



A methodological framework to integrate motion capture system and virtual reality for assembly system 4.0 workplace design



Marco Simonetto ^{a,*}, Simone Arena ^b, Mirco Peron ^a

^a Department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology, S P Andersens V 3, 7031 Trondheim, Norway

^b Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Via Marengo, 2, Cagliari 09123, Italy

ARTICLE INFO

Keywords:

Assembly
Workplace
Design
Industry 4.0
Methodological framework
Ageing

ABSTRACT

Nowadays new products are required more and more often. Since a certain product is assembled only on a specific Assembly System (AS), a new AS has to be designed every time a new product is developed. Similarly, since an AS is constituted by one or more workplaces, new workplaces need to be designed every time a new product is developed. However, this is not feasible considering the time- and resource-consuming AS workplace design procedures currently used (e.g., physical mock-ups and computer-aided systems). New solutions have thus emerged to accelerate the AS workplace design procedures, especially since the advent of Industry 4.0 (I4.0) technologies. Specifically, the combined use of motion capture (mocap) systems and Virtual Reality (VR) has been considered very promising, with many researchers showing its potential. However, to the best of the authors' knowledge, none of them suggests a clear methodology to follow when designing AS workplaces using the mocap system and VR. In this paper, we thus aim to fill this gap by developing a methodological framework that describes in detail the different steps to be followed. Moreover, the methodological framework has been developed in such a way that both productivity and Occupational Safety and Health (OSH) considerations are included. Furthermore, it encompasses the current ageing workforce scenario by explicitly including the ageing workforce's main characteristics (reduced flexibility and strength and greater experience of older operators). A simple but representative case study has then been carried out to demonstrate how to use the methodological framework and to prove its validity.

1. Introduction

Nowadays customers require new and customised products more and more often, and companies have hence to be able to easily follow these requirements in order to survive in today's competitive market. Companies thus have to be able to change their Assembly Systems (ASs) in a fast and economic way to cope with the short life-time of the products, i.e., Assembly Systems (ASs) are required to be flexible and reconfigurable (Battaià et al., 2018). This, together with the optimisation of the AS workplaces (defined according to Cavatorta and Dipardo (2009) as (i) the workstation where the assembly tasks are executed, (ii) all the equipment that is necessary to execute the tasks, and (iii) all the systems necessary to store the components that are not convenient to store directly in the workstation), is fundamental to assemble new products at low costs, short time to market, and high reliability of deliveries (Battini et al., 2011; Holubek and Ružarovský, 2014; Porta et al., 2020, Arena et al., 2021). Moreover, due to the presence of human operators in AS

workplaces, their optimisation has to be carried out with respect not only to productivity but also to Occupational Safety and Health (OSH). Human operators are, in fact, fundamental to guarantee the high flexibility required by ASs (Makris et al., 2016), and it is thus important to promote their comfort to improve their OSH, especially their wellbeing. This can be achieved by considering the right ergonomic interventions during the workplace design process. These interventions can involve some adjustments in the AS workplace (Kim and Junggi Hong, 2013) and it is crucial that they also consider the current ageing of the workforce (OECD, 2015). Indeed, the ageing of the operators could have a negative impact on the AS productivity (Strasser, 2018): assembly tasks require physical efforts to be executed, but ageing is known to reduce physical capabilities. For example, Peng and Chan (2019) reported that the musculoskeletal capacity decreases by 20% after the age of 60. Therefore, it is necessary to limit the drawbacks associated with the decreased physical capabilities of the ageing workforce, and this can be done with the proper design of the AS workplace (Truxillo et al., 2015;

* Corresponding author.

E-mail address: marco.simonetto@ntnu.no (M. Simonetto).

[Calzavara et al., 2020](#)). In fact, an effective workplace can lead to a decrease in the physical burden of the human operators, thus reducing the ergonomic risks and improving the OSH ([Roper and Yeh, 2007](#)). This, in turn, results in increased productivity, better working conditions, and operators' wellbeing in an AS ([Eswaramoorthi et al., 2010](#)).

The design of these workplaces can be facilitated by the advent of Industry 4.0 and its technologies ([Burggräf et al., 2019](#)). The term Industry 4.0 is used to indicate the fourth industrial revolution that the industrial environment is currently experiencing ([Wang, 2016](#)). This revolution is moving companies toward a gradual and constant automation of traditional manufacturing practices ([Schwab, 2016](#)) and ASs are involved in this revolution, introducing the concept of Assembly System 4.0 (AS4.0) ([Bortolini et al., 2017; Cohen et al., 2019](#)). In particular, in the AS4.0 the new technologies of Industry 4.0 can be used both to enable better performance ([Battini et al., 2020; Fager et al., 2020; Peron et al., 2020; Simonetto et al., 2020; Arena et al., IN PRESS](#)) and to design their workplaces ([Dolgui et al., 2021](#)). Indeed, regarding this last point, the combined use of the motion capture (mocap) system and Virtual Reality (VR) has been reported to improve the AS workplace design compared to the currently used AS workplace design procedures (e.g., physical mock-ups and computer-aided systems) with respect to both productivity and operators' wellbeing ([Faccio et al., 2017; Battini et al., 2018](#)). Specifically, a mocap system allows the creation of a digital copy of the operator in real time thanks to "*a virtual representation of the skeleton and its movements*" ([Bortolini et al., 2020](#)), and this facilitates and improves ergonomic assessments, since AS workplace designers have access to the exact evolution over time of the position and orientation of the operator's different limbs in a common reference system ([Oyekan et al., 2017](#)). VR, instead, gives the opportunity to create a three-dimensional environment where users can interact efficiently with three-dimensional objects in real time using their natural senses and skills ([Riva, 2002](#)). The adoption of a mocap system and VR during the design phase of an AS makes it possible to overcome the main limitations of the currently used AS workplace design procedures, i.e., subjective and time-consuming assembly time measurements and ergonomic assessments ([Battini et al., 2011; Battini et al., 2014](#)). The combined use of these two technologies, in fact, enables fast and reliable assembly time measurements and ergonomic assessments (see [Section 2.1](#) for more details).

It is hence clear that the potentialities associated with the use of these technologies are enormous, but it is still unclear how to maximise the associated benefits. In fact, to the best of the authors' knowledge, a clear description of the methodology that needs to be followed when designing using the mocap system and VR is still missing, and this represents one of the main reasons why "*their adoption within real industrial environments is still very limited*" ([Prabhu et al., 2016](#)). In this work, to fill this gap, we developed a methodological framework that AS workplace designers can follow when using mocap and VR. Specifically, the methodological framework herein developed gives a central role to the operator. In more detail, the operator is included in the methodological framework by considering his/her main characteristics, i.e., (i) physical strength and joint mobility and (ii) experience. This is extremely important in consideration of the current ageing of the workforce. In fact, a reduction in physical strength and joint mobility and an increase in experience is known to be associated with the ageing workforce ([Börsch-Supan and Weiss, 2016; Roda et al., 2019; Peng and Chan, 2020](#)). Characteristic (i) is considered in the ergonomic assessments, where, referring to the work of [Wolf and Ramsauer \(2018\)](#), we modified the ergonomics index Rapid Entire Body Assessment (REBA). Dealing with (ii), then, the experience of the ageing workforce is considered in the design phase: thanks to the experience they gained over the years, they can provide advice that can simplify and speed up the design procedure ([Di Pasquale et al., 2020](#)). The methodological framework has then been successfully applied to a simple but representative case study to prove its validity and to demonstrate its use.

The rest of the paper is organised as follows. In [Section 2](#) we present a

narrative literature review dealing with the design of AS workplaces ([Section 2.1](#)) and thereafter the impact of the ageing workforce on productivity and OSH performance in AS workplaces ([Section 2.2](#)). Specifically, in this work we focus only on operators' wellbeing as OSH performance. [Section 3](#) then presents the methodological framework developed herein. In [Section 4](#) the case study is described and discussed. Finally, [Section 5](#) concludes the work.

2. Literature review

In this section, a narrative literature review is conducted in order to have an overview of the evolution of the AS workplace design procedures ([Section 2.1](#)) and of the impact of the ageing workforce on productivity and OSH performance in these workplaces ([Section 2.2](#)). Specifically, as in the rest of the work, we focus only on operators' wellbeing as OSH performance.

2.1. Design of the assembly system workplace

AS workplace design, defined by [Launis et al. \(1996\)](#) as the "process and activity which leads to the birth of the workplace", has been subject to substantial changes over the last years. From what we will refer to as the "traditional AS workplace design procedure", i.e., the construction of the physical workplace mock-up proposed by [Das and Sengupta \(1996\)](#), in fact, new design procedures have been developed, especially thanks to the technological developments over the years, aiming to overcome the main limitations of the traditional AS workplace design procedure (i.e., time- and resource-consuming).

Based on the pioneering work of [Warnecke and Haller \(1982\)](#) and [Bauer and Lorenz, \(1985\)](#), [Zha and Lim \(2003\)](#) suggested overcoming these limitations using computer-aided systems. Specifically, they developed an algorithm that optimised the AS workplace design in a virtual environment, hence eliminating the need to create several physical mock-ups. Similarly, [Udosen \(2007\)](#) studied the possibility of optimising the AS workplace design thanks to a computerised heuristic. Through a case study, they demonstrated the possibility of optimising the AS workplace with respect to the cycle time in a faster and easier way compared to the traditional approach. However, the use of computer-aided systems became unsatisfactory when the urge to include also ergonomic considerations in the AS workplace design emerged.

The continuously increasing flexibility required by the market over the last years has in fact rendered the use of human operators in AS fundamental. The operators' capability to easily adapt to changes in production has in fact been considered essential in order to cope with the market's characteristics. Therefore, the concept of the human-centred AS workplace has started to arise ([Giacomin, 2014; Caputo et al., 2019](#)), pointing out the necessity to include ergonomic considerations in AS workplace design ([Neubert et al., 2012; Šišková and Dlabač, 2013](#)). Worthy of mention in this perspective is the work of [Battini et al. \(2011\)](#), who developed a methodological framework to optimise the AS with respect to both productivity and operators' wellbeing.

However, despite some improvements, the computer-aided systems have not been fully capable of adapting to these needs. In fact, although much has been done from the initial procedure where a physical mock-up was needed to evaluate the operators' wellbeing in the computer-aided designed AS workplace through photos and/or videos of the assembly operations, some limitations still exist ([Naddeo et al., 2014](#)). Specifically, although in their latest versions computer-aided systems make it possible to study both productivity and operators' wellbeing directly in the virtual environment ([Feldmann and Junker, 2003](#)), hence overcoming the limitations of using physical mock-ups and photos and/or videos of the assembly operations for the ergonomic assessments ([Realyvásquez-Vargas et al., 2020](#)), the results are not fully representative of the reality. In fact, the ergonomic assessments are carried out on a virtual operator which does not represent the reality, since its

movements and anthropometrical data differ from those of the operator for whom the AS workplace is being designed.

Recently, the combined use of the mocap system and VR has emerged as a new AS workplace design procedure that can overcome these limitations (Jayaram et al., 2006; Di Pardo et al., 2008). Specifically, this AS workplace design procedure consists in creating first the virtual environment in which the operator is immersed through the use of VR. The operator is then equipped with a mocap system that allows the creation of the operator's digital twin, i.e., a digital copy of the operator that is a truthful representation of the reality. In this way, the operator can virtually perform all the activities that he would normally do during his job, but without the need for a physical mock-up. Moreover, the ergonomic assessments are carried out on the operator's digital twin, which has the same anthropometric data and makes the same movements. Furthermore, it is also possible to carry out the ergonomic assessments in real time (Vignais et al., 2013; Battini et al., 2014).

Some researchers have thus been attracted by the potentialities offered by the combined use of the mocap system and VR for AS workplace design, and they have started investigating these

potentialities in more detail (Peruzzini et al., 2017; Vosniakos et al., 2017; Michalos et al., 2018; Caputo et al., 2017; Battini et al., 2018). Peruzzini et al. (2017), for example, evaluated the AS workplace design procedure in a steel pipe manufacturer using either the mocap system and VR or a computer-aided system, and they reported that the outcomes of the AS workplace design procedure were substantially improved using the former thanks to the more accurate ergonomic assessments that could be obtained. Similar results were obtained also by Vosniakos et al. (2017) for the assembly of small to medium aircraft wings, and by Caputo et al. (2017) for assembly tasks in a lab environment. Michalos et al. (2018) then further proved the efficacy of this design procedure, focusing on the assembly of a robotic wrist. Specifically, they demonstrated that through the combined use of the mocap system and VR it was possible to easily redesign the robotic wrist AS workplace and to improve its performance in terms of the distance walked and task execution times. Finally, Battini et al. (2018) further investigated the potentialities of this design procedure, suggesting the possibility of coupling the mocap system and VR with a heart rate monitoring system in order to include also fatigue considerations in the AS workplace design.

However, despite the increasing interest in the use of the mocap system and VR for AS workplace design, to the best of the authors' knowledge a clear and detailed procedure to follow when designing the use of these technologies is still missing. In this work, we thus aim to fill this gap by developing a methodological framework that the AS workplace designer can follow, allowing full exploitation of the potentialities associated with the combined use of the mocap system and VR. Moreover, with the methodological framework we aim to overcome another limitation of the current design procedures, which, in fact, give only limited consideration to the operators. The different physical strength and joint mobility that can characterise the operators (due to their different ages, for example) are not considered in the ergonomic assessments, and their different levels of experience are not considered in any way in the current design procedures either. In the methodological framework herein developed we overcome these limitations. Specifically, the operators' physical strength and joint mobility are included in the ergonomic assessments, while their experience is used for useful advice concerning the AS workplace layout (e.g., the position of components and/or tools).

2.2. Ageing in the assembly system workplace

It is widely known that the world population is ageing, with the most developed countries having the highest share of older people (United Nations, 2018). This has great repercussions on the labour market, which is naturally experiencing an ageing workforce due to the necessity of increasing the retirement age (Hanson and Lindgren, 2020). This represents a key issue in some industrial sectors, especially in manufacturing. In fact, in a sector such as manufacturing where repetitive movements are often required, the decline of the operators' physical functions as the years go by (e.g., reduced musculoskeletal force, flexibility and motion capability) certainly represents a threat (Shephard, 2000; Ilmarinen, 2001; Bouma, 2013; Cote et al., 2014; Bures and Simon, 2015; Truxillo et al., 2015; Peng and Chan 2019; Orrù et al., 2020; Peng and Chan, 2020). For example, Roper and Yeh (2007) reported that, as a consequence of the decline of the operators' physical functions, musculoskeletal disorders (MSDs) are one of the most commonly found health risks among ageing workers. Similar observations can be found also in Jones et al. (2013). Specifically, Landau et al. (2008), analysing the assembly operations in the automotive industry, reported that lumbar spine and head-neck-shoulder symptoms are the most frequent MSDs that ageing workers suffer from, in agreement with Qin et al. (2014). It is hence clear that, to reduce the occurrence of MSDs, the ergonomic risks need to be reduced. To do so, Balderrama et al. (2015), for example, suggested assigning ageing workers to appropriate job positions, where the work demands match their physical

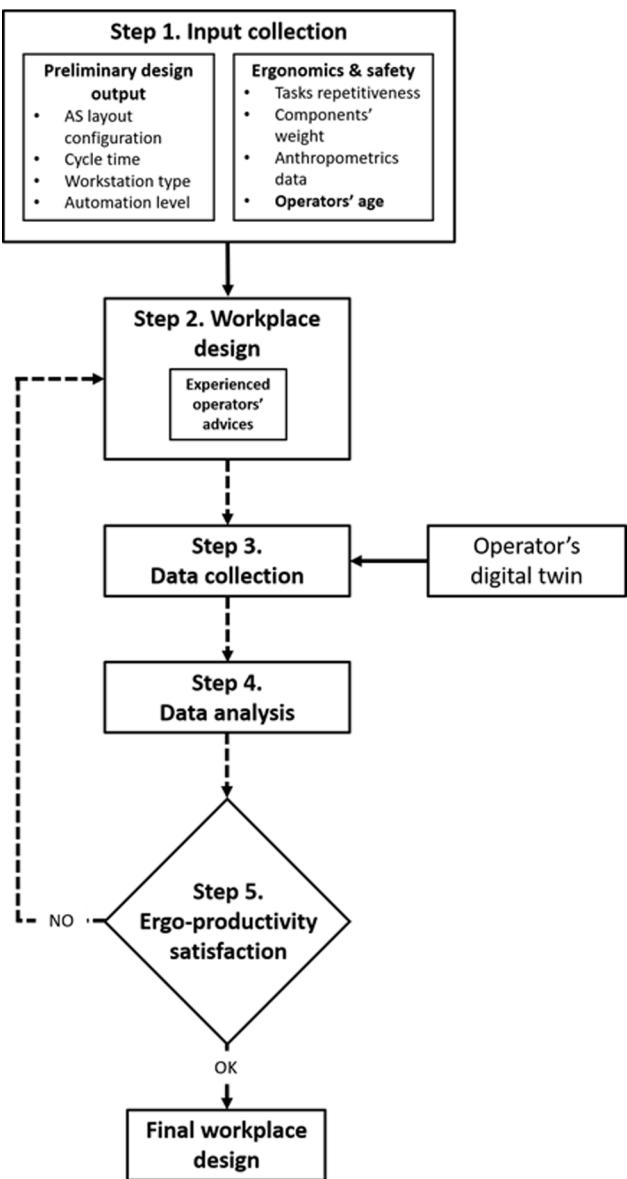


Fig. 1. Methodological framework. The dashed arrows indicate the steps subjected to possible changes during the iterative process.

abilities. Similarly, Kovalski-Trakofler et al. (2005) suggested that ageing workers should avoid activities involving extreme joint movements, excessive force and highly repetitive movements since they involve high ergonomic risks.

Moreover, Varianou-Mikellidou et al. (2020), confirming the results of Roper and Yeh (2007) and Pennathur et al. (2003), reported that the decline of the operators' physical functions with increasing age affects also their efficiency. Compared to their younger colleagues, in fact, ageing workers are reported to be slower in their reactions and movements, as well as to require longer resting times after physical efforts (Zieschang and Freiberg, 2011). This, in turn, decreases their productivity. Göbel and Zwick (2009), in fact, reported that the productivity decreases after the age of 40. Similar results were also obtained by Alessandri et al. (2020) and by Abubakar and Wang (2019). Specifically, the latter reported that the decrease in productivity starts already at the age of 38, with an increase of 1% in the average task execution time every year after that age. However, Börsch-Supan and Weiss (2016) reported the opposite findings. In fact, evaluating truck assembly, they reported that the productivity profile of individual workers was increasing until the age of 65, and they explained their results by observing that older workers were able to compensate for the decline of their physical functions thanks to the experience gained over the years. In fact, although ageing workers were found to make slightly more errors than their younger colleagues, they made hardly any severe errors due to their increased experience. Similar results were found also by Roosaar et al. (2019) and Kim (2019), who showed that ageing workers remained at least as productive as their younger colleagues thanks to their experience.

From what is reported above, there clearly emerges a need to consider explicitly the age of the operators in ergonomic and productivity-related considerations, especially when designing the AS workplace. For example, acting on the components location, extreme joint movements could be avoided, as well as limiting the negative impact of the ageing workers' slower movements. In this work, we developed a methodological framework for the workplace design that explicitly considers the age of the operator, including both the negative and positive aspects (reduced physical functions and increased experience, respectively), as better described in the previous section.

3. Methodological framework

In this section the methodological framework developed to guide an AS workplace design that includes both ergonomic and productivity-related considerations is reported (Fig. 1) and explained in detail. Specifically, the AS workplace design procedure considered deals with the combined use of the mocap system and VR. Before moving forward, it is worth mentioning that the methodological framework is meant to be used during the detailed design phase, and it has been developed in such a way that it can be combined with already existing frameworks for AS design. For example, the framework developed herein can be used for carrying out steps 5 to 8 of Battini's framework (Battini et al., 2011).

3.1. Step 1 – Input collection

The first step is the collection of the input parameters. Since, as mentioned earlier, the methodological framework developed herein is meant to be used in the detailed design phase, we consider the known outputs of the preliminary design phase, and therefore the (i) AS layout configuration, (ii) cycle time (paced/un-paced), (iii) workstation type (i.e., open/closed, parallel/serial, two-sided, ...), and (iv) automation level (i.e., percentage of automation, type of equipment, ...) are known. Moreover, the product characteristics that influence ergonomics and safety (e.g., component weights) are also known in this design phase. Furthermore, the operators who will work on the AS workplace under development are generally known, and thus also their anthropometric data and age.

3.2. Step 2 – Workplace design

Once the inputs have been collected, the AS workplace design can be carried out. In this step, contrary to the traditional AS workplace design approach where physical mock-ups are needed, the workplace is designed virtually, using a 3D modelled environment. Many different alternatives can hence be easily developed and assessed, without the need to build a physical mock-up for each alternative. This, as already stated before, brings great benefits in terms of time and cost reduction.

During this phase, it is fundamental that the AS workplace designers are assisted by experienced operators. In fact, as we saw from the literature review, operators are affected by a gradual decrease of both physical and cognitive abilities with increasing age (Shepard, 2000; Bouma, 2013; Bures and Simon, 2015), and experienced operators, thanks to the experience gained over the years, can provide useful advice to the AS workplace designers to take these aspects into consideration. For example, to ensure their wellbeing, older operators might be required to make fewer movements, move fewer heavy objects, and do fewer complex activities during their daily assembly activities. Experienced operators, then, based on their knowledge, can advise the AS workplace designers on the proper position of, e.g., components and equipment to avoid poor work postures and unnecessary movements. Moreover, experienced operators can suggest to the AS workplace designers whether (i) the operators need to be supported by new equipment (e.g., lifter, automatic screwdrivers, collaborative robots, etc.) and (ii) the environmental conditions (e.g., lighting) need to be adapted or not, based also on their age. Moreover, in this phase, it is crucial that the AS workplace designers and the experienced operators adopt a holistic approach, where they consider productivity and operators' wellbeing as two complementary aspects, not as two separate entities. The AS workplace layout influences, in fact, both the productivity and operators' wellbeing through the whole assembly process: for example, the positioning of a component (or tool) in a certain location with the aim of making the assembly tasks faster might have a negative impact on the operators' wellbeing, and vice versa. Moreover, it is equally important that the AS workplace designers and the experienced operators do not consider each task as single, separate entities, but as a part of a wider aspect. Sometimes, in practice, some trade-offs are necessary to reach the overall objectives: the productivity and/or safety of an assembly task might need to be penalised to reach the desired goals in terms of productivity and operators' wellbeing for the whole assembly process.

It is worth noting that in this step, although many software tools are available to model a 3D environment, only those software tools that can interact with the mocap system and with VR can be used (e.g., Siemens Jack™). The interaction with the mocap system is, in fact, a crucial aspect since it makes it possible to obtain the real movements of the operator and to accurately replicate them in the 3D modelled environment.

3.3. Step 3 – Data collection

Once the virtual workplace is built, the collection of the data can take place. In this step, an operator needs to be equipped with the mocap system and with VR. Thanks to the combined use of the mocap system and VR, he will be immersed in the 3D modelled environment, being able to move and to interact with it. In this way he can carry out the assembly process virtually, without the need for any physical mock-up. While the virtual assembly process is being carried out, the mocap system allows the recording of the assembly operations (from now on we will refer to this as "mocap-based recording"), as well as the physical data (e.g., body joint angles, body segment orientation and positions) that will be used in Step 4 to evaluate the ergonomics. For the sake of clarity, from now on we will refer to these physical data as "ergonomics-relevant data", and they are available for each frame of the mocap-based recording (the frame rate can usually be decided beforehand). It will be clear in the description of Steps 4 and 5 that this represents a very

important aspect.

Before moving to the description of Step 4, it is worth mentioning that at the beginning of Step 3 a crucial activity is needed to be able to collect useful and reliable data. A digital twin of the operator carrying out the virtual assembly process needs to be created before carrying out the virtual assembly process. In this way, we ensure that the anthropometric data of the operator's digital twin corresponds to those of the operator who will perform the virtual assembly process. This is fundamental for obtaining accurate and reliable ergonomic assessments. In this step, we recommend that the operator chosen to carry out the virtual assembly process is representative in terms of the anthropometric data of the operators who will work on the AS workplace under development. Considerations about the age of the operator chosen to carry out the virtual assembly are reported in Step 4.

3.4. Step 4 – Data analysis

Once the data are collected, they need to be analysed with respect to productivity and ergonomics. The productivity can be evaluated by means of time-related parameters (e.g., task execution times), which in the following we will refer to as “productivity KPIs”, while the ergonomics can be evaluated using ergonomic indexes (RULA, REBA, NIOSH, OWAS, etc.). During the data analysis step, in order to optimise the outcomes, the AS workplace designers are required to divide the whole assembly process into the different assembly tasks that constitute it. Thus, each assembly task has to be associated with its own data (mocap-based recording and ergonomics-relevant data). In this way, the AS workplace designers can evaluate the productivity KPIs and the ergonomics index scores for each assembly task. The former can be evaluated through the mocap-based recording of the assembly: the task execution time, for example, can be evaluated based on the length of the mocap-based recording of the task under consideration. For the ergonomic scores, instead, the AS workplace designers have to consider the ergonomics-relevant data of each frame that constitutes the assembly task under consideration. Through simple formulas, these data can be converted into the ergonomic scores in a fast way (the process can be automated by using EXCEL, MATLAB or any other similar tool). For example, considering the REBA index, the relative angle between the neck and the trunk corresponds to the “neck score” in the REBA index. By doing so, it is hence possible to evaluate for each task the average and the distribution of the ergonomic scores (i.e., considering again the REBA index, how frequently is the REBA score equal to 1, to 2 and so on). Moreover, by analysing jointly the mocap-based recording of each task and the REBA scores of each frame constituting that specific task, it is possible to determine the subtasks that involve high ergonomic risks and to link them to the AS workplace layout, hence facilitating the AS workplace design improvement procedures. While doing this, the AS workplace designers can also note, for each task, what we will refer to as a value-added ratio, i.e., the ratio between the time spent on necessary activities and the total task execution time. In this way, it is easier to identify which tasks are characterised by highly unproductive activities (i.e., activities that do not add value for the assembly operations, e.g., moving, travelling, etc.), hence having a negative impact on the productivity KPIs, and to link them to the AS workplace layout.

During the ergonomic assessments, it is crucial that the age of the operator is explicitly considered. However, this is still overlooked in the literature, and, to the best of the authors' knowledge, only [Wolf and Ramsauer \(2018\)](#) proposed a solution for this. In detail, they proposed to modify the ergonomic scores by means of age-based multipliers, and they suggested evaluating these age-based multipliers by means of mathematical formulas. Specifically, they suggested obtaining these mathematical formulas by interpolating literature data about the decline in the ability under consideration (muscular strength, aerobic capacity, etc.) with respect to age. For example, they were interested in an age-based multiplier for strength reduction in order to include age considerations in the KIM ergonomics index. To evaluate this age-based

Table 1

Execution time, average REBA score and value-added ratio for each task in the as-is configuration.

Task	Task execution time (s)	Average REBA score		Value-added ratio (%)
		Age = 27	Age = 60	
1	19.0	3.40	3.82	62.2
2	7.2	2.30	3.51	60.3
3	14.5	3.51	3.88	62.0
4	72.6	4.63	5.23	54.5
5	87.5	4.47	6.65	37.8
6	62.0	4.50	5.40	67.6
7	6.3	3.42	4.42	77.1
8	18.0	4.36	4.96	41.5
9	19.4	3.91	5.33	29.3
10	75.8	4.29	4.84	60.4
11	62.5	5.03	5.96	69.3
12	22.2	2.60	3.12	40.6
13	16.2	1.76	2.14	73.2
14	56.1	4.51	5.25	48.0
15	59.1	3.49	4.36	43.4
16	132.1	3.94	4.78	43.0
17	28.1	3.90	4.32	41.7
Total	758.6	4.12	4.97	51.2

multiplier ($f_{strength}$), they developed the mathematical formula reported in Equation (1) by fitting the data available from the literature regarding the changes in the muscular strength with respect to age.

$$f_{strength}(\%) = 0.00058 \cdot \text{age}^3 - 0.08478 \cdot \text{age}^2 + 3.24439 \cdot \text{age} + 62.92006 \quad (1)$$

It is worth noting that the values of $f_{strength}$ provided by Equation (1) are in line with the age-based multipliers of the REFA method and with those provided by ISO 11228 and EN 1005.

Building on this approach, we suggest in Equation (2) the age-based multiplier for joints flexibility reduction ($f_{flexibility}$), which is needed when the ergonomic indexes contain assessments on joint flexibility (e.g., allowable joint angle limits in the REBA index). To obtain the mathematical formula reported in Equation (2), we fitted the joints flexibility reduction data reported in Table 1 of Wolf and Ramsauer's work (2018).

$$f_{flexibility}(\%) = -0.00019 \cdot \text{age}^3 + 0.034286 \cdot \text{age}^2 - 2.538095 \cdot \text{age} + 145 \quad (2)$$

By considering these age-based multipliers in the ergonomic assessments, we can ensure that the age of the operator is explicitly considered (see Appendix A for more details on how to include the age-based multipliers in the REBA index). Specifically, we strongly recommend following a precautionary approach, where the age of the oldest operator who will work on the AS workplace under development is used in these formulas.

It is not strictly necessary that the operator used for the virtual assembly is the oldest operator who will work on the AS workplace under development, and it can also be a younger colleague. The choice depends on the following considerations and a trade-off decision might be needed. On the one hand, if the oldest operator is used as the operator for the virtual assembly, any potential decrease in productivity associated with the increase of age is included. However, if the technological skills of the oldest operator are limited, it might take too much time to train him sufficiently to carry out a virtual assembly process that is representative of the reality. On the other hand, if a younger colleague is used for the virtual assembly, the chances of low technological skills are limited, but any potential decrease in productivity associated with the increase of age will get lost. The choice depends therefore on the workforce characteristics (in terms of technological skills) and on the assembly process under consideration (i.e., whether the assembly process is affected timewise by the age of the operator or not). However, whatever the choice is, the ergonomic assessments have to be modified with the age-based multipliers calculated with the age of the oldest



Fig. 2. Pump assembled in the case study.

operator.

3.5. Step 5 – Ergo-productivity satisfaction

The productivity KPIs and the ergonomic scores obtained from the previous step serve as input in this step, the ergo-productivity satisfaction. This is a decision step, where the AS workplace designers have to decide whether the productivity KPIs and ergonomic scores are satisfactory or not (with respect to the company's requirements, legal requirements, etc.). If they are, this represents the final AS workplace design, if not, then the user has to go back to step 2.

In the latter case, the workplace designers and the experienced operators can draw on the results of step 4 to improve the AS workplace design by modifying its layout. Thanks to those results, in fact, the workplace designers and the experienced operators know which are the tasks that decrease productivity and operators' wellbeing (i.e., the tasks characterised by low value-added ratios and high ergonomic scores, respectively). Moreover, they also know which subtasks are responsible for these criticalities and how they are linked to the AS workplace layout. Again, it is important that, when redesigning the AS workplace, the AS workplace designers and the experienced operators adopt a holistic approach, i.e., they (i) do not focus only on the critical tasks and (ii) do not consider productivity and operators' wellbeing as two separate entities, but as two complementary aspects. This is fundamental, since focusing the AS workplace improvements only on one single task and on one single aspect (i.e., productivity or ergonomics) per time would not lead to the best results achievable, since the modification of one task has impacts also on other tasks, sometimes worsening them. Once an improved design has been identified, the workplace designers can move again through steps 3–5. It should be noted that the operator's digital twin does not need to be created (or modified) every time the iteration takes place, unless the operator carrying out the virtual assembly operation changes.

4. Case study and discussion

To demonstrate how to use the methodological framework developed herein and to prove its validity, we used a simple but representative case study carried out at the Logistic 4.0 Lab at NTNU. Specifically, in the case study we applied the methodological framework for the redesign of the AS workplace of a medium/big size pump (Fig. 2), which is constituted of 25 components assembled through 17 main tasks (information about the components and the different tasks can be found in Appendix B).

The case study was carried out as follows. First, a second-year Ph.D. student working on AS4.0 designed the initial workplace, which from now on we will refer to as the "as-is configuration". In this phase, the AS

workplace was built physically in approx. 10 h, and the Ph.D. student decided the AS workplace layout, e.g., the location of components and tools (wrenches and manual and automatic screwdriver), sub-assemblies' feedings, etc., by himself, i.e., without any support from more experienced personnel. It is worth noting that since the focus of the case study is only on the methodological framework, we considered the pump to be assembled in a single workplace. Although this does not faithfully reproduce the real industrial scenario where the assembly process is carried out among several AS workplaces (i.e., in an assembly line), we decided to consider a single workplace to facilitate the understanding of how to apply the methodological framework.

Then, we gathered all the information necessary to carry out the redesign of the AS workplace according to the methodological framework, i.e., (i) which are the tasks that negatively affect the productivity and the operators' wellbeing, and (ii) which are the subtasks that are responsible for these criticalities and their link to the AS workplace layout. The redesign of a current workplace can, in fact, be considered equivalent to the case where the first virtual design does not satisfy the ergo-productivity requirements and a second iteration is needed: as during the second iteration the methodological framework requires that information, in the same way they are needed in the case of a redesign.

To obtain that information it was hence necessary to carry out the assembly process and to collect and analyse the data according to Step 3 and Step 4 of the methodological framework, respectively. The assembly process was carried out by the Ph.D. student mentioned above (to whom we will refer as the "case-study operator" in the following), who was trained for two hours the day before the *Data Collection Step* in order to increase his assembly skills. During the *Data Collection Step*, the case-study operator was equipped with a mocap system to obtain the mocap-based recording and the ergonomics-relevant data. The mocap system used was the inertial motion capture system developed by Synertial, which consisted of 29 inertial measurement units (IMUs) that, thanks to an advanced compensation system, guaranteed to obtain very accurate ergonomics-relevant data. Specifically, the IMUs being placed on a full body suit, these data covered the full body, including also the hands (15 IMUs on the body and 7 on each hand). The mocap system was connected to a personal computer via a WIFI connection (this was possible because all the sensors communicate with a small portable multi-processing unit that in turn communicated with the personal computer), and the required data were obtained by using the Synertial SynDash software. It should be noted that to obtain reliable ergonomics-relevant data the case-study operator's digital twin was needed (see the previous section for more details), and to do so we used Synertial AutoCal.

The outcome of the *Data Collection Step* consisted of a 758.6-seconds mocap-based recording of the assembly process constituted by 45,519 recording frames (and hence ergonomics-relevant data). These data were then analysed according to the *Data Analysis Step* of the methodological framework. Following the procedure of the *Data Analysis Step*, we divided the mocap-based recording of the whole assembly process into the 17 different assembly tasks. In this way, we were able to evaluate the productivity KPIs and the ergonomics index scores for each assembly task. Specifically, we considered the tasks execution times and the REBA index as the productivity KPI and ergonomics index, respectively. The execution time and the average REBA score of each task are reported in Table 1. It is worth noting that the age of the case-study operator (27 years) was explicitly considered in the ergonomics assessment by means of the age-based multipliers $f_{strength}$ and $f_{flexibility}$, which assumed a value of 1 and 0.98, respectively. Moreover, for the purpose of showing the importance of considering the age of the operators in the ergonomic assessments, in Table 1 we report also the (fictitious) case where the age of the case-study operator was 60 years ($f_{strength}$ and $f_{flexibility}$ equal to 0.77 and 0.75, respectively). As can be seen, this has a marked impact on the ergonomic assessments, and this can be clarified even better if the distribution of the ergonomic scores is considered (see

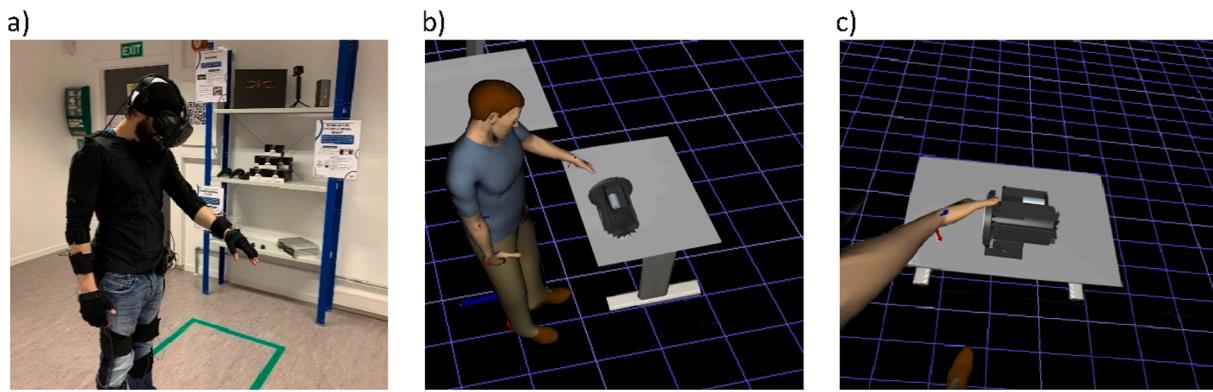


Fig. 3. Detail of the virtual assembly: operator equipped with the mocap system and VR (a), (b) virtual operator (c) view of the assembly operation in VR.

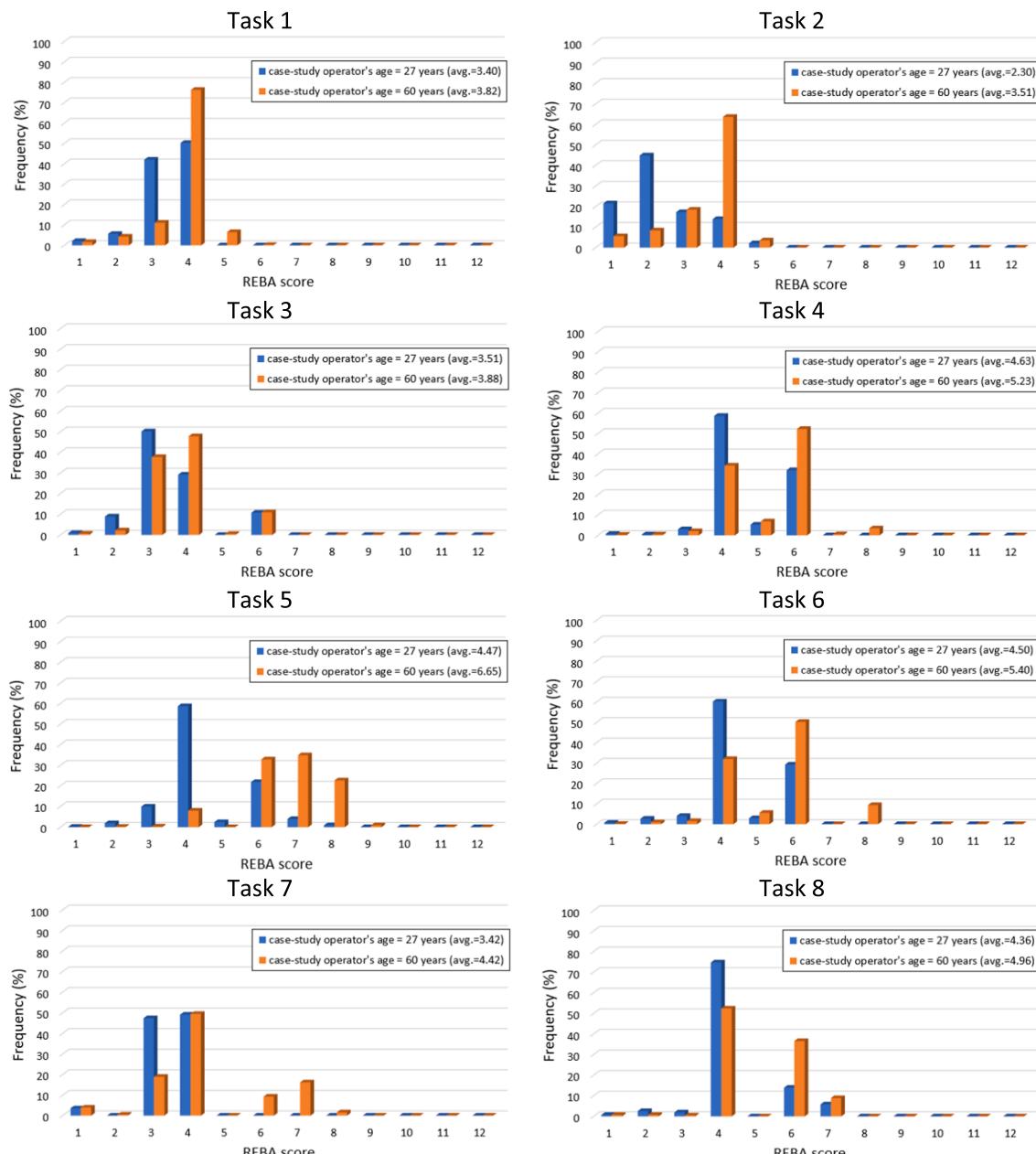


Fig. C1. REBA scores (average and distribution) for each task considering the real age (blue histograms) or a higher fictitious age (orange histograms) of the case-study operator in the ergonomic assessments of the as-is configuration.

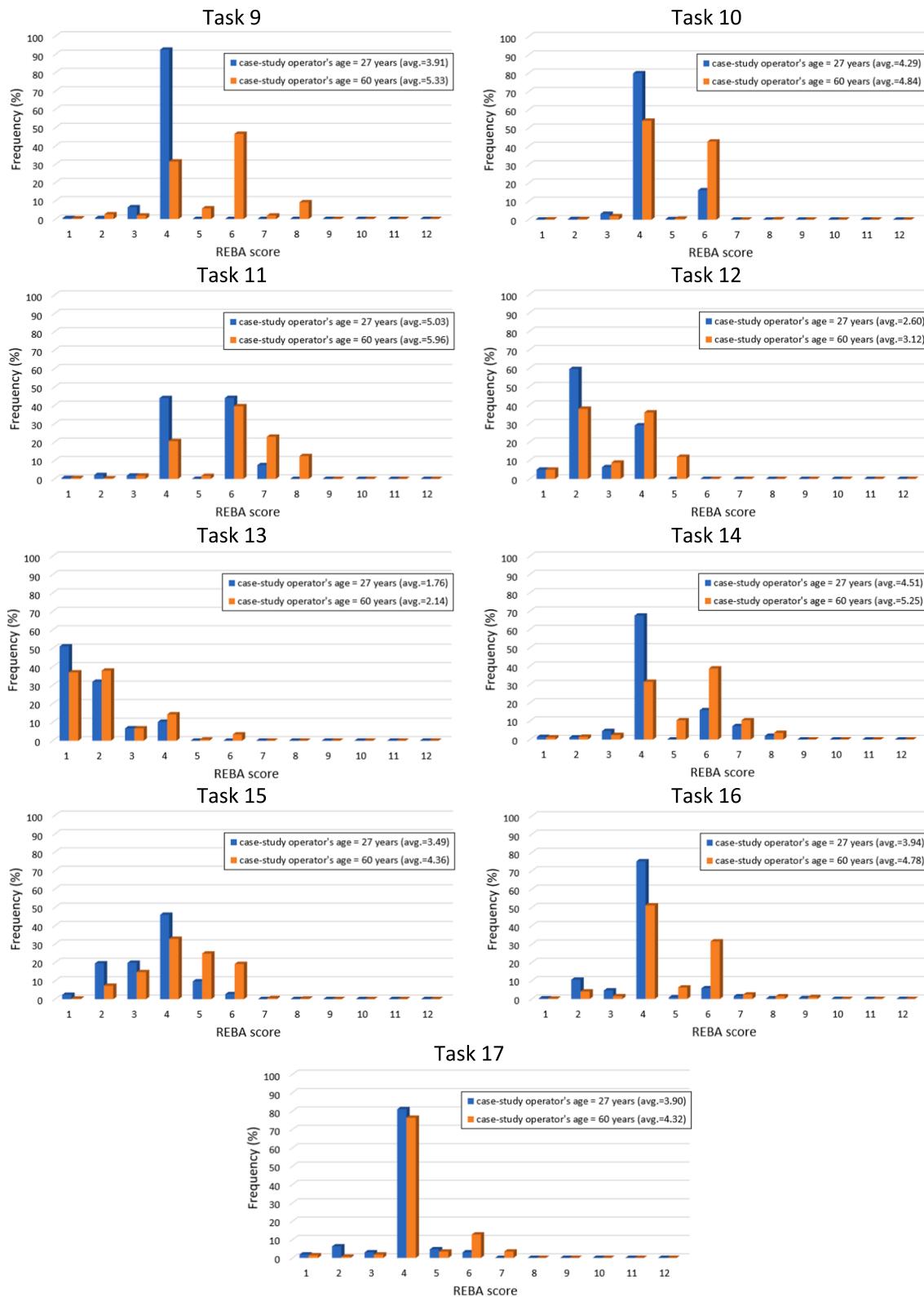


Fig. C1. (continued).

Fig. C.1 in Appendix C). Therefore, as suggested in the methodological framework, in the following, we will consider the age of the case-study operator equal to 60 years when dealing with any ergonomic consideration. Moreover, as reported in the *Data Analysis Step*, we analysed jointly the mocap-based recording of each task and the REBA scores of each frame constituting that specific task to identify the subtasks that

present a high ergonomic risk (i.e., REBA score equal to or higher than 8) and how these are linked to the AS workplace layout. Furthermore, while doing so, we evaluated the value-added ratio for each task (which are also reported in Table 1) and we determined the unproductive activities responsible for low value-added ratios, as well as their link to the AS workplace layout.

It was hence possible to identify the tasks that reduced the productivity (i.e., tasks with low value-added ratios) and the operators' well-being (i.e., tasks with high ergonomic risks), which are:

- For productivity: tasks 5, 8, 9, 12, 14, 15, 16 and 17
- For operators' wellbeing: tasks 4, 5, 6, 7, 9, 11, 14 and 16

Moreover, we identified also the subtasks responsible for these criticalities and we linked them to the AS workplace layout, finding that they were mainly due to the location of the components.

After collecting this information, we were then able to proceed with the redesign of the AS workplace according to the methodological framework developed herein. In the following, we will describe in detail the procedures carried out in the different steps of the methodological framework. Specifically, since we applied the methodological framework for a redesign (that we said before to be equivalent to a second iteration) we will discuss only Steps 2–5.

4.1. Step 2 – Workplace design

In this Step, the AS workplace was redesigned virtually using Siemens Jack™. Specifically, we adopted Siemens Jack™ to model the 3D environment because it can interact with the mocap system and with the VR available in the Logistic 4.0 Lab (Synertial mocap and HTC VIVE™, respectively). The redesign procedures were carried out by a postdoctoral fellow in digital production and logistics systems, together with a full professor in industrial logistics. The former assumed the role of the AS workplace designer, modelling the 3D environment, while the latter assumed the role of the experienced operator, providing advice to the AS workplace designer concerning the AS workplace layout. Specifically, to provide meaningful advice, the information obtained from the analysis of the as-is configuration, in which there were tasks decreasing the productivity and the operators' well-being, as well as subtasks that were responsible for these criticalities and their link to the AS workplace layout, was crucial. Having ascertained that the inadequate location of certain components was the main cause of the low value-added ratios and high ergonomic risks of the activities reported above, the full professor was able to identify some improvement actions. Specifically, when providing his advice, the full professor adopted the holistic approach mentioned in the methodological framework, considering the repercussions that repositioning components and tools (and modifying the AS workplace layout in general) to increase the value-added ratio of a certain task could have on the ergonomic risk level of that task (and vice versa) and on the productivity and operators' well-being of the whole assembly process. Some examples of advice were that:

- adjusting the height of the workstation could reduce the ergonomic risks in tasks 4 and 14, with no impact on the productivity (or on that task or the whole assembly process);

- the relocation of the components necessary to reduce the ergonomic risks in tasks 6, 7 and 11 could slightly affect the productivity (slightly higher task execution time); however, relocating these components allows an increase in the overall productivity of the assembly process since the repositioning of other components is then possible.

Based on these and other suggestions from the full professor, the workplace was then virtually designed in approx. 5 h.

4.2. Step 3 – Data collection

This step was already described in detail when dealing with the as-is configuration, but its main parts will now be summarised.

The assembly process was carried out virtually by the case-study operator equipped with the mocap system and with the VR available in the Logistic 4.0 Lab (i.e., Synertial mocap and HTC VIVE™,

Table 2

Execution time, average REBA score and value-added ratio for each task in the redesigned configuration.

Task	Task execution time (s)	Average REBA score		Value-added ratio (%)
		Age = 27	Age = 60	
1	20.9	3.48	3.92	56.7
2	8.3	3.62	3.84	52.4
3	12.9	4.37	4.67	70.0
4	70.7	4.22	4.78	56.0
5	52.3	4.27	5.12	63.3
6	69.5	3.88	3.97	60.3
7	6.9	3.35	3.84	70.6
8	13.5	2.79	2.97	55.3
9	9.3	3.10	4.17	61.0
10	78.1	3.19	3.87	58.6
11	64.3	4.06	4.13	67.4
12	13.1	3.35	3.75	68.9
13	17.3	3.54	3.91	68.6
14	38.2	3.58	3.87	70.5
15	49.3	3.48	4.17	52.1
16	98.0	3.57	4.10	57.9
17	19.0	3.74	3.80	61.5
Total	641.6	3.74	4.24	60.6

respectively) (Fig. 3). It is worth recalling that the case-study operator was trained for 2 h the day before collecting the data in order to familiarise himself or herself with the VR and to learn how to interact with the 3D modelled environment.

The assembly process was recorded through the mocap system, which allows recording of the assembly operations and the ergonomics-relevant data. Specifically, the mocap-based recording was 641.6 s long and consisted of 38,493 recording frames (and hence ergonomics-relevant data).

It is worth noting that to collect useful and reliable data it is necessary to have the digital twin of the case-study operator in order to ensure that the anthropometric data of the physical and virtual operator correspond. However, this time it was not necessary to develop it again since it was already available from the assessment of the as-is configuration.

4.3. Step 4 – Data analysis

The outcome of Step 3 (a 641.6-seconds mocap-based recording of the assembly process constituted by 38,493 recording frames and as many sets of ergonomics-relevant data) was then divided into the 17 different assembly tasks and analysed in terms of task execution times and the REBA index (the chosen productivity KPI and the ergonomics index, respectively) (Table 2), lasting approx. 2 h. Again, to further emphasise the importance of considering the age of the operators in the ergonomic assessments through the age-based multipliers, we report in Table 2 the average REBA score for each activity considering two ages of the case-study operator, i.e., the real one (27) and the fictitious one (60). More details of the ergonomic assessments can be found in Fig. C.2 in Appendix C.

4.4. Step 5 – Ergo-productivity satisfaction

In this step, according to the methodological framework, the productivity KPI and the ergonomic scores have to be compared with the company's requirements (or any other requirement) to evaluate whether the AS workplace design is satisfactory or not. However, since our case study was not carried out in collaboration with any company but in the Logistic 4.0 Lab in order to illustrate the use of the methodological framework and to prove its validity, we did not have any benchmark values. Therefore, we simply evaluated whether the

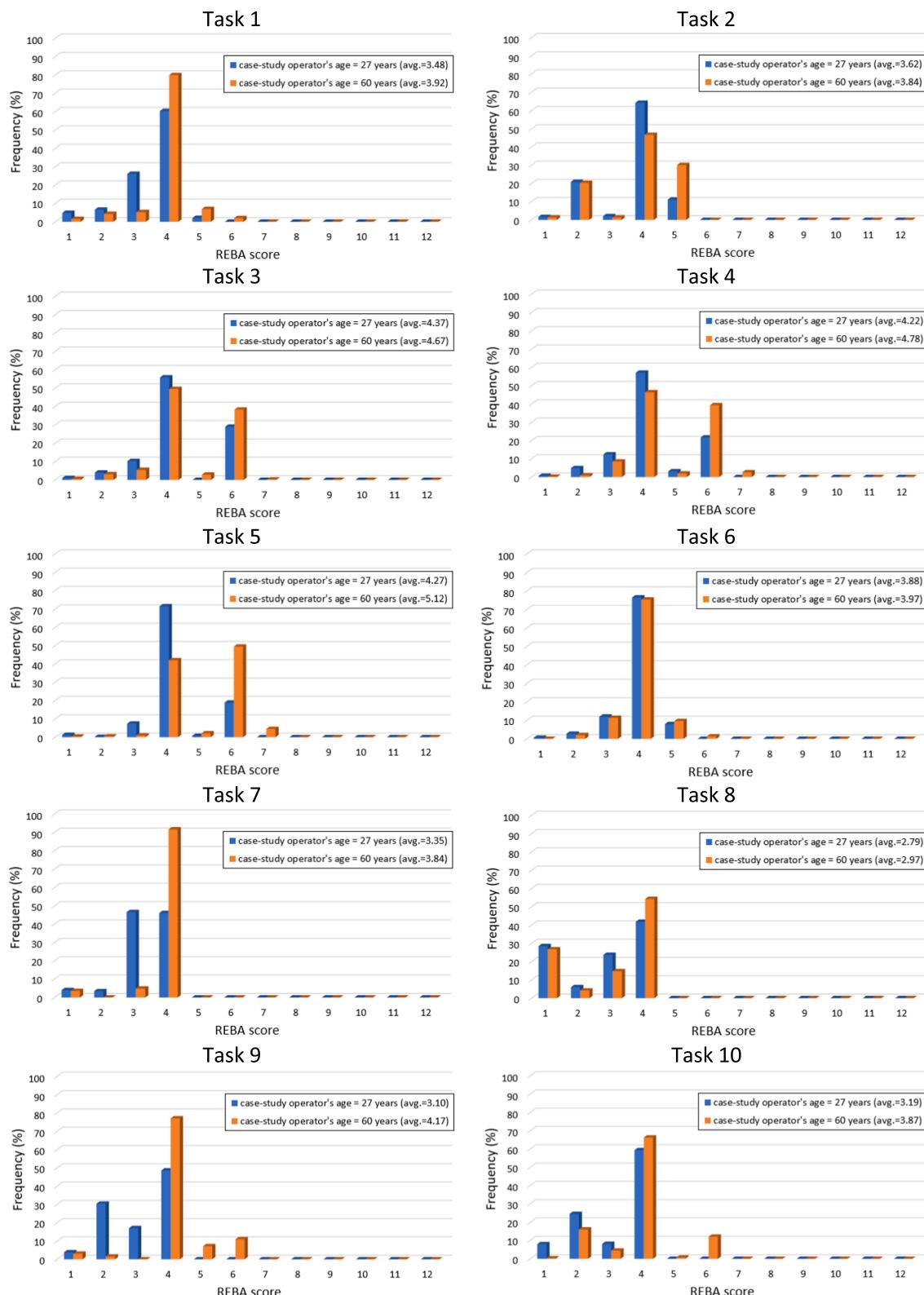


Fig. C2. REBA scores (average and distribution) for each task considering the real age (blue histograms) or a higher fictitious age (orange histograms) of the case-study operator in the ergonomic assessments of the redesigned configuration.

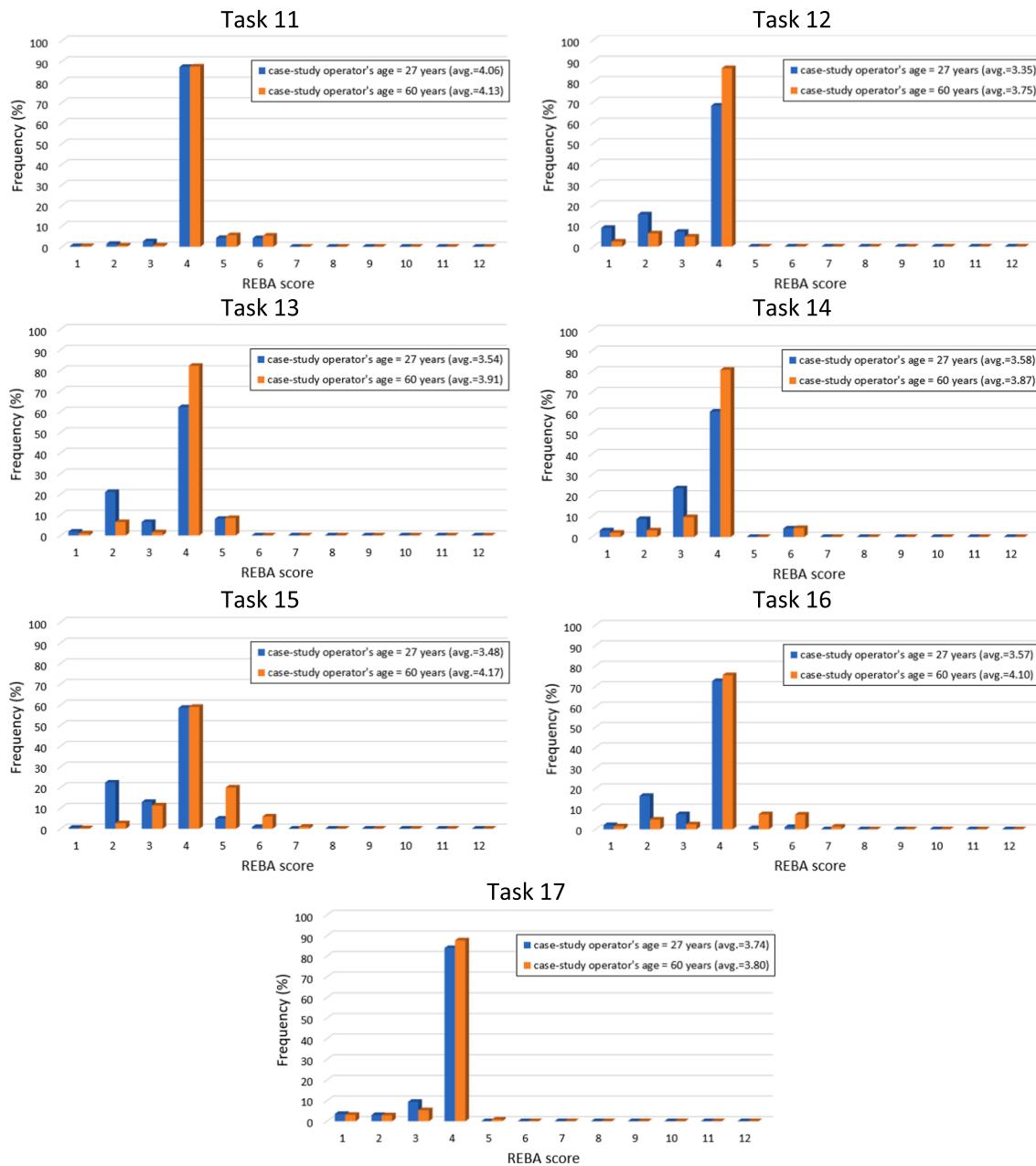


Fig. C2. (continued).

redesigned AS workplace performed better than the as-is configuration with respect to both productivity and operators' wellbeing (a comparison of the as-is and redesigned configuration is reported in Table 3). From the analysis of the task execution times it emerges that, although some tasks are characterised by higher execution times (tasks 1, 2, 6, 7, 10, 11 and 13), the total assembly time in the redesigned configuration is lower than in the as-is configuration (758.6 vs 641.6 s). The methodological framework developed herein, in fact, allowed us to identify the unproductive activities (e.g., travelling to pick the right tool, moving to pick the right component, etc.) and their causes (i.e., many components and tools were stored in locations which were not optimal). This information was then used by the experienced operator (i.e., the full professor in industrial logistics in our case study) to provide advice on how to eliminate and/or reduce some of these unproductive activities (hence the higher value-added ratios in the redesigned configuration). However, while giving this advice, the experienced operator had to make some trade-off decisions, penalising the execution times of some

tasks to favour the total assembly time. This is part of the holistic approach mentioned in the methodological framework, where each task is not considered as a single entity, but as a part of a wider context.

Moreover, since the holistic approach jointly considers productivity and ergonomics, the overall operators' wellbeing was also increased. In fact, although some tasks are characterised by a higher average REBA score in the redesigned configuration (tasks 1, 2, 3, 12 and 13), the overall average REBA score decreased. Furthermore, no tasks with high ergonomic risks (i.e., REBA score equal to 8 or higher) were present in the redesigned configuration (Figs. C.1 and C.2 in Appendix C).

It is worth reiterating the importance of considering the age of the operator in the ergonomic considerations. As can be seen from Tables 1-3, considering different ages of the case-study operator through the age-based multipliers had a marked impact on the REBA scores: for example, the average REBA score of task 5 in the as-is configuration moved from 4.47 to 6.65 by considering the age of the case-study operator equal to 60 instead of 27 years. The effects of considering the case-study

Table 3

Tasks execution times, REBA average scores (both considering the age of the case-study operator equal to 27 years and 60 years) and value-added ratios in the as-is and redesigned configuration.

Task	Task execution time (s)		Average REBA score				Value-added ratio (%)	
			Age = 27		Age = 60			
	As-is	Redesigned	As-is	Redesigned	As-is	Redesigned	As-is	Redesigned
1	19.0	20.9	3.40	3.48	3.82	3.92	62.2	56.7
2	7.2	8.3	2.30	3.62	3.51	3.84	60.3	52.4
3	14.5	12.9	3.51	4.37	3.88	4.67	62.0	70.0
4	72.6	70.7	4.63	4.22	5.23	4.78	54.5	56.0
5	87.5	52.3	4.47	4.27	6.65	5.12	37.8	63.3
6	62.0	69.5	4.50	3.88	5.40	3.97	67.6	60.3
7	6.3	6.9	3.42	3.35	4.42	3.84	77.1	70.6
8	18.0	13.5	4.36	2.79	4.96	2.97	41.5	55.3
9	19.4	9.3	3.91	3.10	5.33	4.17	29.3	61.0
10	75.8	78.1	4.29	3.19	4.84	3.87	60.4	58.6
11	62.5	64.3	5.03	4.06	5.96	4.13	69.3	67.4
12	22.2	13.1	2.60	3.35	3.12	3.75	40.6	68.9
13	16.2	17.3	1.76	3.54	2.14	3.91	73.2	68.6
14	56.1	38.2	4.51	3.58	5.25	3.87	48.0	70.5
15	59.1	49.3	3.49	3.48	4.36	4.17	43.4	52.1
16	132.1	98.0	3.94	3.57	4.78	4.10	43.0	57.9
17	28.1	19.0	3.90	3.74	4.32	3.80	41.7	61.5
Total	758.6	641.6	4.12	3.74	4.97	4.24	51.2	60.6

operator's age are even more evident if Fig. C1–C2 in Appendix C are considered: many tasks that did not involve high ergonomic risk when the case-study operator was considered young (age = 27 years) became high-risk when he was considered old (age = 60 years). Therefore, as reported in the methodological framework, the ergonomics assessment should always include the age of the operator. But the highest age should be considered when designing an AS workplace not only because it allows consideration of the fact that some activities might not be of high ergonomic risk for young operators, but because they might become so when the age increases.

5. Conclusion

In this paper, we answered the need for a clear description of the methodology that needs to be followed when designing an AS workplace using the mocap system and VR. The combined use of the mocap system and VR has, in fact, emerged as a breakthrough in AS workplace design, since it makes it possible to overcome the main limitations of the currently used AS workplace design procedures. For example, the combined use of the mocap system and VR does not require the large amount of time and resources needed by the traditional AS workplace design procedure (i.e. the construction of a physical workplace mock-up) to optimise the AS workplace design, since several AS workplace designs can be easily and rapidly created and tested digitally. Moreover, the use of the mocap system and VR can also overcome the main limitation of computer-aided systems (i.e. ergonomic assessments not fully representative of the reality) since the mocap system allows the creation of a digital copy of the operator that is a truthful representation of the reality. However, prior to our work, it was still unclear how best to use them for AS workplace design in order to fully exploit their enormous potentialities, especially when aiming to maximise the AS workplace design considering both the productivity and the operators' wellbeing. The methodological framework developed herein solved this issue, providing five simple steps that can be followed when designing an AS workplace with the mocap system and VR. Moreover, the methodological framework makes it possible to consider the current labour market, since it provides the possibility to include ageing workers and their

associated benefits and drawbacks in the AS workplace design procedure. Furthermore, the methodological framework allows both the productivity and operators' wellbeing to be maximised considering a holistic approach.

The validity of the methodological framework has been proved by means of a simple but representative case study. The methodological framework was successfully applied to the redesign of the AS workplace of a medium/high size pump. Specifically, the task assembly times were reduced by around 15%, and the ergonomic risks were also reduced from high to medium. Fundamental for these achievements was the detailed data analysis step described in the methodological framework, which made it possible to easily identify the tasks that were critical for the productivity and for the operators' wellbeing. Moreover, the possibility to design the workplace virtually halves the time spent on building the AS workplace (the digital AS workplace was built in approx. 5 h, while the physical one in approx. 10 h).

However, to prove its validity further, the methodological framework needs to be applied in other case studies, where real industrial applications, bigger sample sizes (meaning the number of operators considered) and the repetitiveness of the data are considered. Nevertheless, the potentialities of the methodological framework have been shown to be considerable, and they will be further investigated in the future in order to overcome the main limitations just described.

CRediT authorship contribution statement

Marco Simonetto: Investigation, Conceptualization, Writing – original draft, Software, Methodology. **Simone Arena:** Methodology, Conceptualization, Writing – review & editing. **Mirco Peron:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft.

Declaration of Competing Interest

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

Appendix A

Here we will show how to include the age-based multipliers $f_{strength}$ and $f_{flexibility}$ in the ergonomic assessment. We will limit our demonstration to the REBA index, but the same procedure can be applied to any other ergonomic index containing allowable joint angle limits.

REBA is an ergonomic index used to evaluate the ergonomic risks of the whole body, assigning a score to the following body regions: neck, trunk, legs, upper and lower arms, and wrists. The former three are evaluated in the so-called body segment section A, while the latter three in the so-called body segment section B. The scores of the two body segments are modified considering additional adjustments and then combined to obtain the ergonomic risk. Specifically, the assessment of the body segment section A consists of six steps:

1. Locate neck position,
2. Locate trunk position,
3. Locate legs position,
4. Look-up posture score in Table A,
5. Add force/load score,
6. Score A,

similarly to the body segment section B:

7. Locate upper arm position,
8. Locate lower arm position,
9. Locate wrists position,
10. Look-up posture score in Table B,
11. Add coupling score,
12. Score B

The age-based multipliers need to be considered in Steps 1–3, 5, 7–9, specifically $f_{strength}$ in Step 5, while $f_{flexibility}$ in the others. Considering first $f_{strength}$, Step 5 in the traditional REBA corresponds to the following:

$$\begin{cases} \text{if } load < 11\text{lbs.} = +0 \\ \text{if } load 11 \text{to} 22\text{lbs.} = +1 \\ \text{if } load > 22\text{lbs.} = +2 \end{cases}$$

Step 5 in the REBA, modified to include age considerations by introducing the age-based multiplier $f_{strength}$, corresponds to:

$$\begin{cases} load < (11 \cdot f_{strength})\text{lbs.} = +0 \\ load(11 \cdot f_{strength}) \text{to} (22 \cdot f_{strength})\text{lbs.} = +1 \\ load > (22 \cdot f_{strength})\text{lbs.} = +2 \end{cases}$$

Similarly for $f_{flexibility}$. Considering as an example Step 1, the traditional REBA is:

$$\begin{cases} load < (11 \cdot f_{strength})\text{lbs.} = +0 \\ load(11 \cdot f_{strength}) \text{to} (22 \cdot f_{strength})\text{lbs.} = +1 \\ load > (22 \cdot f_{strength})\text{lbs.} = +2 \end{cases}$$

Modifying Step 1 to include age considerations through the age-based multiplier $f_{flexibility}$ leads to:

$$\begin{cases} neckangle < 0^\circ = +2 \\ 0^\circ \leq neckangle \leq 10^\circ \cdot f_{flexibility} = +0 \\ 10^\circ \cdot f_{flexibility} < neckangle \leq 20^\circ \cdot f_{flexibility} = +1 \\ neckangle > 20^\circ \cdot f_{flexibility} = +2 \end{cases}$$

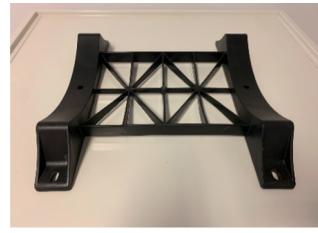
Similarly for Steps 2, 3 and 7–9.

Appendix B

In Table B1, the 25 different components constituting the pump used in the case study are gathered, while in Table B2 the different tasks are described.

Table B1

Components constituting the pump.

Tank	Square nuts	Caps
		
Engine	Pump base	Tank support
		
Valve	Fan cover	Small screws
		
Hydraulic cover	Rubber O-ring	Hoop
		
Long circular screw	Nut type 2	Metallic tube
		
Pressure gauge	Electrical housing cover	Long shank screws
		

(continued on next page)

Table B1 (continued)

Tank	Square nuts	Caps
Electrical components	Phillips head screws	Internal grey ring
		
Square screws	Long shank Phillips screws	Metallic disc
		
Square gasket		
		

Table B2

Tasks description.

Task number	Task description
1	Assembly of the <i>pressure gauge</i> on the <i>metal tube</i>
2	Assembly of the <i>metallic disc</i> on the <i>electrical components</i>
3	Assembly of the <i>square gasket</i> on the <i>electrical components</i>
4	Assembly of the <i>metallic tube</i> on the <i>electrical components</i> (using <i>Long shank Phillips screws</i>)
5	Assembly of the <i>electrical components</i> on the <i>engine</i> (using <i>Phillips head screws</i>)
6	Assembly of the <i>electrical housing cover</i> on the <i>electrical components</i> (using <i>long shank screws</i>)
7	Assembly of the <i>internal grey ring</i> on the <i>engine</i>
8	Assembly of the <i>valve</i> on the <i>hydraulic cover</i>
9	Assembly of the <i>rubber O-ring</i> on the <i>engine</i>
10	Assembly of the <i>hydraulic cover</i> (with the <i>valve</i> in it) on the <i>engine</i> , using the <i>hoop</i> (and the <i>long circular screw</i> and <i>nut type 2</i>)
11	Assembly of the <i>fan cover</i> on the <i>engine</i> (with <i>small screws</i>)
12	Assembly of the <i>metallic tube</i> on the <i>hydraulic cover</i>
13	Assembly of the <i>caps</i> on the <i>metallic tube</i> and on the <i>hydraulic cover</i>
14	Assembly of the <i>tank</i> on the <i>tank support</i> (with two of the <i>square nuts</i>)
15	Assembly of the <i>pump base</i> on the <i>tank</i> (with two of the <i>square nuts</i>)
16	Assembly of the <i>engine</i> on the <i>pump base</i> (with <i>square screws</i>)
17	Assembly of the <i>metallic tube</i> on the <i>tank</i>

Appendix C

Fig. C1 reports the REBA scores (average and distribution) for each task. To show the importance of considering the age of the operators in the ergonomic assessments, we carried out these assessments considering both the real age of the case-study operator (27 years, blue histograms) and a higher, fictitious age (60 years, orange histograms).

Fig. C2 reports the REBA scores (average and distribution) for each task considering both the real age of the case-study operator (27 years, blue histograms) and a higher, fictitious age (60 years, orange histograms).

References

- Abubakar, M.I., Wang, Q., 2019. Key human factors and their effects on human centered assembly performance. *Int. J. Ind. Ergon.* 69, 48–57.
- Alessandri, G., Truxillo, D.M., Tisak, J., Fagnani, C., Borgogni, L., 2020. Within-individual age-related trends, cycles, and event-driven changes in job performance: a career-span perspective. *J. Bus. Psychol.* 35 (5), 643–662.
- Arena, S., Roda, I., Chiacchio, F., 2021. Integrating modelling of maintenance policies within a stochastic hybrid automaton framework of dynamic reliability. *Appl. Sci.* 11 (5), 2300.
- Arena, S., Florian, E., Orrù, P.F., Sgarbossa, F., Zennaro, I., A novel Decision Support System for managing predictive maintenance strategies based on Machine Learning approaches. *Safety Science*, 2021, Article in press.
- Balderrama, C., Flores, J., Maldonado, A., 2015. The effects of age to meet the standard production rate. *Work*, 51(4), pp.827-837.
- Battaia, O., Otto, A., Sgarbossa, F., Pesch, E., 2018. Future trends in management and operation of assembly systems: from customized assembly systems to cyber-physical systems. *Omega* 78 (July), 1–4. <https://doi.org/10.1016/j.omega.2018.01.010>.
- Battini, D., Faccio, M., Persona, A., Sgarbossa, F., 2011. New methodological framework to improve productivity and ergonomics in assembly system design. *Int. J. Ind. Ergon.* 41 (1), 30–42.
- Battini, D., Finco, S. and Sgarbossa, F., 2020. Human-Oriented Assembly Line Balancing and Sequencing Model in the Industry 4.0 Era. In *Scheduling in Industry 4.0 and Cloud Manufacturing* (pp. 141-165). Springer, Cham.
- Battini, D., Persona, A., Sgarbossa, F., 2014. Innovative real-time system to integrate ergonomic evaluations into warehouse design and management. *Comput. Ind. Eng.* 77, 7–10.
- Battini, D., Calzavara, M., Persona, A., Sgarbossa, F., Visentini, V. and Zennaro, I., 2018. Integrating mocap system and immersive reality for efficient human-centred workstation design. *IFAC-PapersOnLine*, 51(11), pp.188-193.
- Bauer, W., Lorenz, D., 1985. *New Methods of Ergonomic Work Design. In Toward the Factory of the Future*. Springer, Berlin, Heidelberg, pp. 897–902.
- Bortolini, M., Faccio, M., Gamberi, M., Pilati, F., 2020. Motion Analysis System (MAS) for production and ergonomics assessment in the manufacturing processes. *Comput. Ind. Eng.* 139, 105485. <https://doi.org/10.1016/j.cie.2018.10.046>.
- Bortolini, M., Ferrari, E., Gamberi, M., Pilati, F., Faccio, M., 2017. Assembly system design in the Industry 4.0 era: a general framework. *IFAC-PapersOnLine* 50 (1), 5700–5705.
- Börsch-Supan, A., Weiss, M., 2016. Productivity and age: evidence from work teams at the assembly line. *The Journal of the Economics of Ageing* 7, 30–42.
- Bouma, H., 2013. Accommodating older people at work. *Gerontechnology* 11 (4), 489–492.
- Bures, M., Simon, M., 2015. Adaptation of production systems according to the conditions of ageing population. *MM Sci. J.* 2015 (02), 604–609.
- Burggräf, P., Kampker, A., Kreisköther, K., Adlon, T., Riegauf, A., Dorn, B., Casla, P., Marguglio, A. and Donvito, G., 2019, July. Enabling Smart Workplaces by Implementing an Adaptive Software Framework. In *International Conference on Applied Human Factors and Ergonomics* (pp. 116-127). Springer, Cham.
- Calzavara, M., Battini, D., Bogataj, D., Sgarbossa, F., Zennaro, I., 2020. Ageing workforce management in manufacturing systems: state of the art and future research agenda. *Int. J. Prod. Res.* 58 (3), 729–747.
- Caputo, F., Greco, A., Egidio, D.A., Notaro, I. and Spada, S., 2017, July. A preventive ergonomic approach based on virtual and immersive reality. In *International Conference on Applied Human Factors and Ergonomics* (pp. 3-15). Springer, Cham.
- Caputo, F., Greco, A., Fera, M., Macchiaroli, R., 2019. Digital twins to enhance the integration of ergonomics in the workplace design. *Int. J. Ind. Ergon.* 71, 20–31.
- Cavatorta, M., Dipardo, M., 2009. Improving the ergonomics of the workplace to enhance productivity and safety. In *Indoor Work Living Environ. Heal. Saf. Perform.*, chapter 8, pages 293–306.
- Cohen, Y., Naseraldin, H., Chaudhuri, A., Pilati, F., 2019. Assembly systems in Industry 4.0 era: a road map to understand Assembly 4.0. *Int. J. Adv. Manufact. Technol.* 105 (9), 4037–4054.
- Cote, M., Kenny, A., Dussetschleger, J., Farr, D., Chaurasia, A., Cherniack, M., 2014. Reference values for physical performance measures in the aging working population. *Hum. Factors* 56 (1), 228–242.
- Das, B., Sengupta, A.K., 1996. Industrial workstation design: a systematic ergonomics approach. *Appl. Ergon.* 27 (3), 157–163.
- Di Pardo, M., Riccio, A., Sessa, F., Naddeo, A. and Talamo, L., 2008. Methodology development for ergonomic analysis of work-cells in virtual environment (No. 2008-01-1481). SAE Technical Paper.
- Di Pasquale, V., Miranda, S., Neumann, W.P., 2020. Ageing and human-system errors in manufacturing: a scoping review. *Int. J. Prod. Res.* 58 (15), 4716–4740.
- Dolgui A., Sgarbossa F., Simonetto M., 2021. Design and management of assembly systems 4.0: systematic literature review and research agenda. *International Journal of Production Research*. DOI is: 10.1080/00207543.2021.1990433.
- Eswaramoorthi, M., John, M., Rajagopal, C.A., Prasad, P.S.S., Mohanram, P.V., 2010. Redesigning assembly stations using ergonomic methods as a lean tool. *Work* 35 (2), 231–240.
- Faccio, M., Gamberi, M., Piana, F. and Pilati, F., 2017. Motion analysis system for the ergonomic assessment of manufacturing and assembly manual activities. Proceedings of the Proceedings of XXII Summer School “Francesco Turco”, Palermo, Italy, pp.13-15.
- Fager, P., Calzavara, M., Sgarbossa, F., 2020. Modelling time efficiency of cobot-supported kit preparation. *Int. J. Adv. Manufact. Technol.* 106 (5-6), 2227–2241.
- Feldmann, K., Junker, S., 2003. Development of new concepts and software tools for the optimization of manual assembly systems. *CIRP Ann.* 52 (1), 1–4.
- Giacomin, J., 2014. What is human centred design? *Des. J.* 17 (4), 606–623.
- Göbel, C., Zwick, T., 2009. Age and productivity—Evidence from linked employer employee data. ZEW-Centre for European Economic Research Discussion Paper, (09-020).
- Hanson, T., Lindgren, P.Y., 2020. No country for old men? Increasing the retirement age in the Norwegian armed forces. *Def. Peace Econ.* 1–26.
- Holubek, R., Ružárovský, R., 2014. The methods for increasing of the efficiency in the intelligent assembly cell. In *Applied Mechanics and Materials* (Vol. 470, pp. 729–732). Trans Tech Publications Ltd.
- Ilmarinen, J.E., 2001. Aging workers. *Occupational and environmental medicine*, 58(8), pp.546-546.
- Jayaram, U., Jayaram, S., Shaikh, I., Kim, YoungJun, Palmer, C., 2006. Introducing quantitative analysis methods into virtual environments for real-time and continuous ergonomic evaluations. *Comput. Ind.* 57 (3), 283–296.
- Jones, M.K., Latrelle, P.L., Sloane, P.J., Staneva, A.V., 2013. Work-related health risks in Europe: are older workers more vulnerable? *Soc. Sci. Med.* 88, 18–29. <https://doi.org/10.1016/j.socscimed.2013.03.027>.
- Kim, J., 2019. Aging Workforce, Firm Productivity and Labor Costs in Korea: Are Older Workers Costly to Firms? *Asian Econ. J.* 33 (2), 115–142.
- Kim, S.E., Junggi Hong PhD, A.T.C., 2013. Ergonomic interventions as a treatment and preventative tool for work-related musculoskeletal disorders. *International Journal of Caring Sciences*, 6(3), p.339.
- Kowalski-Trakofler, K.M., Steiner, L.J., Schwerha, D.J., 2005. Safety considerations for the aging workforce. *Saf. Sci.* 43 (10), 779–793.
- Landau, Kurt, Rademacher, Holger, Meschke, Herwig, Winter, Gabriele, Schaub, Karlheinz, Grasmueck, Marc, Moelbert, Ingo, Sommer, Michael, Schulze, Jens, 2008. Musculoskeletal disorders in assembly jobs in the automotive industry with special reference to age management aspects. *Int. J. Ind. Ergon.* 38 (7-8), 561–576.
- Launis, M., Vuori, M., Lehtelä, J., 1996. Who is the workplace designer?—Towards a collaborative mode of action. *Int. J. Ind. Ergon.* 17 (4), 331–341.
- Makris, Sotiris, Karagiannis, Panagiotis, Koukas, Spyridon, Matthaiakis, Aleksandros-Stereos, 2016. Augmented reality system for operator support in human–robot collaborative assembly. *CIRP Annals – Manufact. Technol.* CIRP 65 (1), 61–64. <https://doi.org/10.1016/j.cirp.2016.04.038>.
- Michalos, George, Karvouniar, Anna, Dimitropoulos, Nikolaos, Togias, Theodoros, Makris, Sotiris, 2018. Workplace analysis and design using virtual reality techniques. *CIRP Ann.* 67 (1), 141–144.
- Naddeo, A., Cappetti, N., Califano, R., Vallone, M., 2014. Manual assembly workstation redesign based on a new quantitative method for postural comfort evaluation. In *Applied Mechanics and Materials* (Vol. 459, pp. 368-379). Trans Tech Publications Ltd.
- Neubert, N., Bruder, R., Toledo, B., 2012. The charge of ergonomics—A model according to the influence of ergonomic workplace design for economical and efficient indicators of the automotive industry. *Work* 41 (Supplement 1), 4389–4395.
- OECD, 2015. *OECD Employment Outlook 2015*. OECD Publishing, Paris.
- Orrù, P.F., Zoccheddu, A., Sassi, L., Mattia, C., Cozza, R., Arena, S., 2020. Machine learning approach using MLP and SVM algorithms for the fault prediction of a centrifugal pump in the oil and gas industry. *Sustainability* 12 (11), 4776.
- Oyekan, John, Prabhu, Vinayak, Tiwari, Ashutosh, Baskaran, Vinubha, Burgess, Mark, McNally, Rob, 2017. Remote real-time collaboration through synchronous exchange of digitised human–workpiece interactions. *Fut. Generat. Comput. Syst.* 67, 83–93.
- Peng, Lu, Chan, Alan H.S., 2019. A meta-analysis of the relationship between ageing and occupational safety and health. *Saf. Sci.* 112, 162–172.
- Peng, L., Chan, A.H., 2020. Adjusting work conditions to meet the declined health and functional capacity of older construction workers in Hong Kong. *Safety science* 127, 104711.
- Pennathur, Arunkumar, Contreras, Luis Rene, Arcuate, Karina, Dowling, Winifred, 2003. Manual dexterity of older Mexican American adults: a cross-sectional pilot experimental investigation. *Int. J. Ind. Ergon.* 32 (6), 419–431.
- Peron, M., Sgarbossa, F., Strandhagen, J.O., 2020. Decision support model for implementing assistive technologies in assembly activities: a case study. *Int. J. Prod. Res.* 1–27.
- Peruzzini, Margherita, Carassai, Stefano, Pellicciari, Marcello, 2017. The benefits of human-centred design in industrial practices: re-design of workstations in pipe industry. *Procedia Manuf.* 11, 1247–1254.
- Prabhu, Vinayak Ashok, Song, Boyang, Thrower, John, Tiwari, Ashutosh, Webb, Phil, 2016. Digitisation of a moving assembly operation using multiple depth imaging sensors. *Int. J. Adv. Manufact. Technol.* 85 (1-4), 163–184.
- Porta, M., Arena, S., Fiori, V.L., Pau, M., Orrù, P.F., 2020. Assessment of ergonomic risk in industrial field: Analysis of the operators' body postures through wearable sensors. *Proceedings of the XXV Summer School ‘Francesco Turco’*, 259899.
- Qin, Jin, Lin, Jia-Hua, Buchholz, Bryan, Xu, Xu, 2014. Shoulder muscle fatigue development in young and older female adults during a repetitive manual task. *Ergonomics* 57 (8), 1201–1212.
- Realyvásquez-Vargas, A., Arredondo-Soto, K.C., Blanco-Fernandez, J., Sandoval-Quintanilla, J.D., Jiménez-Macías, E., García-Alcaraz, J.L., 2020. Work standardization and anthropometric workstation design as an integrated approach to sustainable workplaces in the manufacturing industry. *Sustainability* 12 (9), 3728.
- Riva, Giuseppe, 2002. Virtual reality for health care: the status of research. *Cyberpsychol. Behav.* 5 (3), 219–225.
- Roda, I., Arena, S., Macchi, M., Orrù, P.F., 2019, September. Total Cost of Ownership Driven Methodology for Predictive Maintenance Implementation in Industrial Plants. In *IFIP International Conference on Advances in Production Management Systems* (pp. 315-322). Springer, Cham.

- Roosaar, Liis, Masso, Jaan, Varblane, Urmas, 2019. Age-related productivity decrease in high-waged and low-waged employees. *Int. J. Manpower* 40 (6), 1151–1170.
- Roper, Kathy O., Yeh, Daniel C., 2007. Ergonomic solutions for an aging workforce. *J. Facilities Manage.* 5 (3), 172–178.
- Shephard, Roy J, 2000. Aging and productivity: some physiological issues. *Int. J. Ind. Ergon.* 25 (5), 535–545.
- Schwab, K., 2016. The Fourth Industrial Revolution. Crown Publishing Group, New York.
- Simonetto, M., Peron, M., Fragapane, G., Sgarbossa, F., 2020. In: October. Digital Assembly Assistance System in Industry 4.0 Era: A Case Study with Projected Augmented Reality. Springer, Singapore, pp. 644–651.
- Šíšková, V., Dlabac, J., 2013. Environmental management system as the part of the methodology for optimization of assembly workplaces. *International Journal of Mathematical Models and Methods in Applied Sciences*.
- Strasser, H., 2018. The “art of Aging” From an Ergonomics Viewpoint - Wisdoms on age. *Occup. Ergon.* 13 (S1), 1–24.
- Truxillo, D.M., Cadiz, D.M. and Hammer, L.B., 2015. Supporting the aging workforce: A review and recommendations for workplace intervention research.
- Udosen, U.J., 2007. Computer Aided Construction, Evaluation And Improvement Of A Workplace Assembly Layout Using CADWORK. In Advanced Materials Research (Vol. 18, pp. 353-358). Trans Tech Publications Ltd.
- United Nations, 2018. World Population Ageing 2017 [WWW Document]. URL <https://www.un.org/en/development/desa/population/theme/ageing/WPA2017.asp> (accessed 11.2.20).
- Varianou-Mikellidou, Cleo, Boustras, Georgios, Nicolaidou, Olga, Dimopoulos, Christos, Anyfantis, Ioannis, Messios, Paris, 2020. Work-related factors and individual characteristics affecting work ability of different age groups. *Saf. Sci.* 128, 104755. <https://doi.org/10.1016/j.ssci.2020.104755>.
- Vignais, Nicolas, Miezal, Markus, Blaser, Gabriele, Mura, Katharina, Gorecky, Dominic, Marin, Frédéric, 2013. Innovative system for real-time ergonomic feedback in industrial manufacturing. *Appl. Ergon.* 44 (4), 566–574.
- Vosniakos, G.-C., Deville, J., Matsas, E., 2017. On immersive virtual environments for assessing human-driven assembly of large mechanical parts. *Procedia Manuf.* 11, 1263–1270.
- Wang, K., 2016. Intelligent predictive maintenance (IPdM) system-industry 4.0 scenario. *WIT Trans. Eng. Sci.* 113, 259–268.
- Warnecke, H.J., Haller, E., Warnecke, H.J., 1982. Computer-aided planning of manual assembly workplaces. *CIRP Ann.* 31 (1), 371–375.
- Wolf, M., Ramsauer, C., 2018, August. Towards an Age-Differentiated Assessment of Physical Work Strain. In Congress of the International Ergonomics Association (pp. 189–205). Springer, Cham.
- Zieschang, H., Freiberg, S., 2011, May. ERGONOMIC DESIGN OF WORKPLACES-PREVENTION FOR ALL GENERATIONS. In Contemporary Ergonomics and Human Factors 2011: Proceedings of the international conference on Ergonomics & Human Factors 2011, Stoke Rochford, Lincolnshire, 12-14 April 2011 (p. 299). CRC Press.
- Zha, X.F., Lim, S.Y.E., 2003. Intelligent design and planning of manual assembly workstations: a neuro-fuzzy approach. *Comput. Ind. Eng.* 44 (4), 611–632.