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A mixed-reality digital set-up to support design for serviceability

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Abstract

Design for serviceability begins with understanding the customer needs related to availability, reliability, accessibility and visibility, and aims at designing optimized systems where maintenance operations are easy and intuitive in order to reduce the time to repair and service costs. However, service actions are difficult to predict in front of a traditional CAD model. In this context, digital manufacturing tools and virtual simulation technologies can be validly used to create mixed digital environments where service tasks can be simulated in advance to support product design and improve maintenance actions. Furthermore, the use of human monitoring sensors can be used to detect the stressful conditions and to optimize the human tasks. The paper proposes a mixed reality (MR) set-up where operators are digitalized and monitored to analyse both physical and cognitive ergonomics. It is useful to predict design criticalities and improve the global system design. An industrial case study has been developed in collaboration with CNH Industrial to demonstrate how the proposed set-up is used for design for serviceability, on the basis of experimental evidence.

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Keywords: Design for serviceability, Digital Manufacturing (DM), Virtual Simulation, Ergonomics, Human-Centred Design (HCD), Sustainability.

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1. Introduction

Numerous studies have recently demonstrated how the adoption of sustainability principles could gain competitive advantages for companies [1]. However, real benefits can be achieved only when both product and process sustainability are introduced during the early design stages in order to optimize sustainability performance

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before product creation and process definition. Only in this case, design solutions are optimized in short time, engineering changes are limited and late optimization loops are avoided [2]. Nowadays the application of sustainability assessment models in industry is mainly based on ex-post analyses to monitor the existing conditions by ad-hoc simulations created on monitoring the real processes [3]. As a consequence, actions are usually taken after the design stage, when products and/or processes are already developed [4]. Virtual Reality (VR) is commonly used throughout the design phase, starting from the conceptual design phase to digital mock-ups validation in the advanced stages of the design process. Indeed, design tasks can be successfully reviewed by full-scale stereoscopic visualization within an immersive virtual environment [5]. Thanks to simulations, service tasks can be numerically analysed in order to determine which procedure is more ergonomic and easy to follow and which design can better support operators. Furthermore, design of tools, environments, layouts and platforms can be modified easily and validated considering ergonomics on virtual prototypes.

The paper proposes a mixed reality (MR) set-up where operators are digitalized and monitored to analyse both physical and cognitive ergonomics during service operations, to support design for serviceability. The proposed set-up consists of physical and virtual mock-ups to support the task simulation involving real users, digital manufacturing technologies to virtualize the real scene into digital ones, motion captures technologies to track objects and users in the real world and to move them into the digital world, and human monitoring devices to assess the users' physical and cognitive conditions. The proposed set-up has been applied in agriculture vehicle design to improve the design of serviceability of some products (i.e., tractors). The paper presents a case study developed in collaboration with CNH Industrial. The experimental data demonstrated the support of the proposed MR set-up to detect the main human-related criticalities from the early design stage and to improve the product and process design to improve serviceability.

2. Research background

Numerous methodologies have been developed in the last ten years for sustainability purposes: from Life Cycle Assessment (LCA) [6] to Life Cycle Cost Analysis (LCCA) [7], to Social Life Cycle Assessment (sLCA) [8]. Some researches have also coupled LCA, LCCA and sLCA to merge lifecycle cost assessment and human-related aspects evaluation [9]. Furthermore, it has been proved that the social dimension of sustainability related to human factors highly affects global efficiency and costs of industrial processes, from material handling to assembly, order picking, and manufacturing and maintenance operations in general [10][11]. Low attention to human factors brings to unnatural positions and dangerous actions executed by operators during their jobs, with consequent lower performances, higher production time, greater absence from work, and a general increase of the Work-Related Musculoskeletal Disorders (WRMSDs), which can cause significant human suffering and economic burdens for employers, workplaces, workers and society [12]. Indeed, WRMSD are caused by many factors, including awkward postures (e.g. bending, stretching, twisting), repetitive movements, using force and manual handling (lifting and carrying) working hours, static postures and repetitive nature of work were identified as some of the risk factors leading to pain and discomfort [13]. WRMSDs have also heavy economic costs to companies (e.g., loss of productivity, training of new workers, compensation costs) and to healthcare systems [14]. As a consequence, an ergonomically deficient workplace can cause physical and emotional stress, low productivity and poor quality of work. The effects of bad workplace ergonomics on productivity, quality of production, safety and costs have been demonstrated also on real case studies [15]. Such evidences are pushing companies to pay increasing attention to the evaluation of ergonomic performances. The most widely adopted methods refer to: NIOSH equation, Ovako Working posture Analysis System (OWAS), Occupational Repetitive Actions (OCRA), Rapid Upper Limb Analysis (RULA), Rapid Entire Body Assessment (REBA) or Workplace Ergonomic Risk Assessment (WERA). More recently several subjective methods have been introduced to better evaluate the human efforts and discomfort in task execution. However, all these methods generally require high level of detail, real process monitoring, and long data processing from direct operators' observation. Only a preventive evaluation of human factors to have an early ergonomic design of the workstations and tasks can effectively prevent WRMSDs optimize the design of industrial systems. A good solution is represented by digital prototyping, which allows simulating the workspace and human interaction before the workplace creation to save money and time for late optimization [16]. Different computer-aided technologies support simulation-based engineering for preventive ergonomic analysis on digital mock-ups, where human actions and behaviors are reproduced by digital human models (DHMs) [17]: Siemens JACK, Dassault Systèmes CATIA/DELMIA HUMAN and RAMSIS are the most used in industrial design. They support the analysis of the WRMSD risk for specific postures, the visibility and accessibility issues, considering specific populations based on international databases. Some tools also include ergonomic observational methods like RULA and OWAS to provide a quick feedback on virtual manikins. Such tools are quite used for the design of manufacturing workplaces [18][19], and are becoming useful also for design for sustainability, to check the feasibility of tasks during the early design stages and to properly plan the maintenance operations to drive product design [20]. However, digital simulations are not usually able to assure a robust estimation of the human workload since simulations are generally referred to discrete analysis on static positions, instead of a dynamic process simulation. As a consequence, simulations provide specific results for a certain analyzed condition, without any indication about corrective actions. Furthermore, digital simulations focus on physical ergonomics mainly, and do not consider cognitive aspects and mental workload.

In order to overcome such limitations, virtual simulation within immersive virtual environments could be coupled with the analysis of human factors by users' physiological parameters monitoring. The investigation of humans' behaviours by physiological data measurement such as heart rate (HR), electrocardiogram (ECG), electroencephalogram (EEG), electro-dermal activity (EDA), has been widely used in medical research to investigate diseases or other disorders and could be moved also to industrial contexts [21]. Indeed, thanks to the improved system miniaturization, the greater system usability, and the reduced technology costs, human parameters' monitoring could be adopted in addition to traditional methods to carry out a more detailed and precise behavioural analysis and workload monitoring. However, such tools are not integrated each other or with digital simulation tools, and collected data need to be properly processed and synchronized to obtain significant feedback.

3. The simulation set-up

3.1. The research approach

The research approach is based on the involvement of users on a MR set-up to simulate the maintenance tasks, the monitoring of the real users' physical and cognitive workload, the users' digitalization into the virtual world, the measure of a set of ergonomics metrics, and data synchronization to obtain significant feedback. Such feedback is used to compare different design alternatives and to guide the product design. A MR set-up consisting of physical and virtual objects simulates the users' interaction with the product. The parts involved directly in a physical interaction with the user, especially those parts that need to be handled, moved, grasped, etc., are simulated by rapid prototyping; other parts are simulated by virtual objects. For instances, space allowance is represented by collisions with object, visibility is analyzed on the virtual scene, etc. The users' physical and cognitive stress is monitored by a set of sensors, which allow analyzing the user experience. In particular: an infrared motion capture system to collect the users' postures and movements in the real space; an eye tracking system to collect data about the users' eye fixations; and a multi-parametric wearable sensor that collect the most significant physiological data (i.e., heart rate (HR), heart rate variability (HRV), breathing rate (BR), acceleration (VMU), posture). The users' digitalization into the virtual world is realized by using a digital manufacturing tool (i.e., Siemens JACK) and a proper plugin to import data from the motion capture system. As a result, the real movements are tracked and directly imported into the virtual world, interacting with the 3D CAD model of the product. Finally, a structured protocol is used to investigate both physical and cognitive aspects. The protocol has been defined on the basis of the Norman's models of perception and human-machine interaction principles, and it has been described into a previous research work [22]. The protocol defined a set of metrics to assess the physical and cognitive workload. The physical workload is measured by postural analysis based on the combination of RULA, REBA and OWAS. The cognitive workload is measured by visibility and accessibility analyses, which considers the visible and reachable areas respectively based on eye tracking data and postural data, and by emotional stress conditions based on HR and HRV analysis.

3.2. The mixed reality simulation set-up

The MR simulation set-up combines virtual environments with physical objects; in order to simulate a realistic human-product interaction supporting tools (e.g., screws, pliers) as well as components to be handled (e.g., tubes, valves, covers) were represented by real objects. The proposed set-up includes:

- a set of 3D printed rigid bodies with markers for full body marking;
- a set of VICON Bonita cameras for motion capture;
- VICON tracking software system (Tracker) for real users' tracking and manikin digitalization;
- Siemens JACK software toolkit for product digitalization;
- HAPTION RTI plug-in for connection among real user movements and virtual manikin movements;
- a GoPro camera to record the scene;
- a pair of Tobii Glasses2 to capture eye movements;
- a Zephyr BioHarness 3.0 sensor to record human physiological data.

Bonita infrared cameras used for motion capture were properly configured according to the workspace to be captured. In the meanwhile, an external video camera (GoPro) recorded the user actions. The eye tracking system (Glasses2) allowed analysing the users' eye movements and fixations, while the multi-parametric biosensor (BioHarness 3.0) monitored in real time the user heart rate (HR) and heart rate variability (HRV), the breathing rate in breath per minute (BPM), the activity level in vector magnitude units (VMU), and the body posture by means of accelerometers and gyroscopes.

Digital mock-ups were created by JACK, which imports different CAD models. A stereoscopic large volume display (6-2 metres) was used for 3D mock-ups visualization, while interaction was simulated by motion capture and real object tracking. Data from motion capture was analysed by Tracker and imported into JACK virtual scene by HAPTION RTI plug-in in order to create personalized manikins. For full body motion capture, a set of ad-hoc rigid bodies was created by rapid prototyping and tracked data interfaced within JACK. Eye tracking data and human monitoring data were processed by dedicated software respectively, and properly synchronized. Table 1 shows the monitored parameters, the collected data to assess both physical and cognitive workload, and the selected tools. They are organized according to the analyzed workload (physical or cognitive). It provides an overview of how users were monitored and analyzed in the study.

Table 1. Monitored parameters for the physical and cognitive workload analysis

Workload	Monitored parameters	Collected data	Selected tools	Tool typology
Physical	RULA OWAS	Human joint angles	Siemens JACK	Occupant packaging toolkit
	Eye tracking (ET)	Gaze plot, Heat maps	Tobii Glasses 2	Eye Tracker
	Activity level (VMU) Posture	Activity diagram Stooping on sagittal plane	Zephyr BioHarness 3.0	Multi-parametric wearable sensor
	Actions	Videos of users and the surrounding environment	GoPro Hero 3	Camera
Cognitive	Heart Rate (HR) Heart Rate Variability (HRV) Breathing Rate (BPM)	HR diagram HRV diagram BPM diagram	Zephyr BioHarness 3.0	Multi-parametric wearable sensor

4. The industrial case study

4.1. Case study description

The use case has been developed in collaboration on a CNHI real case. CNHI is a global manufacturer of agriculture and industrial vehicles, with more than 64 manufacturing plants and 50 research and development centers in 180 countries. It designs and produces tractors, trucks, buses, on-road and off-road powertrain solutions, and marine vehicles. The use case focused on the application of the proposed set-up to support the design of tractors according to design for serviceability principles. The first step was the analysis of the actual maintenance tasks on one of the most widespread tractors produced by the company (APL16x16) and the selection of the more critical tasks on the basis of two main indicators: the frequency of intervention, the SAE J817 assessment risk [23] and the related costs (derived by the maintenance time). SAE index is a synthetic index of the task complexity and risk for the operators, and is widely used to assess the risk of maintenance tasks by users observation on field studies. It is based on a set of scores, assigned to each task features related to the assumed positions, the supporting tools, the accessibility issues, and more. Among all maintenance tasks for the selected tractors, the "replacement of the engine oil filter" task was selected as particularly critical: it is very frequent (the filter has to be replaced every 600 hours, which means about 2-3 months according to the tractors' usage), it requires the disassembly of a huge quantity of components, it takes a long time, and it is affected by limited accessibility due to the design of the product components in the engine compartment. The second step consisted of task analysis in order to describe the human-system interaction workflow and the interaction modalities on the current design. The third step referred to task virtualization and simulation within the MR set-up. The goal is to simulate the maintenance tasks on the current design and to improve the design to improve both cognitive and physical ergonomics as well as service time and costs. Indeed, the use of the MR mock-ups allowed simulating the selected tasks on a variety of design alternative in a quick and easy way, in order to define the more sustainable design. Contemporarily, the operators' physical and mental workload was inferred by human parameters' monitoring.

4.2. Simulation within the MR set-up

Maintenance actions on the current design were simulated by digital mock-ups in order to define the list of tasks to be simulated and the digital workplace to be reproduced. The sub-tasks can be synthetized as follows:

1) disassembling the toolbox;
2) removing the motor hood support;
3) removing the support bracket;
4) removing the engine electrical wiring;
5) unscrewing the engine oil filter with the key and manually (lastly);
6) screwing the engine oil filter with hands and the key.

Finally actions are repeated inversely for re-assembling.

After task analysis, the current product layout was virtually reproduced and operators were involved in task execution within the MR set-up. The physical mock-up included only the oil filter and few components necessary for a direct interaction by users during task execution. Each sub-task was executed into the MR environment by real operators' and moved into the virtual scene by motion capture. Figure 1 shows the MR set-up for the specific case study. Different users referring to different percentiles (5P, 50P and 95P) were involved in the experimental tests in order to consider the effect of body dimensions and heights on accessibility and visibility. According to protocol analysis, RULA, REBA and OWAS results were calculated on digitalized manikins, while visibility and accessibility were analyzed thanks to eye tracking data and postural data, as well as by users' observation by video interaction analysis. Figure 2 shows the results obtained for the analysis of the physical workload for the first sub-task (step 1) of the maintenance procedure analyzed in the case study, on the current layout design. Results highlighted that taller users (95P) can difficultly manage this operation. On the basis of the results collected on the current design layout (Figure 3), the main product optimization actions were defined. In particular, results highlighted that the current procedure is quite difficult due to the numerous steps and the accessibility problems for taller users (95P).

On the basis of such results, the engine compartment was re-designed. The design alternatives were tested into the MR environment in order to find the best solution. The main design changes included four parts:

1. Bracket (which holds the cover)
2. Power Steering Lines
3. Wiring Bracket
4. Left Lamp

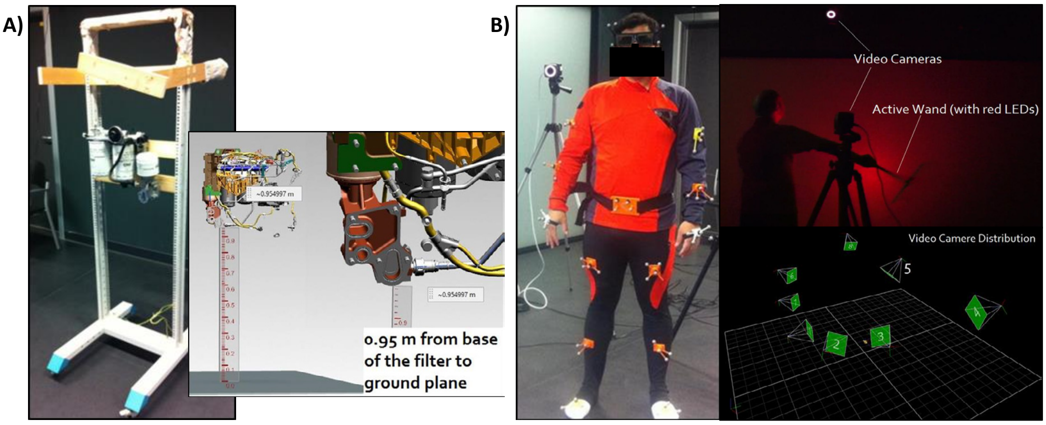


Fig. 1. The case study simulation in the MR set-up: the physical mock-up replicated some parts of the 3D model (A) and the full body motion capture by optical infrared cameras (B)

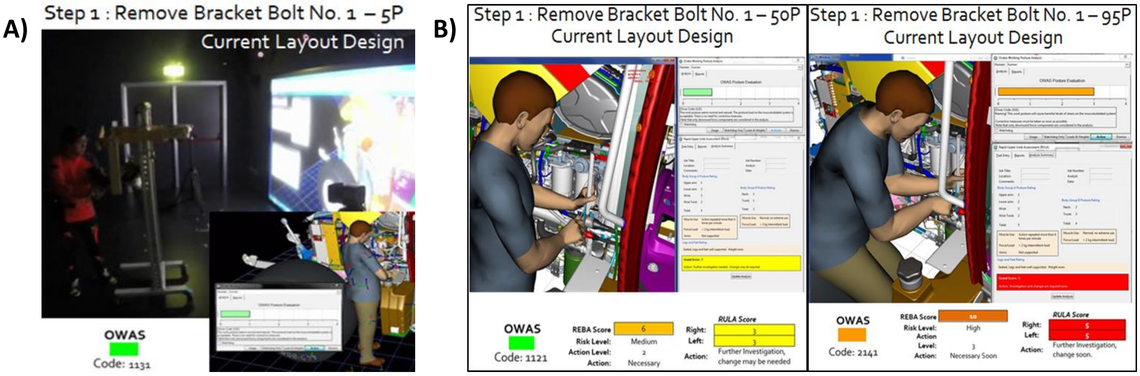
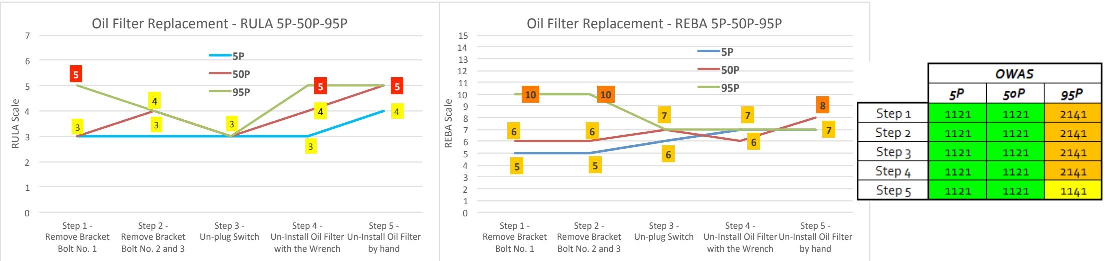


Fig. 2. Results about postural workload: digitalization procedure (A) and results from users belonging to 50P and 95P (B)



	OWAS		
	5P	50P	95P
Step 1	1121	1121	2141
Step 2	1121	1121	2141
Step 3	1121	1121	2141
Step 4	1121	1121	2141
Step 5	1121	1121	1141

Fig. 3. Results about postural workload according to RULA, REBA and OWAS

The final design solution is described in Figure 4. On the basis of the experimental results, the product design was optimized. Figure 5 shows the results collected by tests with users in the MR set-up comparing the current design and the new design, for a specific user (similar results were collected for all users involved). The physical workload has been reduced due to the elimination of several sub-tasks (no more necessary with the new layout) and the postural comfort improvement, as highlighted by the OWAS data and the VMU diagram. The improved accessibility and easy to use is confirmed also by gaze plot and heat map obtained by the eye tracking. In Figure 5, the gaze plot shown for step 3 demonstrated that the new task requires an easier interaction thanks to the new design. Furthermore, the cognitive stress is reduced as demonstrated by the breathing rate and heart rate diagrams.

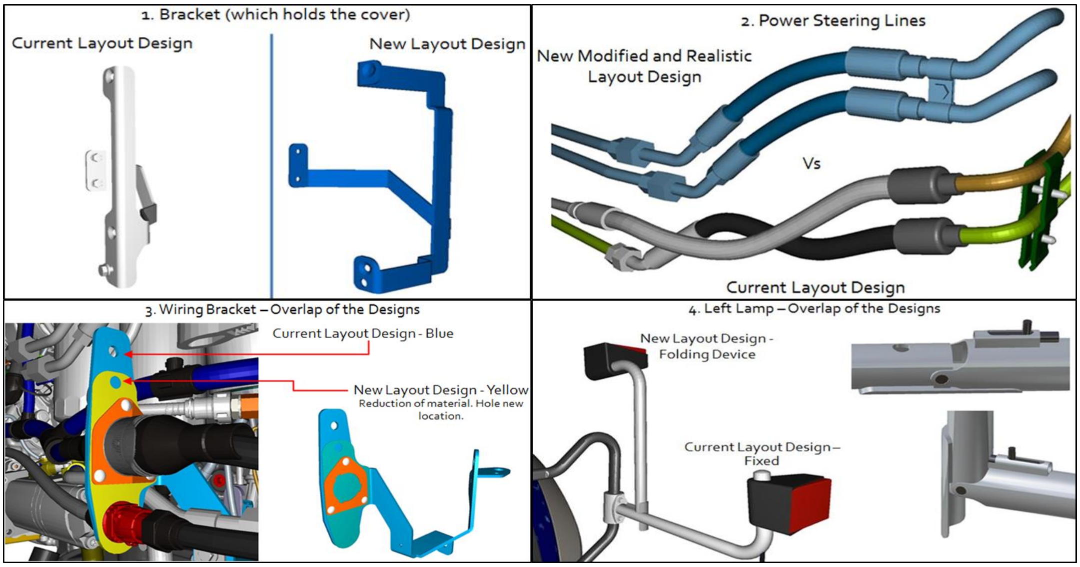
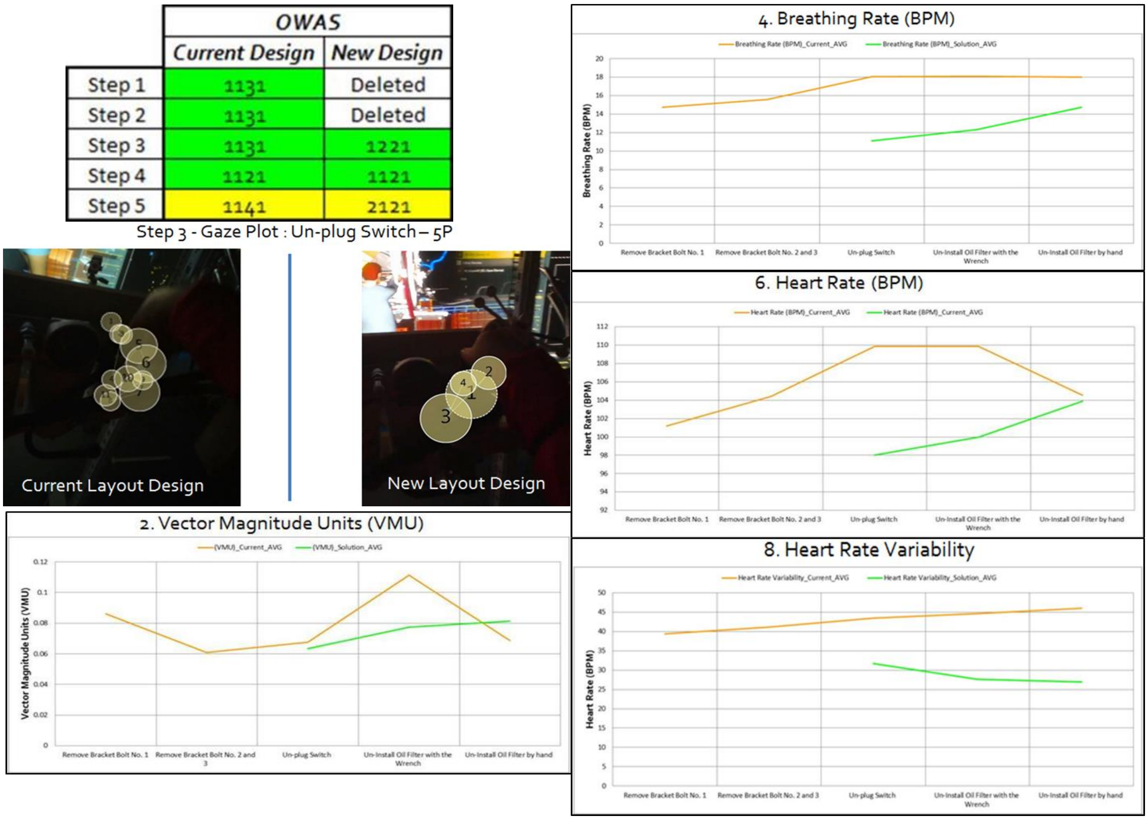


Fig. 4. Main design changes and final design solution to optimize the service procedure for the case study



	OWAS	
	Current Design	New Design
Step 1	1131	Deleted
Step 2	1131	Deleted
Step 3	1131	1221
Step 4	1121	1121
Step 5	1141	2121

Fig. 5. Results comparing the current design and the new design solution, according to the monitored parameters, for a specific user.

5. Conclusions

The paper proposed a MR set-up to support design for serviceability. The set-up is composed by digitalization and human monitoring technologies and allows to test with users' design solutions during the design stages and to predict the human interactions during task execution. The set-up was adopted to support product re-design for an industrial case study, focusing on tractors' serviceability. Human factor assessment was useful to optimize product serviceability, reducing the operators' workload, and fasten the maintenance operations.

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