Transdisciplinary Engineering Methods for Social Innovation of Industry 4.0
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IoT to Enable Social Sustainability in Manufacturing Systems

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Abstract. One of the most actual and consistent driver for industry is sustainability. This topic opens at different problems according to the three sustainability pillars: environment, economic, and social. Regarding the last one, there is a lack for methodologies and tools. Moreover, industries are crossing today a crucial transition in terms of technologies. The so called fourth industrial revolution is ongoing. This is a second challenge for industries that needs to be competitive reducing their time to market integrating new technologies on their production sites. From these perspectives, this work is aimed at highlighting the role of the humans under the Industry 4.0 paradigm. A new transdisciplinary engineering method to favour the sustainable manufacturing is provided. It allows designing a connected environment (IoT framework) aimed at measuring and promoting social sustainability on production sites. The work also remarks the relationship between social sustainability and productivity. Indeed, optimizing the human works permits to improve the quality of the working conditions while improving efficiency of the production system. The case study was performed at an Italian sole producer. The goal of the analysis was to improve and innovate the finishing area of the plant from a social point of view with the perspective of digital manufacturing. An IoT framework has been installed, without affecting the productivity, and the work of 2 operators has been compared in order to identify common problems and define a synergy strategy.

Keywords. Social sustainability, industry 4.0, sustainable manufacturing, digital manufacturing, human factors

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 to the driver, sustainable manufacturing should create great value for a company [1]. 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 [2]. Industry 4.0 can be viewed as an integrated, adapted, optimized, service-oriented, and interoperable manufacturing process enabled by algorithms, big data, and high technologies [3]. 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 objects connected to each other and to the outside world allows having a real-time framework of data, predicting the processes behavior and promptly reacting. 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. A special attention should be also paid to physical and non-physical influencers to implement interventions that can induce positive change and minimize negative behavior for all stakeholders [4]. A transdisciplinary approach is required to adopt a holistic vision and obtain effective benefits. Several competences should be involved such as managers, ergonomists, health & safety executive, designers, data analyst, psychologist, etc.

The main aspects to be faced by the 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 increase the operators' wellbeing. Monitoring key parameters and consequently adapting tasks, work stations, tools, and equipment to fit the worker, help 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 towards their future co-workers such as connected devices, autonomous devices, and software [5]. All these concepts aim to preserve or build up human capital.

In this context, appropriate innovation and engineering approaches should be proposed to promote social sustainability on production sites. For this aim, in this paper a transdisciplinary engineering method to create a connected and sustainable working environment is presented. 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 persperctives to solve ergonomics related and non criticalities and implement appropriate corrective strategies.

The idea is to go towards smart factories capable of reacting, sensing and thinking, given different manufacturing requirements or situations, without excluding man but satisfying its needs.

1. Research background

Garetti and Taisch in 2012 recognized the "manufacturing" as the main pillar of the civilized lifestyle [6]. It will be strongly affected by the sustainability issues playing an important role in establishing a sustainable way ahead. The sustainable manufacturing has not a single definition and passes through different topics. Rödger et al. [7] proposed a holistic framework to integrate sustainability thinking into manufacturing. The idea is to merge life cycle perspectives with product and production in order to optimize the latter in the early design stages.

An interesting literature review about this topic was proposed by Moldavska and Welo [8]. Sustainable manufacturing is often driven by cost factors [9] [10], but the ISO 26000:2010 [11] introduced the topic of social responsibility as the willingness of an organization to incorporate social and environmental considerations in its decision making. Zink [12] considers the sustainability as a chance to include the concept of ergonomics or human factors in a worldwide relevant topic and proposes a global frame for designing sustainable work systems. Ergonomics is not just related to machinery but can be extended to the entire organization every time human factors are involved into the design production process. 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, and 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 the work-related musculoskeletal disorders [13]. Cognitive ergonomics involves psychological processes such as awareness, human information elaboration and movement response, as it concerns human interacting with other system components. Some significant 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 [14], 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 (stress, mobbing and burn out, in particular) 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.

It is known that the quality of life and the quality of production are both dependent on the working environment [15], which influences workers' health, safety, and performance. Lamb and Kwok [16] studied the Indoor Environmental Quality (IEQ) considering noise, light and thermal as comfort factors. Gregori et al. [17] dealt with the acquisition of social related data in a production plant and 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. Romero et al. [18] 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 [19] focused the discussion on new technologies system. They discussed about the benefit of cyber manufacturing systems and their role in the future development. Within the smart factory paradigm, operators are required to be more flexible and acquire new capabilities. For this aim, companies are increasingly relying on smart training systems, based on Virtual Reality and Augmented Reality simulation. Longo et al. proposed an intelligent personal digital assistant to provide quick and effective support to operators about tasks/procedures/equipment [20].

IoT-enabled manufacturing, successfully implemented with a large number of industrial cases, highlights real-time data for production-decision models and smart manufacturing objects modeling. Most of the IoT applications were focused on monitoring domain dealt with remote sensing of physical and environmental parameters [21]. 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 [22]. Moreover, they mainly refer to resources, production, and logistics and rarely focus on monitoring operators' daily tasks in order to improve their working conditions and wellbeing, which is the aim of this work.

To resolve these issues, interdisciplinary research and innovation is needed to provide the basis for the design of adequate manufacturing environments and workplaces. The balance between cost-efficient automation and intelligent use of human capacities in manufacturing will determine the choice for future production and factory location.

2. Method

The present method supports the company growth in a proper sustainable way with the exploitation of IoT technologies. It aims to help designers to define sustainable and innovative plants. In fact, sometimes companies whether they are SMEs or large companies approach to innovation without a structured way. This method permits to walk the path toward innovation considering sustainability pillars.

Following this method, a company can improve its productivity passing through a proper data management system. Data are the basis of development choices. Data acquisition during the life cycle of a plant is supported by IoT framework. Such a framework allows gathering obejetive parameters, which are a prerequisite for an effective social assessment and to help decision makers while improving the production system, highlithing advantages in implementing 4.0 technologies. The method consists in the formalization of the steps needed to improve a production site from the definition of the problem to the corrective action implementation. 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, has lacks in terms of data availability. Then this method was thought in order to perform process analysis and improvements through the connection of the factory itself.

Steps identified for the method are the following:

1. Factory Assessment
   - 1.1. Plant layout
   - 1.2. Resources mapping (plant layout, flows identification, human resources identification, asset analysis)
2. (Re)design goal and boundaries
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 the 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. Implementation and assessment
   - 4.1. Measurement campaign planning
   - 4.2. Data analysis

5. Identify corrective actions (new technologies, process redesign, organizational improvements)
6. Cost assessment of novelties

These six steps should permit a company to define effective strategies for innovative plants. Few steps consist in deeper tasks. With a design perspective, the "Factory Assessment" is the first step of the analysis. The method is thought as a loop (Figure 1). In fact, with a continuous improvement approach the factory should embed new processes and IoT framework as well. IoT design is an iterative approach.

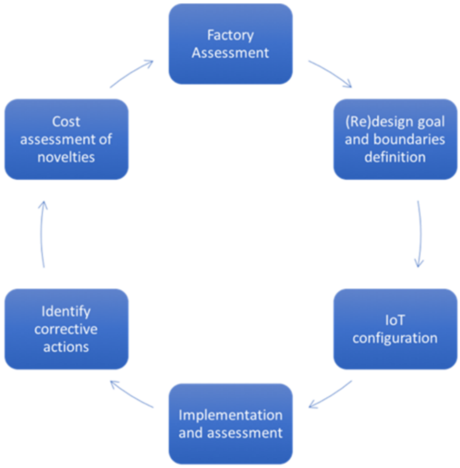

Figure 1. Design method for connected factories.

Going into more detail, the first step of the methodology consists in the definition of a clear State of the Art of the plant by a complete "Factory Assessment". By the experience, in fact, many companies have a base line not clearly defined. With a focus on Italian manufacturing companies, they are growth fast in last 30 years but not in a homogeneous way; new technologies live together with old procedures and inefficient buildings or the opposite. This means that a structured innovation plan was not developed meaning lack of industrial culture and loss of money. The first step of the method permits to analyze this kind of situation understanding in a clear way the plant in terms of structure and resources. The former means identifying the plant layout considering all spaces available. For this kind of analysis, the map of the plant has to be acquired. Knowledge about resources, including humans, permits to identify a clear picture of the competitive advantage of a company. Since resources usually are referred to energy and raw materials, many forms of diagrams and reports are related to them and none of them is related to the human resource state of the art. Understand human resources consists in mapping all man and woman working in a plant considering their skills, age, and experience. Also an asset analysis should be performed in order to understand all machineries of the production plant. Last part of this analysis is the production flow analysis, which permits to understand all the manufacturing stages of the plant. For what concerns this kind of analysis it means to define the complete process layout by IDEF0, Value Stream Mapping or any other diagram to define the plant work flow and management system. This phase permits to completely understand the company and related improvement opportunity on a general level.

The second step consists in defining the main driver of the (re)design strategy. It is in fact important that the design process is driven by a main scope. It should consist for example in reducing the environmental impact of the plant or developing a more efficient layout of the same. In this first step, it is then important to have a general overview on the main opportunity of a redesign. Step 3 consists in defining the IoT environment. This step will be explained in deep in next section. This step is the most important part of the method. It consists in connecting the systems of the factory in order to acquire data for certain analysis.

When the IoT environment is correctly configured step 4 should ran. In this step, it is performed the measurement campaign. Before proceeding with the measurement, it is important that all people related to the process are aware of the measurement in order to not perform actions should collide with the measurement (e.g. process shutdown). In this step the goal of the assessment is taken into account. The data acquisition and the assessment should be compliant with the IoT framework aim (e.g. if the aim of the IoT is only energy monitoring it is impossible to perform a social assessment). After completing the data acquisition phase and performing a data analysis will be possible to define improvement actions depending on inefficiencies.

Finally, a cost analysis will define the opportunity to implement certain actions, according to problems identified.

The method is iterative and the IoT framework should be improved over time.

3. Case study

The case study involved a soles manufacturing industry. The first step consisted in a detailed study of the company from the plant layout to its work organization analysis (flows identification, human resources identification, asset analysis). The plant covered different production areas, but the project considered the carousel packaging area at the finishing production phase, because it comprised most of workers (40%). The carousel area was organized around a conveyor structured on 9 layers where the painted soles were located and then picked, counted and packed in boxes (Figure 2). In particular, the tasks identified were:

1. Box preparation and positioning on the workstation
2. Order control and label printing (VDT)
3. Box classification by label
4. Soles picking and counting
5. Quality control
6. Soles packing with related equipment
7. Box closing
8. Box lifting, transporting and storing
9. Boxes enumeration
10. Work report.

On the other side of the carousel the manual painting area had other operators who performed tasks of painting and quality control of the soles before the packaging phase. The packaging workstations were four, managed by two operators. The workstation consisted of a reclined shelf on which the box to be filled with soles was placed. Further to the packaging activity, the two operators had a subtask of checking orders on the VDT and printing the relevant documents. Once the box had been filled, it was closed, lifted and transported to a storage area and stacked on pallets. Work was organized on five days per week, in a single shift from 6:00 am to 2:15 pm, including a break of 15 minutes after 3 hours of work.

The operators were two females. The first one involved was 46 years old, height 171cm, weight60 kg, BMI 20.52 (normal), with 26 years of experienced. The second operator was 38 years old, height 172cm, weight 52kg, and BMI 17.58 (under-weight), with 10 years of experience. The two performed the test in different days.

Figure 2. Painting Carousel Packaging Area.

Considering the variables aforementioned, a smart objects framework had been configured. The IoT for the case study had included:

- a network connectivity;
- hardware to collect data;
- connected sensors.

In depth, the IoT framework included the following devices, fitted in the working environment and to workers.

A video camera was positioned to have a complete view of the testing site. The reason why was the necessary to capture workers' behaviors performing the working tasks, to include any difference from the usual working pattern. Wearable smart objects had been identified and selected (Figure 3). To monitor vital parameters (heart rate, HR; breath rate, BR), and posture, workers had worn a chest belt. Data were available in real time on a smart tablet, whom dashboard presented variables and relevant thresholds. A steps counter was useful to detect how much the operators had to walk along the carousel and transport the filled boxes. To investigate the level of mental workload and cognitive stress the smart device consisted in a pair of glasses, which tracked and detected the difference in electrical potential.

The working environment had necessary to be assessed with an air-quality smart station. Its not-intrusive presence nearby the working area, provided some air parameters detection, such as temperature, humidity, and indoor pollution (VOCs, CO_2, CO and PM2.5). A Wi-Fi router had been connected to ensure data collection in real-time and remotely.

Both workers worn the connected devices for data collection, by keeping it for the whole test duration, at least for 2.5 hours, decided as a result of the previous observations and considerations of test measurements.

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 at the study was voluntary and granted by a shared release form. The workers' involvement in the decision-making process of the improvement strategies in the workplace and about the working conditions resulted in the awareness of the relevance of the assessment.

Data analysis considered the approach to manage the Big Data, where data downloading from each device (steps monitor, environmental sensors, smart glasses, smart band) have to be classified and cleaned to avoid biases and errors. Each sensor produces a csv file. Once the data are available is possible the detection of eventual peaks and assume potential correlations between the different parameters.

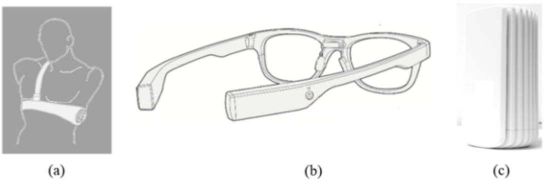

Figure 3. Smart devices. a) vital parameters (HR, BR), and posture chest belt; b) mental workload tracking glasses; c) air-quality station.

4. Results discussion

According to the goal of the analysis, which was the improving and the innovation of the finishing area of the plant from a social point of view, with the perspective of digital manufacturing, are now provided and discussed some results in relation with data interpretation phase.

Starting from posture and vital parameters analysis, data collection for each worker gave information about physical workload. The first operator had worse results in comparison with the second one. Comparing awkward postures in terms of occurrences, there were more warning conditions recurring for the operator 1. The most problematic posture was observed at the box placement task, on the 1st layer of the pallet (20 cm from the floor level). Furthermore, operator 2 in comparison with operator 1 had less low back bending >60° (Table 1 and Table 2), because of her behavior performing the box labelling task. In fact, operator 2 performed the task in a standing position, contrary to operator 1, whose low back posture was inadequate. Another risk factor, associated to low back posture observed was the lack of space to perform subtasks such as the boxes preparation. In fact, in carousel area there was not such space and operators were obliged to prepare and pick boxes in a bad posture condition.

Table 1. Operator 1 - Posture analysis.

Operator 1 - low back posture (ISO11226:2000) Total valid measurements: 9295		
x<20°	20°<x<60°	x >60°
7431	1771	93
79,95%	19,05%	1,00%

Table 2. Operator 2 - Posture analysis.

Operator 2 - low back posture (ISO11226:2000) Total valid measurements: 9188		
x<20°	20°<x<60°	x >60°
8459	713	63
92,07%	7,76%	0,69%

The vital parameters data analysis reported some differences between the two operators even though they perform the same job tasks. Considering operator 2 her HR was higher in the test period (2,5 h) compared to operator 1. Furthermore, for operator 2 BPM averaged 117, whereas operator 1 BPM average was of 89. For what concerns box lifting and transport it was noted that BPM increased, particularly during transport. Considering the two operators characteristics and the activity performed operator 2 resulted more stressed than operator 1. It would be stated that operator 2 is productive as the operator 1 but with more effort.

Mental load data analysis measured peaks of concentration for some subtasks. PET foil separation it is mental impacting because the small thickness of foils, it resulted as an operation that requires precision. Operators are not able to simply separate foils each other while taking them from the sheet stacks. Box movement operation affected not only the physical fatigue but even mental workload. Transport needed high concentration as the soles counting procedure. An interesting mental workload data was registered for VDT operation. In fact, the signal registered was linear.

In the carousel line, there were some issues in terms of air quality. The air sensor in fact had stored many peaks in terms of carbon dioxide emissions. The assumption was the packaging area design. In fact, the manual painting stations, on the other side of the carousel, had have no separation from the packaging area, and packaging operators did not wear protection masks; the reason was because it was supposed they would be safe from particulate emission. Concentration level of CO_2 averaged 1264ppm with a peak of 2512.

The real-time data analysis may induce sudden intervention on the all bad working condition found.

5. Conclusions

In that work, the IoT was exploited to assess plant social relapses on operators, understanding criticalities of the process from a social point of view. IoT related opportunities are huge for a factory but these should be achieved only by adopting a structured method. The method focused on overall sustainability; it has come into detail with the social aspect by the case study. It permits also to understand all the data flows needed to be monitored within a production site by adopting a transdisciplinary approach. Here IoT was thought as the key enabler of new factory technologies; the network permits to monitor the plant in order to understand criticalities should be improved by technological innovations. Without a clear view of the actual limits, a company cannot proceed toward the Industry 4.0.In the proposed case study were identified manufacturing criticalities from a social point of view. By designing and installing an IoT infrastructure it was possible to monitor operators and environment toward a social plant optimization. The assessment permitted to understand many criticalities that should be improved by new technologies, better organizational choices and better process management.

Future works will focus on establishing correlations between data related to the different ergonomics areas (physical, cognitive, environmental, and organizational).

The improvement of the manufacturing system from the social point of view should have positive relapses on operators' health and company productivity both. The method tends to underline that IoT environments is a way to industry 4.0 but a proper data management should be guaranteed. As data are the baseline of the improvements, IoT are fundamental tools in connected factories.

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