design of adequate manufacturing environments and workplaces. Its implementation in a real industrial case study is also described. The finishing area of an Italian sole producer has been analyzed and improved from a social point of view. Different workers' performance and needs have been investigated from different perspectives to solve ergonomics-related problems and implement appropriate corrective strategies. The idea is to go toward human-centered connected factories capable of reacting, sensing, and thinking, given different manufacturing requirements or situations, without excluding humans but satisfying their needs.

3. Methodology

Companies, independently of their size (small and medium-sized enterprises as well as large companies), usually tend to deal with sustainable development without a structured approach. This research proposes a method to allow walking the path toward innovation exploiting IoT technologies and considering the sustainability pillars. In this paper, it focused on the social one by supporting the creation of a human-centered connected factory. The industry can no longer underestimate the consistent application of ergonomics at the workplace, also due to stricter regulations on this matter; therefore, the integration of human factors in the (re)design of production systems is essential. The method consists of the formalization of the steps needed to help designers to define sustainable and innovative plants, from the definition of the problem to the implementation of effective strategies. Many times, industries asked academia to improve a process from a sustainability perspective. Only when a structured methodology was applied, the problem has been solved. Moreover, improvement is a matter of data management, and many companies, especially in the Marche Region, lack data. Then, this method was thought to perform process analysis and improvements through the connection of the factory itself. It is based on the following steps:

1. Step 1. Factory assessment
   1.1 Plant layout
   1.2 Resources mapping
2. Step 2. (Re)design goal and boundaries definition
3. Step 3. IoT configuration
   3.1 Define framework aims
   3.2 Identify variables of the environment
   3.3 Identify sensors on the market
   3.4 Select sensors minimizing the equipment
   3.5 Create the framework
   3.6 Convey all data in a single device
   3.7 Set rules to improve the environment
   3.8 Install actuators in the system
4. Step 4. Implementation and assessment
   4.1 Measurement campaign
   4.2 Data analysis
5. Step 5. Corrective actions identification
6. Step 6. Cost assessment of novelties

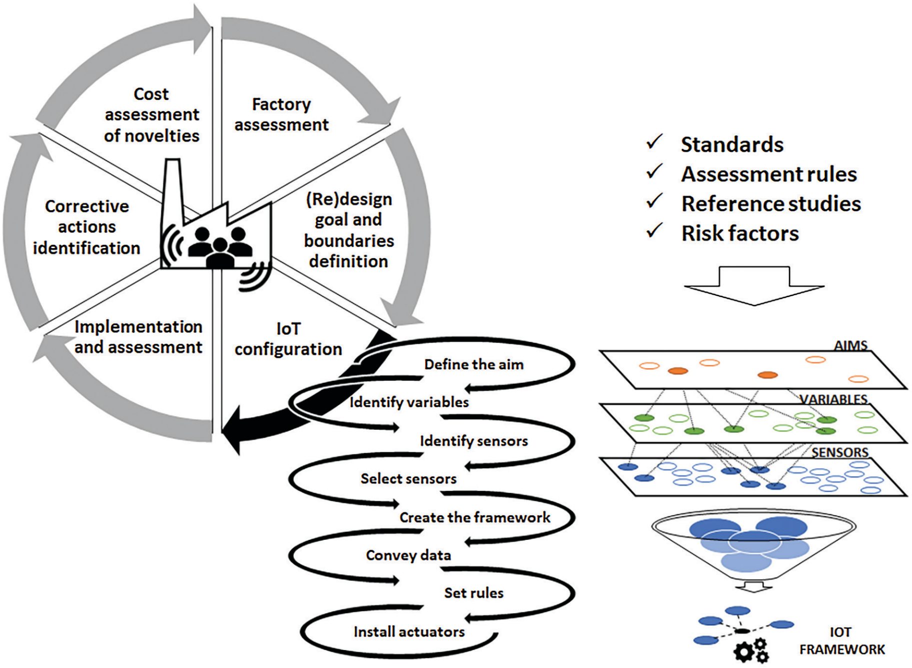

Figure 1: Transdisciplinary engineering method for human-centered connected factories.

As shown in Fig. 1, the method is thought as a loop in accordance with the continuous improvement approach, encouraging factory to constantly evaluate and improve its processes, updating the IoT framework, and dealing with new criticalities. The IoT design also follows an iterative approach. The method involves competencies belonging to different disciplines such as engineering, management, design, occupational health and safety, biomechanics, psychology, and computer science, both internal and external to the company.

In more detail, step 1 consists of the definition of a state of the art of the plant by a complete "factory assessment." By the experience many companies have a baseline not clearly defined. With a focus on Italian manufacturing companies, they have grown fast in the last 30 years but not in a homogeneous way; new technologies live together with old procedures and inefficient buildings or vice versa. It means that a structured innovation plan was not followed, meaning lack of industrial culture and loss of money. The first step of the method permits to overcome this kind of situation by understanding clearly the plant in terms of structure, asset, resources, and flows. The former means analyzing the plant layout considering all spaces available. For this kind of analysis, the map of the plant should be acquired. Knowledge about resources, including humans, permits us to be aware of the competitive advantage of a company. Since resources usually refer to energy and raw materials, many forms of diagrams and reports are related to them, overlooking human resources. Therefore, it is very important to map all people working in a plant considering their characteristics, skills, and experience. Regular visits to the shop floor (e.g. Gemba Walk) can help managers observe the operational reality and understand how processes differ from standard operating procedures. In this phase, the first involvement of the operators takes place. Indeed, it includes the interaction with people who are closest to the production to analyze the process from their point of view. It allows managers to develop the habit of engaging with employees and helps operators feeling more comfortable and open to share information and insights about potential problems. In step 1, also an asset analysis should be performed to understand all machinery of the production plant. It could have different purposes related to productivity, user interaction, energy efficiency, etc. The last part of the factory assessment is the production flows analysis, which permits to understand all the manufacturing stages of the plant from a productive and informative point of view. It means to map the complete process by IDEF0, Value Stream Mapping, or any other diagram aimed to define the plant workflow and management system. This phase permits us to have a clear picture of the factory and the related improvement opportunities on a general level.

Step 2 consists of defining the main driver of the (re)design strategy. For example, it should consist of reducing the environmental impact, improving the workplace organization, or increasing productivity. Clearly defining and sharing the main goal of the (re)design process positively affects employee engagement and behavior. Employees aligned with the company goals are usually more likely to push themselves to achieve them. Especially in this context, sharing objectives and strategies allows operators to understand the win-win nature of companies' initiatives, for example, perceiving them with the finality of improving their well-being rather than controlling their productivity. Moreover, this step ensures the analysis is performed consistently. In this phase, the object of the study has to be carefully defined, possible choices or hypothesis described, and the boundaries established (e.g. workstation, process, and operator). Step 2 can also include the definition of the information granularity expressing the process specificity or generalness and the selection of key performance indicators (KPIs).

Step 3 consists of defining the IoT framework that should support the data acquisition during the life cycle of a plant. It allows gathering objective parameters, which are a prerequisite for an effective assessment and to help decision makers while improving the production system, for example, from an ergonomic point of view. This step is the most important part

Table 1: Examples of objective and subjective methods for data measurement for the research domain.

Objective methods			
Postural measures	*Strained postures* • REBA • OWAS	*Repetitive movements* • RULA • Job strain index • OCRA • PLIBEL	*Handling of loads* • NIOSH equation • Snook and Ciriello tables • Variable lifting index
Physiological measures	*From ECG* • Heart rate (HR) • Heart rate variability	*From breathing analysis* • Breathing rate (BR)	*From EOG* • Pupil diameter • Eye blinks
Subjective methods			
Self-reported measures	*About perceived comfort* • Bedford scale	*About perceived exertion* • Borg scale	
Questionnaires	*About perceived comfort* • NASA-TLX		

of the method. It aims to ensure proper data management. It starts with the definition of specific aims that the IoT framework should satisfy. Standards (e.g. machinery directive), risk factors, and reference studies have to be considered as possible drivers of this phase. It means set key questions for the data analysis. At this point, the variables needed to answer these questions have to be identified. Each aim is associated with a subset of variables, which, in turn, can be measured by a subset of sensors available on the market. Variables should be selected avoiding information overload and underload. Sensors should be selected minimizing the costs and the equipment in a life-cycle perspective. A benchmarking should be performed taking into account several criteria such as interoperability, intrusiveness, accuracy, features, and acquiring protocols. Then, the framework is assembled in the environment, and all data are conveyed in a single device (e.g. database manager) to properly manage them. To make this environment intelligent, a set of rules and algorithms should be defined. They allow performing the most effective actions (online or offline) according to the data collected. Installing actuators in the system permits these actions to be automatically executed. Considering the iterative nature of the method, the IoT framework should be improved over time.

When the IoT environment is correctly configured, step 4 should run. In this step, the measurement campaign is planned and performed. It should be as less intrusive as possible, guarantee the same performance, and avoid production shutdown. Resources, procedures, and documentation should be clearly defined and arranged for time. Especially if operators are involved, a participatory approach is recommended. It allows increasing the people's awareness about the purposes of the analyses, saving time, improving the information quality, and preventing actions that should collide with the measurement. Although this article focuses on the use of the IoT for monitoring the psychophysical status of the operator, it is worth to specify that a set of subjective measurements is also collected to better contextualize and analyze the results. According to the established goal, the following multidimensional assessment methods can be exploited:

(i) Objective methods:
   a. Postural assessment by direct observation: experts are involved to observe operators during their activities and to collect data about anthropometrical data and joint angles, to be subsequently analyzed by different checklists according to activity typology (involved body parts, frequency, loads, etc.);
   b. Physiological parameter measurements: operators wear bio-sensors (e.g. belts and bracelets) able to monitor a set of significant vital parameters during task execution to control physical and cognitive workload and avoid stressing conditions. Different studies have already demonstrated the validity of such methods to detect workers' stress condition (Peruzzini et al., 2018).

(ii) Subjective methods:
   a. Self-reported scales: users are asked to express a quantitative measure of the perceived exertion during their physical activity. They are numerical scales with different points. When a measurement is taken, a number is chosen from the specific scale by the user that best describes their level of stress, according to the particular aspect investigated (e.g. physical exertion, perceived comfort);
   b. Questionnaires: users are asked to rate for each task to investigate the perceived conditions (e.g. workload) by a set of questions, according to a specific evaluation scale.

According to the classification mentioned above, Table 1 presents the most common methods adopted in the industry.

Once gathered, data have to be organized in a database and normalized to reduce their redundancy, ensure their consistency, and improve their integrity. They are then manipulated to derive the exact information decision makers need. It means to analyze trends, correlations, variations, and outliers by using advanced computing capabilities. Both the data acquisition and the data analysis should be compliant with the IoT framework aims (e.g. if the objective is to improve the physical ergonomics, it is unnecessary to analyze the heart rate).

The results of the data analysis process allow defining the best course of action (step 5). Improvement strategies depend on inefficiencies and can act at different levels:

(i) Organizational, which includes shift management, work methods, resource mobilization, and allocation, etc.;
(ii) Operational, which refers to layout, best practices, training, supporting elements, etc.;
(iii) Technological, which could mean both automate, support, or simplify tasks and better maintain, update, or replace asset.

Brainstorming sessions involving different stakeholders (both managers and operators) should be organized to identify the best solutions and support their design and implementation.

Figure 2: Painting carousel packaging area and tasks.

Table 2: Main characteristics of the operators involved in the testing sessions.

	Operator 1 (OP1)	Operator 2 (OP2)
Gender	F	F
Age	46	38
Height	171 cm	172 cm
Weight	60 kg	52 kg
BMI	20.52 kg/m^2 (normal)	17.58 kg/m^2 (underweight)
Years of experience	26	10

Therefore, also in this phase, the direct involvement of workers plays a key role.

Finally, to check the economic feasibility, cost–benefit analysis (CBA) is carried out. Indeed, the benefits achieved have to outweigh the costs incurred by the company within an acceptable period. CBA allows to evaluate the feasibility of the proposed actions and compare the different possible solutions, to select the most suitable measures to implement, according to specific problems identified. CBA is based on a systematic financial method as proposed by Cellini and Kee (2010) to express in monetary terms all flows of benefits and costs over time in terms of their net present value, regardless of whether they are incurred at different times. It is validly used in numerous sectors, including sustainably (OECD, 2018), for evaluating the feasibility of a project or program by systematically summing its benefits and deducting its costs. It represents an advance over traditional forms of valuation in that it includes opportunity costs, cost of externalities, and costs of intangible assets.

4. Case Study

The case study involves a large Italian company, which is one of the worldwide top producers for rubber and polyurethane soles. The analysis followed the six steps as described in the previous section.

The study started with a detailed study of the company production system (step 1), from the analysis of the plant layout to the investigation of its work organization (flows identification, human resources identification, and asset analysis). The whole plant, which consists of 55 000 m^2, is divided into seven different departments and produces 70 000 polyurethane sole pairs and 35 000 rubber sole pairs daily. The study focused on the carousel packaging area at the finishing production phase (Fig. 2), because it comprises most of the workers. When the painting is completed, an operator puts the sole on the carousel that turns to permit the sole to be completely dry. After half a turn, on the other carousel side, the packaging specialist takes the product in pairs and proceeds to packaging. The carousel, which is structured on nine layers, transports different products in different sizes, requiring each operator to manage two or three boxes at the same time. The packaging workstations are four, managed by two operators (Table 2). They consist of reclined shelves on which boxes to be filled with soles are placed.

Table 3: IoT configuration for workers' well-being assessment and KPIs.

KPIs	Measures	Sensors	References
Reduction of physical workload	Heart rate Breathing rate Postural assessment by: • NIOSH • Snook and Ciriello tables • Variable lifting index	Biometric sensors Activity tracker Cameras	UNI EN 1005 (2009) ISO 11226 (2000) ISO 11228-1 (2003) ISO/TR 12295 (2014) Snook & Ciriello (1991) Battevi, Pandolfi & Cortinovis (2016) Waters, Occhipinti, Colombini, Alvarez-Casado, & Fox (2016)
Reduction of mental workload	Eye blink	Eye tracking	Ogawa, Takahashi, & Kawashima (2016)
Improvement of user interface interaction	Eye blink No. interaction steps	Eye tracking	Ogawa et al. (2016)
Improvement of air quality	Fine particles (PM 2.5) Volatile organic compounds (VOC) Carbon dioxide (CO_2) Temperature Humidity	Environmental sensors	Directive 2008/50/EC Leg. Decree 81/2008 (INAIL, 2008) WHO guidelines (WHO, 2016)

Once the boxes have been filled, they are closed, lifted, and transported to the storage area and stacked on pallets. In addition to the packaging activity, the two operators have to check orders on the video display terminal (VDT) and print the related documents. Work is organized on 5 days per week, in a single shift from 6:00 am to 2:15 pm, including a break of 15 min after 3 h of work.

In particular, the packaging process can be split into the following 11 tasks (Fig. 2):

1. T1. Box preparation and positioning on the workstation
2. T2. Order control and label printing (VDT)
3. T3. Box classification by label
4. T4. Soles picking
5. T5. Quality control
6. T6. Soles packing with related equipment
7. T7. Soles counting
8. T8. Box closing
9. T9. Box lifting, transporting and storing
10. T10. Boxes enumeration
11. T11. Work report

One of the main resources of the factory is people: 40% of 170 workers are currently involved within the finishing processes.

Based on these evidence, the company was planning a factory redesign (including an expansion in terms of land use) according to the social sustainability and industry 4.0 paradigms. Such innovation plan led the goal and boundaries definition (step 2). The analysis in particular aimed to improve and innovate the finishing area of the plant from a social point of view with the perspective of digital manufacturing. It focused on the social relapses of the as-is packaging process, which is a completely manual operation. In this phase, also a set of KPIs was defined. In particular, four KPIs were defined as reported in Table 3.

To proceed with the IoT configuration (step 3), the standards and norms related to human workers were taken into account, and the main risk factors related to the different ergonomics domains were identified.

Table 3 indicates, for each KPI, the related measures, as well as the sensors (as smart devices) adopted to measure them.

Considering the variables mentioned above, a benchmarking of sensors available on the market was performed. They were identified and selected according to the following criteria: accuracy, intrusiveness, and multifunctionality (Fig. 3). The IoT framework, which better fits the working environment and workers, was so configured.

To monitor vital parameters [i.e. heart rate (HR) and breathing rate (BR)], workers wore a chest belt sensor. Data were available in real time on a smart tablet, whose dashboard presented variables and relevant thresholds. An activity tracker with steps counter was useful to detect for how many meters the operators have to walk along the carousel and transport the filled boxes. A camera was positioned to have a complete view of the testing area. It was useful to capture workers' behaviors performing the working tasks, to detect any difference from the usual working pattern, and to interpret the trend of the variables appropriately. To investigate the level of mental workload and cognitive stress, workers wore eye tracker glasses able to perform the electrooculogram (EOG) analysis. The working environment was assessed with an air-quality smart station, characterized by a non-intrusive presence and positioned nearby the working area. It provided some air parameters detection, such as temperature, humidity, and indoor pollution (VOCs, CO_2, CO, and PM2.5). The IoT framework also included network connectivity, a Wi-Fi router to ensure data collection in real time and remotely, a PC for data storage, and a tablet for real-time monitoring.

According to the preliminary analysis results, a set of rules and possible actuators will be adopted.

After that, the implementation and assessment phase was carried out (step 4). The framework was installed so as not to affect the everyday working of the plant. Both workers wore smart devices by keeping them for the whole test duration (at least 2.5 h). Past observations and considerations suggested it as the minimum time required to monitor enough working cycles not

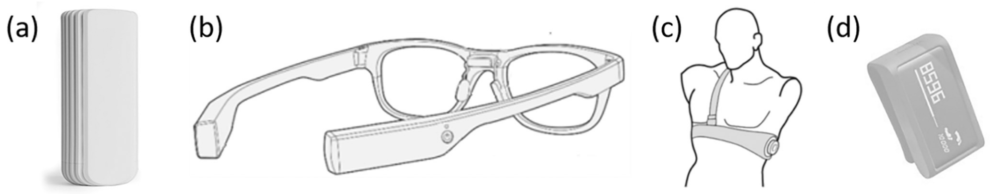

Figure 3: Smart devices: (a) air-quality station; (b) mental workload tracking glasses; (c) vital parameters and posture chest belt; (d) steps counter.

Table 4: Assessment of human posture and the health risks of manual lifting and carrying.

Lower back posture (ISO 11226)						
Measurements	**$x < 20^\circ$**		**$20^\circ < x < 60^\circ$**		**$x > 60^\circ$**	
Operator 1	7431	79.95%	1771	19.05%	93	1.00%
Operator 2	8459	92.07%	713	7.76%	63	0.69%

Manual handling: lifting and carrying (ISO 11228-1)			
Index	**NIOSH variable lifting index**	**Synthetic risk index (carrying)**	**Cumulative mass index**
Operator 1	2.03	0.96	0.04
Operator 2	1.53	0.98	0.04

affected by observer bias. The acceptance of the wearable devices was promoted, thanks to a participatory ergonomics approach. Workers understood the benefit and no risk of the monitoring survey. The workers' participation in the study was voluntary and granted by a shared release form. The workers' involvement in the decision-making process of the workplace improvement strategies resulted in the awareness of the relevance of the assessment. The win-win opportunity of the analysis was successfully recognized. The data analysis consisted of the following steps:

(i) Data download and classification;
(ii) Data cleaning, which allowed eliminating biases and errors (e.g. the operator walked away from the testing area to solve a quality issue with the area manager);
(iii) Peak analysis that permitted to identify limit values for each data flow. Those values were interpolated with the video file to understand which operation was ongoing during a certain peak;
(iv) Data correlations to ensure better data interpretation. A quantitative analysis was performed to verify the presence of similar trends in correspondence of a certain event (e.g. BR and the activity level were checked in case of HR alarms) or task (e.g. HR, BR, and steps were checked in case of T9). Such analysis also allowed identifying false alarms.

Two brainstorming sessions were organized to identify corrective actions able to mitigate the emerged risks (step 5). The first one required the active participation of workers and managers of the packaging area. It allowed analyzing the root causes in detail, exploiting well-known techniques (i.e. 5-why method, 4M fishbone diagram), hypothesizing some solutions, and identifying possible best practices. The second session involved managers of different departments and with different skills in order to skim, define, and concretize the ideas coming from the first session.

At this point, one of the company managers, who generally deal with the valuation of investments, performed the CBA and then assessed the results in collaboration with the department manager, the plant manager, and the human resources manager (step 6).

5. Results

According to the scope of the research, the results are now provided and discussed in relation to the data interpretation phase.

The posture and vital parameters analysis gave information about the operators' physical workload. As shown in Table 4, the packaging process is more physically demanding for the first operator than the second one. Comparing awkward postures in terms of occurrences, she has more warning conditions. Analyzing the posture trend simultaneously with the video, it was noticed how the most problematic posture is due to the box placement (T9) on the 1st layer of the pallet (20 cm from the floor level), as shown in Fig. 4. Sometimes, the operators were also obliged to pick boxes in a bad posture condition because of layout constraint. Indeed, the lack of space in the carousel area does not allow operators to prepare the box comfortably. For OP1, another critical task, from a postural point of view, is the box labeling task (T3). In this case, the two operators perform it in a different way. The second one labels the box in a standing position, contrary to OP1, who bends her back almost 60°. About T4, it was noticed a proactive behavior by operators defined a procedure for the sole picking from the carousel to increase productivity and their health. They decided to let the higher operators pick soles from a higher level of the carousel, obtaining a better fatigue distribution. For both operators, most of the steps taken are related to the following tasks: T4 and T9.

The lifting and carrying analyses were limited to T9 because empty boxes (T1) weigh less than 3 kg. Both operators obtained similar results because they managed the same number of boxes (30), with about the same weight (from 10 to 15 kg), walking roughly the same distances (from 3 to 7 m). However, the NIOSH variable lifting index resulted higher for OP1. It is related to her age that increases the risk of lower back pain.

From the analysis of the vital parameters, significant differences between the two operators emerged, even though they performed the same job tasks. It is mainly due to different HR

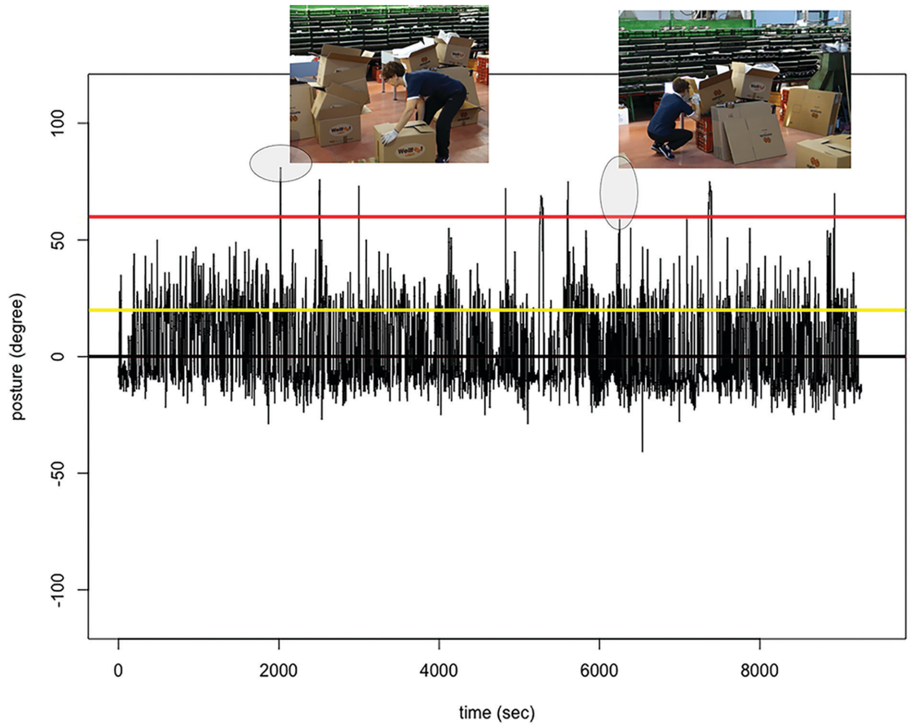

Figure 4: Posture analysis of Operator 1 (yellow and red lines refer to ISO 11226 thresholds 20° and 60°, respectively).

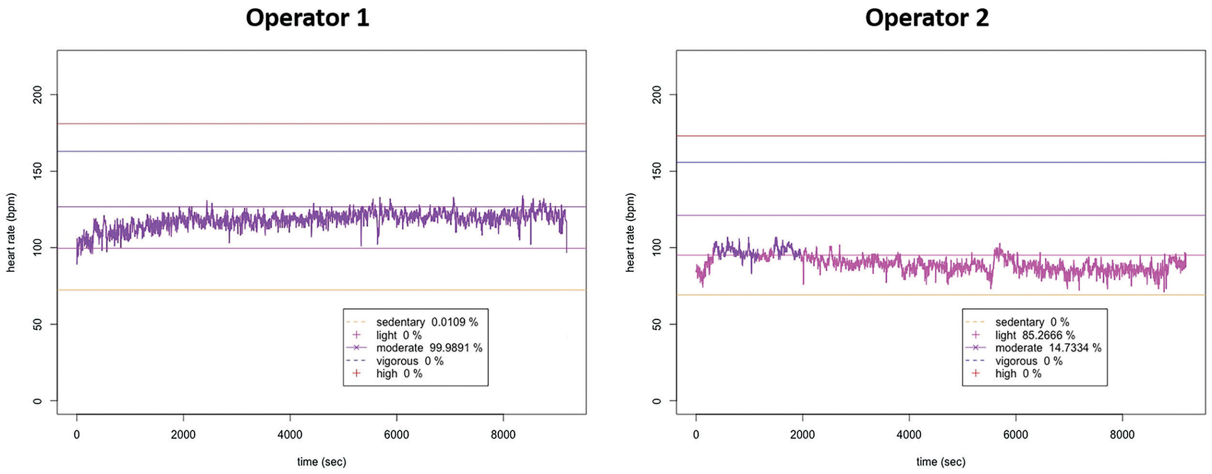

Figure 5: HR trend according to the activity level.

and BR values at rest. Considering the test period, the average HR of OP2 was 117 bpm compared to 89 bpm of OP1. Similarly, the OP2's BR (18 bpm on average) tends to be higher than OP1's BR (14 bpm on average). According to this evidence, the HR and BR variability over time has been analyzed to detect possible correlations with tasks. As shown in Fig. 5, the physical effort of OP1 is mainly influenced by the activity she was performing. In particular, during the box lifting and transport, an increase of beats and breaths per minute was observed. In the first 30 min, this task also generated a change of activity level from light to moderate. Analyzing the HR of OP2, it is possible to notice how she is more influenced by fatigue than tasks. In general, the effort of both operators was acceptable over time; however, OP2 resulted more physically stressed than OP1.

The eye is a source of an electrical potential, which is attributed to metabolic processes occurring in the retina. This potential difference and the rotation of the eye allow measuring a signal known as EOG using a pair of superficial periorbital electrodes. Through the EOG, it was possible to identify three basic eye movement types: saccades, fixations, and blinks. The sensor resolution is 12 bits, range from -1500 to 1500 μV with the sensitivity of 1.37 LSB/μV, where LSB means least significant bit. The analysis results showed how, after 1.5 h, there is a consistent change in terms of cognitive workload. Signals shown in Fig. 6 represent EOG values for 15 s of measurement before and after 1.5 h. It emerged that after 1.5 h, there are continuous peaks, meaning blinks in the EOG graph. It makes difficult to correctly associate peaks to tasks and understand the related

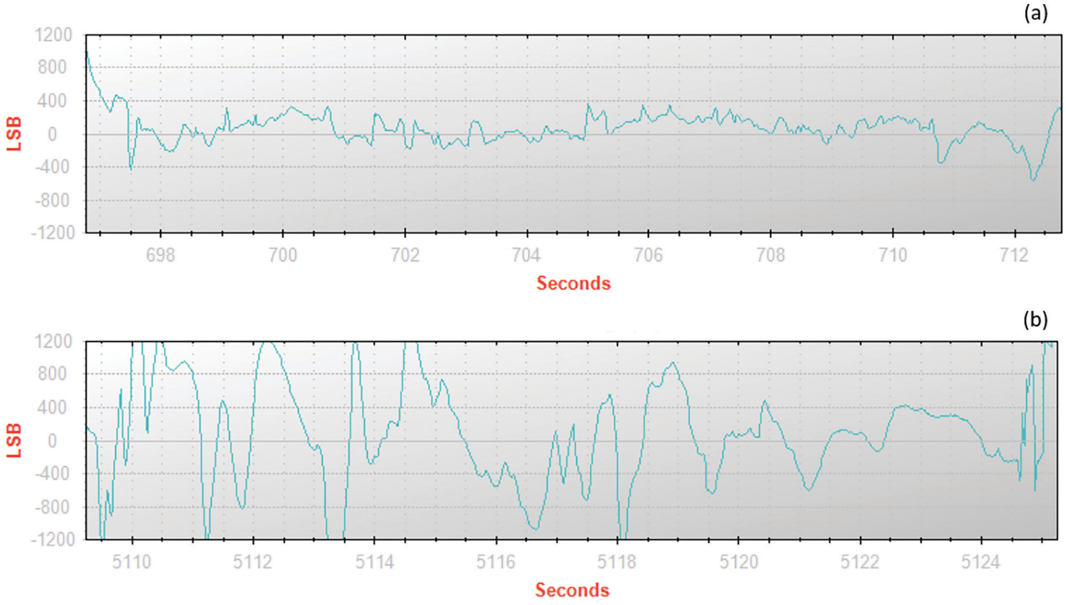

Figure 6: Mental workload trend before 1.5 h (a) and after 1.5 h (b).

impact. Even after the break, the EOG trend resulted still a bit affected by fatigue.

Going more in detail of the first 1.5 h, the mental load trend showed peaks of concentration for specific sub-tasks. The separation of polyethylene terephthalate foil (T6) resulted as the most impactful from a mental point of view (Fig. 7). Operators are not able to simply separate foils from each other while taking them from the sheet stacks. It requires precision because of the small thickness of the foils. Another mental impacting task is the box transportation (T9). It needs high concentration, affecting not only the physical fatigue but even mental workload. Similar trends were also registered during the soles counting.

An interesting mental workload trend was registered during the interaction with the VDT (T2). The signals registered were almost linear. For both operators, the mental load has no peaks, and the saccades have a little delta meaning an acceptable workload required by the task.

As far as the air quality is concerned, all measured values are under the regulatory limits, but some improvement actions are recommended. Concentration level of CO_2 averaged 1264 ppm with a peak of 2512; however, the air sensor had registered many peaks (Fig. 8). It is related to the packaging area layout. The manual painting line, on the other side of the carousel, has no separation from the packaging area, and packaging operators do not wear protective masks because it was supposed they would be safe from particulate emission. However, proactive behavior was noticed. An operator working on the same area, but not involved in packaging operations, started to open the shutter, which permits the external exit, every time the sensor indicated a high concentration of CO_2 in the air (red led). The graphs of Fig. 8 show the benefits of this behavior.

The improvement actions proposed act on different levels: operation, organization, and technology. For example, the definition and the diffusion of best practices on how to perform specific operations could encourage workers to improve their posture, reducing the physical workload. Thanks to the spaghetti diagram, it was possible to verify that the rearrangement of the packaging area layout could reduce the number of steps taken by the operators. The breaks rescheduling could reduce the metal workload that affects operators after 1.5 h from the shift start. Technological investments in more ergonomic pallet, foils dispenser, or aspiration system would generate benefits, respectively, in physical, cognitive, and environmental ergonomics domains.

On the other hand, a possible integration between the shutter and the air-quality sensor to have an automatic shutter opening, according to the CO_2 level, is an example of rules and actuators implementable to make the IoT framework intelligent. It would be the first step toward the smart human-centered factory.

Table 5 summarized for each aim the involved tasks, the corrective actions identified, and the relative cost. Tasks have been classified as sustainable, improvable, and not sustainable according to the related risk level (from no risk to high risk).

The proposed investments are not only costs. Indeed, they generate benefits from both the social and economic point of view. They allow improving the workers' well-being and saving direct and indirect costs associated with work-related musculoskeletal disorders. The former are workers' compensation claims, medical payments, and legal expenses. The latter are related to lost production, insurance premiums, labor turnover (retraining, recruiting, etc.), investigation time/administration, bad publicity, etc.

6. Discussion and Conclusions

This paper proposes a novel transdisciplinary engineering method to assess plant social relapses on operators under the Industry 4.0 paradigm. It exploits the IoT-related opportunities to identify the process criticalities and, consequently, improve its sustainability. The use of wearable technologies for biomechanical risk assessment is thoroughly discussed by Alberto, Draicchio, Varrecchia, Silvetti, and Iavicoli (2018), which highlighted their potentialities and how their application is only at its initial stage. Although in this study, the posture evaluation through IoT devices is limited to the back, it confirmed the following main benefits:

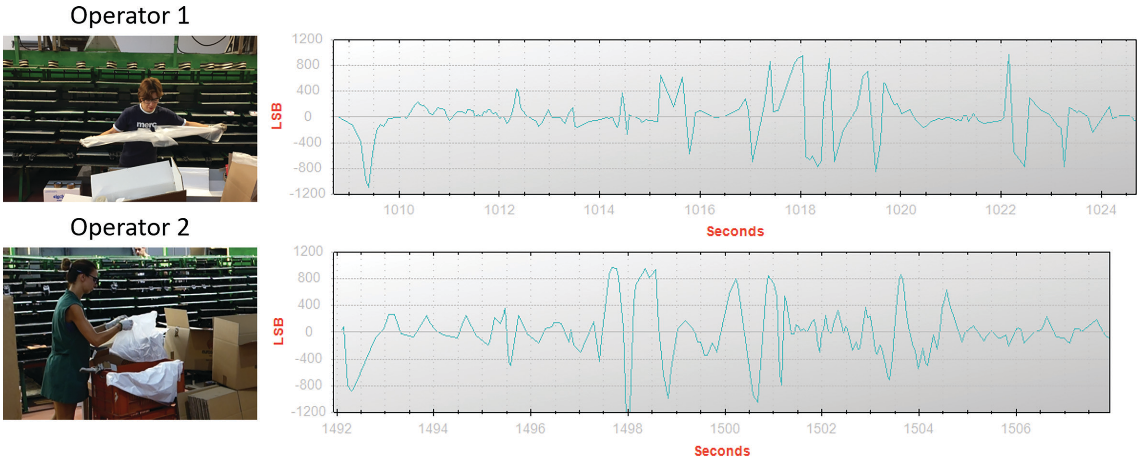

Figure 7: EOG report related to the foil separation task.

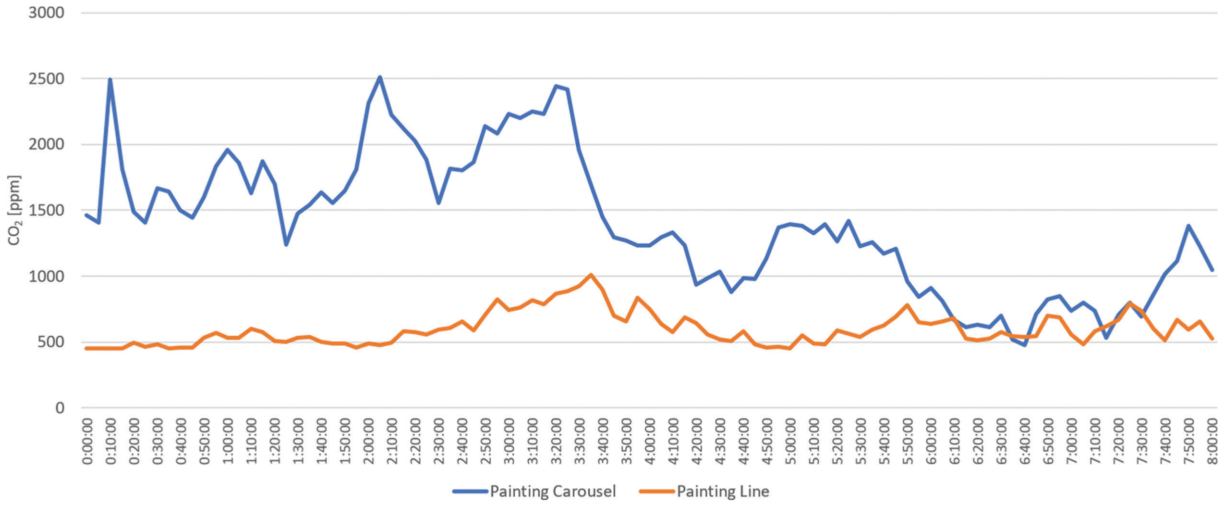

Figure 8: Air quality (CO_2) of the packaging area.

(i) the use of objective data held a wild appeal with the stakeholders as they are not influenced by evaluators' bias ensuring a higher accuracy level and the risk indices can be calculated for the entire shift instead of specific moments of the work cycle;

(ii) the data collection and analysis required fewer resources (time, money, and people).

Based on this evidence, future analysis will consider systems able to monitor the full-body posture and automatically calculate ergonomic risk indices.

The proposed IoT framework allowed evaluating the workers' well-being from different ergonomics domains: physical, cognitive, and environmental. None of the existing works considers all of them concurrently. As highlighted by literature, the use of self-assessment or expert-based approaches still prevails, and the use of physiological techniques is still an open challenge (Thorvald, Lindblom, & Andreasson, 2019). The use of parameters such as HR and BR is often limited to laboratory environments. However, the daily life stress level can be significantly different from the stress level induced in the laboratory (Can, Arnrich, & Ersoy 2019). For this aim, this paper aimed at demonstrating their applicability in a real working context.

The EOG is, for the first time, successfully applied in manufacturing. Indeed, its application in a real working context was limited to office workers (Uema & Inoue, 2017). In the future, the greater potential of this signal could be exploited, for example, to assess the operators' concentration level in critical operations such as the quality inspection.

The approach has been applied to a case study in the footwear industry, which is of considerable qualitative/quantitative importance to the Italian economy. Authors explored dozens of companies of the Italian fashion sector about the attention paid to ergonomics issues. Some of them declared to provide personal protective equipment, ergonomic seats, or ergonomic workstation accessories such as footrest. Although most of the operations are still performed manually by workers, none of them stated to carry out a systematic and rigorous ergonomic risk evaluation. Indeed, most of the existing studies focused on automotive or aviation. This work is the first application in this sector.

Although two operators were sensorized, the analysis involved directly and indirectly about 10 stakeholders (managers and operators). A brainstorming session involving all of them was organized to collect preliminary feedback. The increase of the company awareness about the human factors emerged as

Table 5: Corrective actions and cost assessment.

Aim	Task	Corrective action	Cost
Reduction of physical workload	T3. Box classification by label (IMPROVABLE)	A3. Best practices diffusion	C3. 0€
	T4. Soles picking (IMPROVABLE)	A4a. Sole picking procedure fitting the operator characteristics	C4a. 0€
		A4b. Rearrangement of the packaging area layout	C4b. 0€
	T9. Box lifting, transporting and storing (NOT SUSTAINABLE)	A9a. Rearrangement of the packaging area layout	C9a. 0€
		A9b. Transpallet	C9b. 0€ (available)
		A9c. Ergonomic pallet positioners	C9c. About 2000€/unit
Reduction of mental workload	T0. All tasks (IMPROVABLE)	A0. Breaks rescheduling	C0. 0€
	T6. Soles packing with related equipment (NOT SUSTAINABLE)	A6. Foils dispenser installation	C6. Less than 100€/unit
	T7. Soles counting (IMPROVABLE)	A7. Bar code scanner to automatically recognize the content of each box and update the work report	C7. Less than 50€/unit
	T11. Work report (SUSTAINABLE)	A11. Bar code scanner to automatically recognize the content of each box and update the work report	C11. Less than 50€/unit
Improvement of user interface interaction	T2. Order control and label printing (VDT) (SUSTAINABLE)		
Improvement of air quality	T0. All tasks (IMPROVABLE)	A0a. Manual shutter opening	C0a. 0€
		A0b. Automatic shutter opening	C0b. About 200€
		A0c. Aspiration system installation	C0c. About 250€/unit

one of the main benefits. As well as the implementation of the corrective actions described in the previous section, this outcome implied the inclusion of the social sustainability in the corporate pillars, its sharing through official documents, and the planning of further analyses. Accordingly, the workers' well-being will be re-evaluated to quantify the improvements obtained. Long-term benefits will also be considered.

The direct involvement of operators in most of the analysis stages stimulated their active participation, as stated by Vink et al. (2006). Exploiting, sharing, and implementing the best practices identified by the operators themselves (T3 and T4) is a concrete example. Moreover, the involvement of operators in the design of the solutions allowed considering well-being and performance concurrently, as suggested by Hoffmeister et al. (2015). Results confirmed that the improvement of the manufacturing system from the social point of view has to be a win-win strategy with positive relapses on both operators' health and company productivity.

The sample size is one of the main limitations of this study. To make it statistically significant, the approach experimentation will be extended to more companies and operators. It will contribute to the ongoing development and adjustment of the method.

Future works will also focus on establishing correlations between data related to the different ergonomics domains (physical, cognitive, environmental, and organizational). They will be based on quantitative analysis aimed at identifying and estimating the relationships between variables. Moreover, an interesting challenge is the definition of an overall social sustainability index based on human factors. In the last years, some attempts to provide a global index have been made by researchers; however, they focus on assessing business impacts on people, society, and other stakeholders or do not consider monitoring of the physical and cognitive well-being of workers (Rajak & Vinodh, 2015; Cao, Wang, Yi, & Zhou, 2016). Therefore, future researches should aim to select a set of indicators about human factors, from objective and subjective evaluations, and synthesize them into a comprehensive index of workplace sustainability. For this aim, some integrative techniques such as the Grey relational analysis could be applied (Bhanot, Rao, & Deshmukh, 2016). Particular attention should be paid to the inclusion of physiological measurements, for which careful analysis of the most significant signal features must be carried out. A similar approach could also be exploited to support the action plan definition. For example, company performance, economic indicators, and social parameters could be efficaciously combined to identify the best intervention strategy. Some of them could be defined exploiting computer-integrated simulations based on virtual prototypes and digital human models. The final aim will be to automatically suggest the best corrective actions to solve the problems that occurred.

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