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Digital manufacturing systems: a framework to improve social sustainability of a production site

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Abstract

The topic of digital manufacturing is increasingly emerging in industry. One of the main scope of data digitalization is achieving more efficient factories. Different techniques and tools under the Industry 4.0 paradigm were already discussed in literature. These are aimed mostly at boosting company efficiency in terms of costs and environmental footprint. However, from a sustainability point of view, the social theme must be equally considered. While energy flows or costs can be already monitored in a production plant, this is not valid for data related to human effort. Monitoring systems aimed at supervising factory social sustainability were not already discussed in literature. The aim of this paper is to propose a method to acquire social related data in a production plant. The method is supported by a smart architecture within the concept of IoT factory. Such architecture permits to monitor the parameters that could influence social sustainability in a production site. After a discussion on production plants facilities and features, the parameters that need to be considered to guarantee socially sustainable manufacturing processes are identified. A set of sensors controls these data taken from different sources, including operator vital signs. Operations as well as humans are monitored. Data acquired by sensors are collected by a central server. A decision maker can interpret the data and improve the production system from a social point of view, implementing corrective actions. Data can be exploited not only for social assessments but even for other analyses on the production system. Guaranteeing social sustainability could boost the factory productivity.
A case study is included in the paper: smart sensors are implemented in a production line to understand the operations efficiency in terms of social sustainability.

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Keywords: social sustainability; smart sensors; digital manufacturing

1. Introduction

Today sustainability is a crucial topic that industries should deal with. Indeed, developing sustainable industrial processes, products or services is essential to guarantee a respectable growth of society, compliant to new standards and guidelines [1], considering that industries have the largest impact on resources consumption in comparison with residential, commercial and transport sectors [2]. Therefore, industries must develop efficient strategies to design and improve their production systems, overcoming the last sustainability standards (e.g., ISO 26000 [3]). However, a crucial aspect in the modern digital manufacturing era is to guarantee also human growth and wellbeing, considering also social aspects while developing new production systems, together with more traditional environmental aspects. Human aspects of sustainability are already integrated in the human-centered design (HCD) approach that aims at improving workers' capability, health and safety. These issues are particularly thorny since they have a relevant impact on the industrial management system in general, which must provide healthy and safe working conditions. Considering that workers are the actors during the machineries use, the sustainable design of any production system has to include also workers and

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human-related issues. In this sense, the social driver could positively contribute to guarantee workers' health and the overall socio-economic development. In this context, it is possible to talk about "design for social".

This paper proposes a set of guidelines to let designers face social sustainability aspects during the design and development of new production systems. It starts from the clarification of the main topics of digital manufacturing, under the new paradigm of Industry 4.0, in association with social issues, to define a proper "design for social" methodology. The method embeds a social issue matrix that analyzes possible solutions to solve the main human-related criticalities. To support the methodology a smart manufacturing framework introduced in order to digitalize social data taken directly from the shop floor. Finally, an industrial case study is proposed; it describes the design phase of a woodworking machining system exploiting the human-centred guidelines provided.

2. State of the art

In order to promote sustainable development, manufacturing companies are recently asked to overcome a purely economic vision, paying more and more attention to the environmental impact of their products and processes as well social issues and workers' wellbeing [4]. Indeed, realizing a sustainable process means facing all the three dimensions of sustainability at the same time (i.e., planet, profit, and people). In this context, traditional aspects such as cost reduction, productivity increase, resources efficiency, and high quality are no longer sufficient. They have to be integrated with new social items: e.g., working environment conditions, workers' satisfaction, workers' safety, physical and ergonomics [5][6].

Furthermore, it is worth to consider that nowadays industries are shifting to the new manufacturing era of Industry 4.0, dealing with the digitalization of data and the creation of knowledge to be used by intelligent production systems [7]. New cloud-based services (i.e., collaborative manufacturing, cloud computing, virtual manufacturing, etc.) are available for the industrial sector thanks to the advances in sensor and communication technologies [8]. This new paradigm represents a real opportunity towards a value-oriented sustainable manufacturing [9]. It shifts the manufacturing system to an upper level of data management (e.g., predictive maintenance, big data management), which creates a closer relation with humans. Hao and Helo investigate the potential of smart personal wearable devices in improving human–machine interactions in manufacturing industries [10]. As reported in a recent study by the Boston Consulting group [11], the industry 4.0 requires new skills to workers and creates new working modalities, offering new job opportunities while eliminating some job families.

As a consequence, the analysis of human factors and ergonomics is crucial to ensure a sustainable working performance, as demonstrated by [12][13][14][15]. Furthermore, the evaluation of social impact can validly be used to identify the most critical points which affect productivity and efficiency in the life cycle assessment [16], since the interaction between humans and machinery systems frequently represents the bottleneck of the production line and is a potential manifold of hazards. A human-centered approach can promote the analysis of possible uprising of those hazards and understanding of how the production parameters are affected by workers' performance and vice versa. Furthermore, "design for social" can also support process decision-making, to find the best working place and the optimal conditions to eliminate the potential hazards, to maintain the production system, and to control the impacts of the manufacturing process even outside the company boundaries [17]

Since the 1980s, it is known that the workforce performance was related to productivity, so several studies and methods have been proposed to deal with ergonomic aspects in workplaces [18] [19] and solve problems related to physical workload [20], promoting a workstation redesign and creating concrete benefits in terms of process costs [21]. Cognitive parameters are more difficult to measure, but they are complementary to the physical ones and mainly related to the human-machine interaction. In this field, engineers have to limit the human errors and optimize the mental workload [22]. Studies do not propose a prevention method to avoid working capability losses or improving performance efficiency merging physical, cognitive and environmental aspects. Furthermore, there is a lack of efficient methods to carry out a fast evaluation of social sustainability for manufacturing system, to be used during design phases to pearly optimize the workplace design considering also social aspects.

3. Methodology for "design to social"

In order to support the design of sustainable production systems including also social aspects, a human-centred method able to merge human factors and technical issues has been developed. It aims to improve the workers' conditions at the shop floor, which is directly related to the improvement of global system productivity. In particular, the method helps identifying inefficiencies in terms of space or resources, to be applied during the design of a new plant or to improve the efficiency of an existing one. The method is composed by 4 steps, and each of them uses data and knowledge acquired from the previous one, as shown in Fig.1:

1. *Layout assessment:* it allows optimizing the plant layout according to the specific company processes. It consists in the analysis of physical space occupied by any process entity and of the actual process workflow, by using production flow data. After that, a detailed analysis of the workflow is carried out to identify the current wastes in terms of space and activities (e.g., unused space, disorganized areas, space destined to auxiliary activities). Considering the available resources and production capacity (i.e., energy flows, required materials, cycle times) a new system arrangement is proposed. Finally, a complete and clear vision of the actual process in terms of spatial, resources and productive constraints is created. Such step can be carried out when a new layout is defined or when a re-layout is possible. It is recommended every time when a significant change at organizational and productive level is possible.

2. *Virtual prototyping*: it focuses on the development of the new manufacturing system by the system virtualization and simulation on virtual mock-ups. It includes the definition of the machine/s purpose and requirements, the identification of the technical solutions, and the development of the system 3D model. It considers economic, technical and social aspects (i.e., workers' skills, workers' physical and cognitive issues or limitations) to find the most suitable trade-off between the company needs. A new solution able to optimize the involved manufacturing processes (e.g., time and cost reduction, lower environmental impact, higher product quality), ensure safety (e.g., less risks, less accidents, higher maintainability), and increase the employees wellbeing (e.g., healthier working conditions, less stress, higher satisfaction) is proposed. According to the HCD approach, human factors are considered (i.e., tasks to be carried out, interactions with devices, machines and interfaces) during the entire design process, by mapping the specific workers' characteristics and understanding their influence on interaction. A list of specific parameters related to risks factors has been defined in the so-called Social Decision Matrix (SDM) that represents the main innovation of the proposed method. SDM (Fig.1) is proposed as an effective tool to drive the design on the basis of the specific social issues characterizing the context of use. According to such matrix, different scenarios can be analyzed and simulated on the virtual model to identify the most useful corrective actions. Immersive and interactive virtual environments can be used for a more effective system simulation by also involving real users' [23].

3. *Physical prototyping:* it includes the physical realization of the model defined as the optimal solution in a virtual environment, and the definition of a customized sensor system able to monitor the most significant parameters related to workers and the surrounding environment, in order to create a feedback loop and to create a robust knowledge about the effective workers' conditions.

4. *Social sustainability assessment*: it aims at analyzing the on-field sustainability performances of the new system prototype to assess the workers' physical and cognitive performances, identify possible criticalities, and define the improvements actions. For this aim, data collected by the prototype sensor system are elaborated by filling in the co-called System Social Datasheet (SSD) that defines the most critical issues for workers and machines, and proposes a proper action and maintenance plan. This datasheet represents the social ID card of the system, collects data from the planned periodical tests, and stores the sustainability system impacts (in terms of energy consumption, environmental impact, economic impact, and physical and cognitive ergonomics) to quantify in a scientific manner the social inefficiencies. Such datasheet can be updated due the system continuous improvement. Data collected could be also integrated in social plant assessment techniques (e.g., social life cycle assessment considering the stakeholder workers [24]).

These four steps were thought considering a typical product/process design procedure. Step one to three are a simplification of a classical design methodology. Starting from a state of the art (layout assessment) a physical prototype should be developed passing through a virtual model. The last step is settled to insert social theme into the classical design methodology. Each step embeds analysis activities for a proper validation of the step. Following this approach means developing socially well designed processes.

4. The design tool: Social Decision Matrix

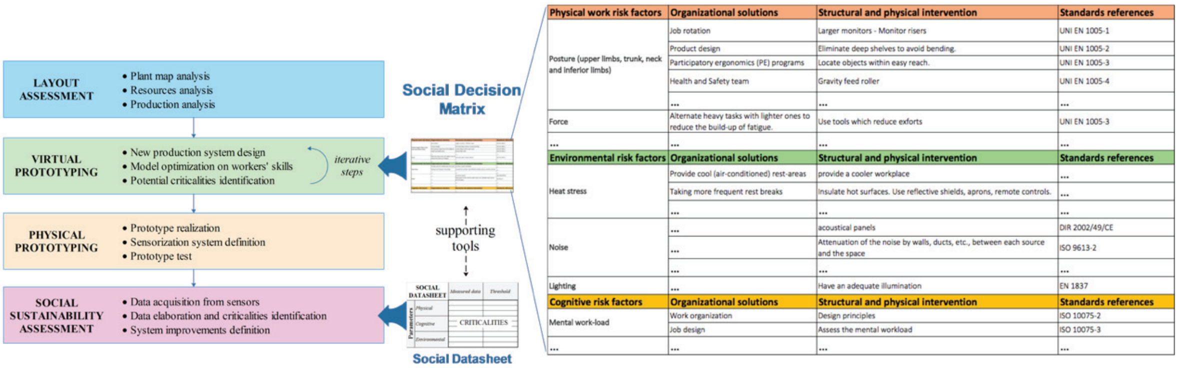
The SDM represents the main novelty of the proposed method to support designers in the correlation between the different risk factors to be considered to carry out the social assessment of the production system. It is a "decision matrix" since it correlates different parameters, and it has been called "social" since it is inspired by the literature concerning the assessment of social topics. The SDM matches the principal ergonomics parameters with the possible organizational and physical solutions to adopt, according to the existing international norms and standards available as well as the most common evaluation methods for physical and cognitive ergonomics. The possible functional solutions, made up of physical and organizational aspects, have been collected from experiences shared by literature and database solutions from Labor Organizations. Fig.1 shows a simplified scheme of the entire matrix defined by authors due to space limits.

The SDM can be used by designers during the virtual prototype definition and simulation to identify possible design solutions and the main criticalities from a social point of view. Each risk factor can correspond to two different level interventions: physical or organizational. An organizational solution consists in improving the system from a management level, while a physical intervention consists in an improvement action to implement within the virtual model. Designers can improve the model by the feedback from the SDM and improve the virtual model by a new solution to be simulated again, into an iterative process. The enriched matrix will serve for the design of future systems.

The measurement of the proposed parameters (e.g., posture, force, view cones, reach zones, interface layout) allows driving the design toward more efficient performances in terms of workers wellbeing and satisfaction, operations and production quality.

From a social point of view, parameters refer to physical and cognitive measurements on the operators, and health and safety conditions are directly related to them. Physical parameters are objectively measureable by tracking systems or digital human modeling tools; instead cognitive ones can be elicited by users' monitoring (e.g., eye-tracking, navigation maps, EGG). Specific matrices can be defined case by case, according to the context of use.

About physical parameters, standard references to identify the threshold limits are taken from the international guidelines (i.e., ISO, ACGIH TLV, OSHA, etc.) but tools are not available for these purposes. A computerized system to measure the physical parameters in order to control the workers performance directly on machines will be developed. For instance, the energy demands for specific tasks can be derived by monitoring the oxygen consumption in respect to the posture assumed, the force required, the task repetition and duration, the recovery time; furthermore, physical parameters are related to human-machine interaction by considering which command or item is touch or handled. Those parameters could cause the occurrence of work related musculoskeletal disorders (WRMSDs) [25]. About the cognitive aspects, heat stress, cold stress, body vibration, lighting, noise and indoor pollution due to machinery waste products can affect the workers' reactions. They can be monitored and related to the process and workers' performances. Numerous examples have been taken from literature [26]. Also hypothermia can be a consequence of workers' long exposure to extreme cold temperatures, heat stress or heat related illnesses with the associated risks to health and decrements to safety behavior [27] [28]. Furthermore, poor lighting can lead to severe safety injuries (e.g., falls and trips over obstacles), failure to collect critical task information and eyestrain [29]. Such parameters are measurable with *a priori* job analysis and machine design analysis by the proposed SDM as a valid design tool. What is important to prevent for work related disturbs is the application of the threshold limit values during the machine design stage.



Physical work risk factors	Organizational solutions	Structural and physical intervention	Standards references
Posture (upper limbs, trunk, neck and inferior limbs)	Job rotation	Larger monitors - Monitor risers	UNI EN 1005-1
	Product design	Eliminate deep shelves to avoid bending.	UNI EN 1005-2
	Participatory ergonomics (PE) programs	Locate objects within easy reach.	UNI EN 1005-3
	Health and Safety team	Gravity feed roller	UNI EN 1005-4
	...	...	...
Force	Alternate heavy tasks with lighter ones to reduce the build-up of fatigue.	Use tools which reduce exforts	UNI EN 1005-3
...	...	...	...
Environmental risk factors	**Organizational solutions**	**Structural and physical intervention**	**Standards references**
Heat stress	Provide cool (air-conditioned) rest-areas	provide a cooler workplace	...
	Taking more frequent rest breaks	Insulate hot surfaces. Use reflective shields, aprons, remote controls.	...
	...	...	...
Noise	...	acoustical panels	DIR 2002/49/CE
	...	Attenuation of the noise by walls, ducts, etc., between each source and the space	ISO 9613-2
	...	...	...
Lighting	...	Have an adequate illumination	EN 1837
Cognitive risk factors	**Organizational solutions**	**Structural and physical intervention**	**Standards references**
Mental work-load	Work organization	Design principles	ISO 10075-2
	Job design	Assess the mental workload	ISO 10075-3
...	...	...	...

Fig. 1 - The proposed "design for social" methodology and the Social Decision Matrix (SDM)

5. The monitoring tool

Social sustainability assessment proposed by the method could be improved by an efficient data acquisition framework. The latter permits to support the "design to social" methodology. Here smart technologies for manufacturing are introduced into the production system in order to define a framework to improve productivity. The framework consists in a smart digital infrastructure integrated into the plant where different sensors are connected. These sensors are aimed at monitoring those parameters presented previously by the social matrix paragraph. The framework is structured as Fig.2. This was thought under the paradigm of digital manufacturing systems. In this context, the framework tends to collect data real time. It consists in a central server that is connected to three main families of sensors: sensors on human, sensors on operation, sensors within the shop floor. Central server embeds the database of data. Those data can be also stored in a Cloud space to promote the remote management of the plant. Internal management systems as MES or ERP can communicate with the social database. The three families of sensors refer to a set of sensors registering specific data for a social analysis. Sensors on humans concern smart tracker on the operator body. These can acquire parameters directly on the workers. In this case, characterizing parameters could be body temperature or heart rate. Sensors on operations concern parameters related to a specific operation (e.g., vibrations, noise). Furthermore, sensors on shop floor are aimed at acquiring parameters such as temperature or humidity. Monitoring those parameters permits to understand if working conditions of the plant are influencing the company social sustainability then the company productivity. Moreover, these parameters could be exploited for other analysis not concerning directly the social topic (e.g. plant environmental assessment, production optimization). The decision maker is the first user of the whole framework. He has the role to manage the manufacturing system according to the social topic. This kind of framework is completely new in the manufacturing context because if sensorized plant already exist, none of them collect data with an orientation to social data acquisition. The issue of data security and plant wiring will be discussed in future paper.

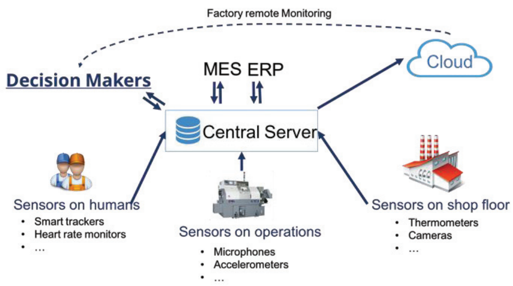


Fig. 2 – The digital monitoring framework for social parameters

6. The industrial case study

The case study refers to the design and development of a woodworking machine tool, in the context of the TAALM

(Technology for Ambient-Assisted Living Manufacturing) project, funded by the Marche Region, Italy. The aim of the project was to realize an assistive working environment that favors human-machine interaction and social sustainability, considering human needs within the design phase. The main actions were oriented to reduce the workers movements, guarantee a healthy working environment, and improve the global process efficiency. The proposed method was firstly introduced and implemented to support the design into this project. Firstly, a light layout assessment of the plant was done to identify available space for the new system. Then, the design requirements and the production constraints were defined to develop a virtual prototype (Fig.3).

The main requirements of the woodworking machine were as follows:

- maximum area: $50m^2$
- maximum size of parts to be processed: 140x160x3200 mm
- reduce worker operation and zero worker movements
- maximum dust pollution: $3mg/m^3$
- maximum noise pollution: 82Db

The system was divided into 3 main parts: the machine, the warehouse, and the principal unit. The machine was composed by different functional groups: base and CNC workbenches, main unit with manipulator and multi-functional unit, secondary unit with multi-function and secondary manipulator, machining cabin and its protection. The warehouse is integrated with the machine and has six level structure (until 160 pieces) and two elevators to support piece handling and automatic transportation. The main unit, that permits the cell management, was studied with ergonomics features for a proper usability and easiness of use by the worker. This particular study is out of scope of this paper and was argued in Peruzzini et al. [30].

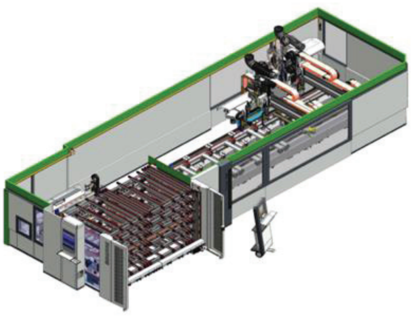


Fig. 3 – The 3D system prototype

Once the 3D model was developed, the monitoring system has been studied. Five different sensing systems were provided for the prototype. These are aimed at monitoring vibration, noise, dust, smells, and workflow. The complete sensing system is made of 3 main modules: 1) audio acquisition system, 2) image acquisition and classification system, and 3) dust and smells acquisition system. Every sub-system embeds a control board that processes the signal acquired by relative sensors, depending on the sensing activities involved. Data are sent to the central board by an Ethernet wiring. The digital signal processing algorithm and the computational intelligence are embedded within the central unit. Audio acquisition is based on commercial unidirectional microphones with specific sensibility and a work range between 20Hz and 20kHz. Image acquisition system permits to verify the correct flow of operations by the operators. Image sensors will acquire image during the tool management by the operator. A wrong tool mount means scraps or machine and tools failure. The worst event, due an incorrect worker operation is the part burning. The acquiring sensor was thought as a camera working in backlight conditions. A camera acquires the image of the tool before the task and after the task, so that the image comparison permits to understand weather or not the tool had some breaks. Dust and smell are monitored by two different sensors, respectively an optical acquisition system based on diode emission at infrared frequencies and a phototransistor that provides a tension value proportional to the level of dust detected, and a smell sensor based on the change of air conductibility, that provides a current value proportional to the gas concentration.

The main board feed power to sensor and share data with them. A human machine interaction system was provided in order to permit the workers read and interact with results. When the complete sensing system was studied, the physical prototype of the machining system was carried out (Fig. 4).

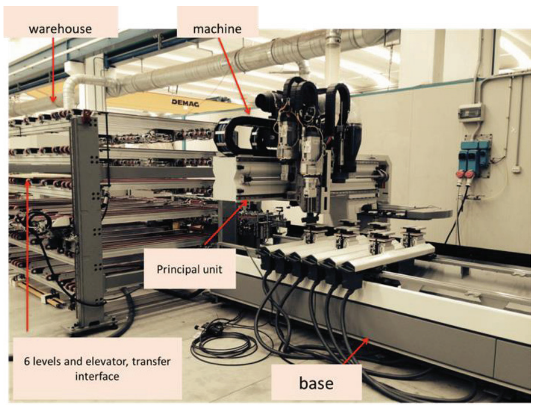


Fig. 4 – The system physical prototype

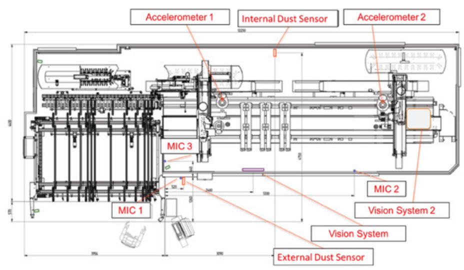


Fig. 5 – Sensing system layout

In Fig. 5 the complete sensing system layout is proposed. It is possible to identify three different microphones, two dust sensors and two vision systems. Accelerometer were installed for vibrations testing. The latter test is out of the scope of the present paper.

Through the presented sensing system, few test were performed on the physical prototype. Those test permit to verify a proper working condition both for the operator and for the process itself. Six tests were performed to guarantee the best noise conditions, each of them embeds different tasks. During test sound pressure level (SPL) were evaluated in order to understand main criticalities for the process or the operator. On the spectrograms are identified faults by non-compliant pressure level occurrences.

The SDM for the case study, supporting the design and optimization stages, is presented in Fig.6 (simplified matrix due to space limits).

Physical work risk factors	Organizational solutions	Structural and physical intervention	Standards references
Posture (upper limbs, trunk, neck and inferior limbs)		Larger monitors - Monitor risers	UNI EN 1005-1
		Eliminate deep shelves to avoid bending.	UNI EN 1005-2
		Workstation design has to respect the workers' anthropometric measures	ISO 14738
Environmental risk factors	**Organizational solutions**	**Structural and physical intervention**	**Standards references**
Noise		Attenuation of the noise by walls, ducts, etc., between each source and the space	ISO 9613-2
		acoustical panels	DIR 2002/49/CE
Indoor pollution		air filtration/cleaning	
Cognitive risk factors	**Organizational solutions**	**Structural and physical intervention**	**Standards references**
Mental workload		easy and intuitive control panels	

Fig. 6 – Social Decision Matrix for the case study (simplified)

Finally, according to the proposed method, the social sustainability assessment was carried out. The digital framework previously presented has been here exploited. Considering Fig. 2, only the operation sensors were arranged. Tests with users were developed to validate the efficiency of the machine in terms of performance as well as its social benefit for workers. In particular, tests were conducted exploiting the noise, dust and vision system, as follows:

Noise:

- outside the operation cabin to understand noise in stand-by mode and operating mode and impact on the human working condition during machine standard operation;
- inside the cabin while a wrong operation is occurring and impact on the human working condition during maintenance intervention;

Dust:

- pollution level outside the cabin and impact on the human working condition during machine standard operation;
- pollution level inside the cabin and impact on the human working condition during maintenance intervention and cleaning tasks;

Vision:

- identification of tool change and workers condition during tool change.

6.1. Results

Tests on the system prototype allows defining the best working conditions, no criticalities for the operator were identified. Moreover, it emerged the importance of the virtual model where a cabin was carried out. This cabin permits to limit dust and noise, performing accurately the function it has to exploit. In Table 1 results from tests with users are summarized. In particular, the conditions monitored in terms of dust, noise, and tool change are reported from a technical viewpoint (i.e., how sensors can monitor the working conditions) and social (i.e., how workers performance is affected in respect to previous conditions, without the new machine).

Table 1 - Test results

Sensor system	Measurement unit	Working conditions	Workers performance*
Dust	Dust concentration (mg/m3)	< 0.1mg/m3 (threshold: 0.34mg/m3), under limit conditions (3 mg/m3) Noise - 50%	More healthy conditions (+60%) Fewer problems especially during maintenance operations (-20%)
Noise	SPL - Sound Pressure Level (dB LeQ)	< 85 dBD (threshold value) Cabin reduces 3dB in comparison of standard systems.	Higher mental concentration and less mental load (+30%) Higher subjective satisfaction (+20%)
Vision	Positioning {x,y,z} (mm)	System accuracy: 100%	No check for tool change. Less changes (-25%)

** in respect to previous conditions (without the new machine)*

7. Conclusions

This paper presents a method to promote social sustainability in industries. The main novelty of the proposed method is 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. Workers tasks can be simulated and predicted, and consequently optimized from the design phase. The method proposes four steps to deal with during the design process to define socially sustainable production systems. The Social Decision Matrix focuses on common social problems occurring within a production plant (e.g., related to health and safety). Thanks to such tool, designers and engineers can implement efficient decision within the system prototype in order to overcome potential social limits of the model. The matrix can be enriched by new decision in order to improve the knowledge of the company on the social topic. The method suggests the definition of a social monitoring system to understand, during the design process, if parameters such as noise and pollution are within the threshold limits. This fact guarantees a safer and healthier working environment. Another finding of this paper is the social framework data acquisition system. The framework, in the context of digital manufacturing, could boost the social awareness of a company on social theme. The framework opens to the theme of social sustainability optimization for manufacturing. The method and related tools were exploited in a real case study and relapses on productivity and worker safety are shown. The machine and the sensing system itself were validated by the test case. Occupational health and the wellbeing of workers could improve company productivity saving costs, avoiding disease. Data acquired by test can be implemented within further analysis such as S-LCA or CSR (corporate sustainability reports).

The proposed approach based on the use of real data monitored by a sensor system will be simpler and more effective in the next future thanks to technologies in the context of Industry 4.0. Innovative sensors in the context of IoT could permit to define simple sensing architecture having more precise data. Future works will be focused on the deep definition of IoT system here introduced and related Social Decision Matrix to pave the way to the adoption of new technologies to promote social sustainability.

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