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Impact of Cobot parameters on the worker productivity: Optimization challenge

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A B S T R A C T

In the era of Industry 4.0 and the introduction of new technologies, collaborative workplaces represent the potential to increase the efficiency of manufacturing systems. The presented research focuses on studying the impact of changing the speed and acceleration of a Cobot to the number of finished products at a collaborative workstation, the average assembly time, and the utilization of the Cobot and worker. In a laboratory experiment, it was demonstrated that changing the parameters of the Cobot significantly affects the optimization parameters of the collaborative workstation productivity. The results indicate an increase in production capacity with an increase in the speed and acceleration of the Cobot, while at the same time highlighting the importance of uniform utilization and occupancy of the Cobot and worker. The findings are particularly interesting from the influence of the Cobot's audio and video effects on worker, when reducing the average assembly time while increasing the Cobot's capabilities. The results and findings presented open up important new areas of research in the field of social, time and financial justification of collaborative workplaces.

A R T I C L E   I N F O

Keywords:
Collaborative robot;
Cobot;
Collaborative operation;
Robot parameters;
Worker productivity;
Working scenarios;
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1. Introduction

In the era of Industry 4.0 [1], where the role of making the right decisions in optimizing existing or newly proposed manufacturing system is key to achieving global competitiveness of the company. The optimization of manufacturing systems and its efficiency refers to both machines (technology) and workers (their knowledge and social paradigms) [2, 3]. The correct and equal distribution of occupancy between workers and machines plays a key role in sustainable production systems in terms of social, environmental and financial aspects. Implementing an effective model to acquire new knowledge about technologies that can increase efficiency is crucial [4]. According to the literature [5], classical single-objective approaches do not provide satisfactory solutions, especially when dealing with problems with high market dynamics and continuous optimization trends. Given the global shortage of workers (especially in developed countries), collaborative robots (Cobots) represent a new opportunity for companies willing to invest into new financially feasible technologies. In this case the research question appears: how efficient we can place them into the existing or newly proposed manufacturing system [6]. Proper design of collaborative workplaces (cooperation between worker and Cobot) is the main challenge for researchers and engineers who want to increase manufacturing efficiency [7]. In doing so, we encounter the issues of collaboration safety, time and economic justification, and their impact on the entire manufacturing system under consideration [8]. The researchers point out the importance of using simulation modelling methods [9] that allow us to effectively evaluate the time efficiency of collaborative workplaces from the individual optimization parameters of the system [10] in a real-world industrial environment [11]. Different applications of collaborative workplaces [12] require the use of different optimization approaches [13], where we need to ensure safe and efficient parameters of the collaborative machines (Cobot) due to the specificity of the considered cases [14]. In this case, data-driven predictive models [15] prove to be the most reliable methods, where we use numerical and graphical simulation results to investigate the appropriateness of introducing and correctly determining collaborative machines [16]. Collaborative workplaces and their design in manufacturing systems present new challenges also from the ergonomic design point of view [17, 18], where the classical methods of ergonomic studies do not satisfy the criteria of a collected big data at high production dynamics. The impact of collaborative workplaces on the efficiency of the manufacturing systems [19] and the link with adaptive models [20] to monitor the importance of effective implementations are based on the performance of preliminary studies in which researchers compare simulation and real-world data of manufacturing systems [21]. The major limitation of the existing research is in the area of describing how the parameters of the Cobot affect the efficiency of the co-worker, not only from the worker's point of view, but also with respect to the efficiency of the Cobot and the manufacturing system as a combined unit.

In this research, we address the research question of whether changing the operating parameters of a Cobot affects the efficiency of the manufacturing system and the occupancy of the worker itself. Based on the results, limitations, and issues of previous research works [19, 21], in this paper, we aim to present an experimental method to study the change of speed and acceleration of a Cobot on the effectiveness of a collaborative workplace. We focus on the multi-objective evaluation of the collaborative workplace optimization parameters with the detailed study of the assembly times, production quantities, and occupancy of the collaborative workplace from the Cobot and worker perspective.

2. Problem description

Cobot's properly set parameters can have a big impact on the efficiency and capacities of the manufacturing system. To set up a proper parameter of robots/machines can be a real challenge, especially when it comes to Cobot's. It is not necessary that highest working parameters brings the highest number of finished orders, shortest operating times and highest machine utilization. The optimum working parameters depends on the structure of collaborative workplace, application type and defined sequence of tasks [22].

Most integrators/production engineers define Cobot's working parameters their preference and existing knowledge or based on suggestions from Cobot's producers. In many cases, parameters are not set up properly or are even set up to the maximum limit of the machine. With higher defined parameters, integrators want to achieve more finished products in less time. In most cases, such a decision leads to positive results as the machine's operating time is reduced, but is it really only about the machine operating time, or there are also other variables we have overlooked inside the collaborative workplace?

At observing of collaborative workplaces and their operations, we noticed that worker movements change or adapt according to parameters of the collaborative device [19, 22]. Such a finding, immediately raised a question of whether the speed and acceleration of the Cobot could have an impact on workers performance indicators (average worker assembly time, number of finished products and worker occupancy)? To determine the correctness or incorrectness of our predictions in the best possible way, we had proposed the design of the collaborative workplace and determine the most suitable type of collaborative application, presented in section three.

2.1 Collaborative workplaces

To find out if there is a relation between the parameters of the collaborative robot and the assembly time of the workers, we had to design the structure of the experiment, a collaborative workplace layout and a collaborative operation. In the initial research phase, we had to think about what type of application and type of collaboration between the Cobot and the worker to design.

In Fig. 1 four types of collaboration between the Cobot and the worker are presented. The first type is a caged cell. At caged cell type, a collaboration level is zero, the robots are in cages and there is no possible interaction between the worker and the robot. At this type mainly industrial robots are installed. At second type, so called coexistence, the Cobot and the worker work in the same space without fence between them, but they do not share the same workspace. Next type of collaboration is sequential or synchronized. The worker and the Cobot share their workspace but not at the same time, movements needs to be sequential. The last type of collaboration according to literature [23] is cooperation. At this type of work, the level of collaboration is the highest, the worker and the Cobot share the same workspace at the same time. In cooperation type the use of Cobot instead of industrial robot is necessary, because of integrated safety features that allow to work in direct contact. Even that in Cobot safety features are installed, the integrator still needs to perform risk assessment and design the operation as save as possible [24].

To mention, definition of collaboration types differs between the individuals, because the community is still split about their opinions and definitions. But there is not a lot of differences between the sources, mainly in names and small details.

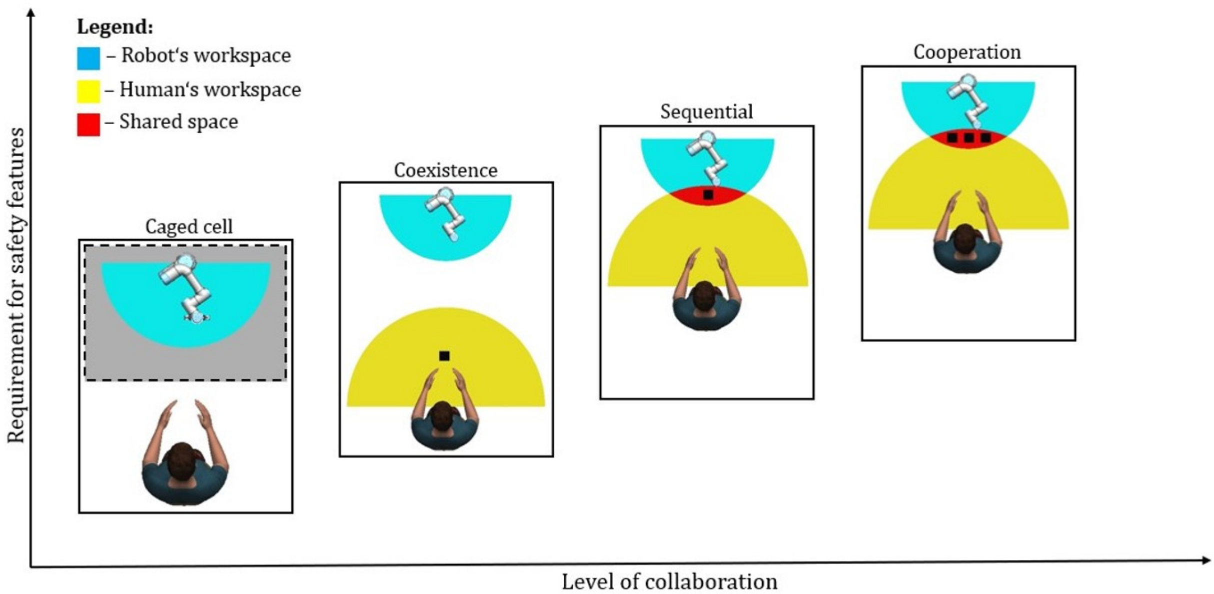

Fig. 1 Types of Cobot and worker collaboration

2.2 Manufacturing efficiency

Initially, the definition of manufacturing productivity in terms of production is the ratio of output to input in production and is a measure of efficiency. If something is produced, we want to know how long it takes to produce it. While productivity focuses more on increasing the quantity produced, efficiency refers to the quality and effectiveness of the manufacturing system. In our research work we are focused on the collaborative workplace's efficiency in correlation to its performance parameters. We are focusing on evaluating the ability to do or produce products without wasting material, time, cost, or energy. The efficiency is often expressed as a percentage, with 100 % being the ideal goal so that the product is produced at the lowest average total cost per item at the highest possible workplace occupancy. In presented research work we are measuring efficiency with the parameter of the number of hours of productive quality assembly work divided by the number of minutes available in the experiment run. The optimization methods and workers training can lead to improved manufacturing efficiency. For this purpose, the key performance indicators (KPI) were used to help evaluate Cobot and worker efficiency when the parameters of Cobot speeds and accelerations are changing. In general: if you want to increase manufacturing efficiency, you essentially want to produce more output in the same amount of time. Finding a constant balance between productivity and manufacturing efficiency is critical to keeping your manufacturing running optimally. In Fig. 2 we can see optimization perspectives with which company can achieve high manufacturing system KPI's.

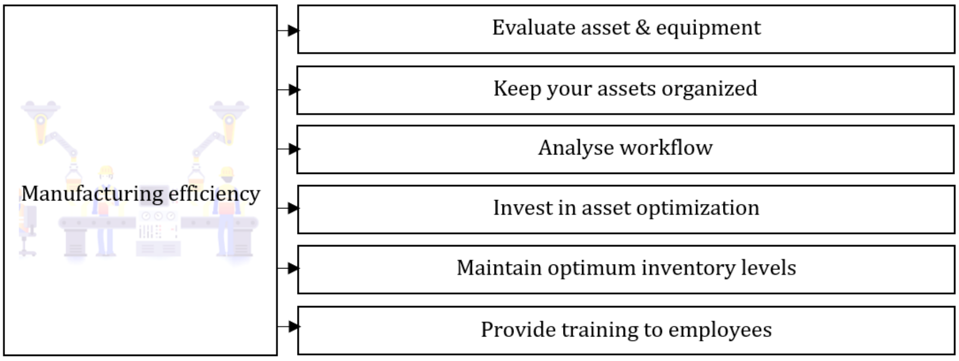

Fig. 2 Manufacturing efficiency, optimization perspectives

3. Experiment description

The presented experiment was prepared according to the collaborative workplace standards listed in the literature [7], the research focuses on the reproducibility of the experiment in a laboratory environment, initial simulation model in Siemens software is shown in Fig. 3, where the selected building blocks are standard elements, as presented in subsection 3.1. The experimental environment is presented in detail in the subsections of the collaborative workspace description and the experimental design, where the experiment design is prepared in correlation with different experts from the field of social, medicine and technical sciences.

Fig. 3 Collaborative workplace simulation model for laboratory experiments

3.1 Collaborative workplace description

The experiment was conducted with the laboratory environment, so the collaborative workplace was adapted to laboratory conditions in terms of size and application type. Collaborative workplace consisted of a worktable ③, a collaborative robot UR3e ⑦, a collaborative gripper Robotiq 2F-85 ⑥, a switch with indicators light in green and red colour ④ and button ⑤, and two types of semi-finished products ① ②. A Lego brick size of 4×2 represented the semi-finished product 1 ① while a brick size of 2×2 represented the semi-finished product 2 ②. The finish product consisted of one semi-finished product ① and two semi-finished products ② assembled together, as shown in Fig. 4.

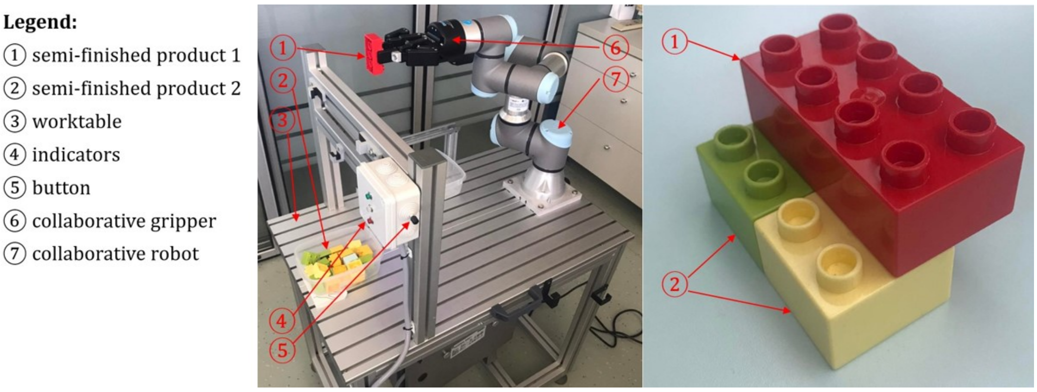

Fig. 4 Layout of the collaborative workplace (left) and the finished product (right)

The assembly operation consisted of assembling three semi-finished products into one finished product. The sequence of assembling was predefined to get the most objective results. At the beginning of the collaborative operation, the indicator light glowed red. The red light signalled that the Cobot is working and the worker is not approved to enter the robot area, but the worker can prepare himself. At the beginning, the collaborative robot picked up the semi-finished product and brought it to the collaboration/assembly area. When the robot reached the assembly area, it stopped, the indicator light changed from red to green and the worker was allowed to assemble. After the worker attached two semi-finished products ② to the semi-finished product ①, he or she pressed the button to send the signal about the completed work. The indicator light changed back from green to red and the Cobot moved the finished product into the box. The procedure was repeated until the total time of 30 minutes, for each experiment, was reached.

3.2 Experiment design

To test our hypothesis optimal, we decided to design an assembly operation, a collaborative assembly operation, where the Cobot and the worker work sequential. At sequential type, they share the same workspace but at different time intervals. The sequential type of collaboration in our case was ideal because we still provided the contact between them and we could obtain objective results about a relation between the parameters of the robot and the operation time of the worker. In the next phase of experiment planning, we had to determine the structure of the experiment, length of the experiment and Cobot parameters (speed and acceleration). We decided to limit our experiment to 30 minutes and divide it into four phases as seen in Table 1.

The experiment was divided into four phases. In the first phase, the Cobot and the worker worked separately. The worker manually assembled the finished products for 5 minutes. The goal of the first phase for the worker was to get used to such a type of the work and to the proximity of the Cobot. After 5 minutes, phase 2 has begun. Phase 2 lasted 10 minutes and consisted of collaborative work. The worker assembled the finished products with the help of the Cobot. The speed and acceleration of the Cobot were set to 60 %. After phase 2, phase 3 had started, it was set up the same way as phase 1, mainly to relax the worker. The worker and Cobot worked separately for 5 minutes. The goal of phase 3 was to release the pressure from the worker from the previous phase in which the worker collaborated with the Cobot. In the last phase of the experiment, phase 4, the worker worked with the Cobot again. Phase 4 lasted the same amount of time as phase 2, but the parameters of the Cobot were set higher, at 100 %. Cobot parameters (Table 2) were define based on attempted test in laboratory, simulation model presented in Fig. 3 and the specifics of the application type. After the experiment was completed, we obtained the results, describing collaborative workplace efficiency from phase 2 and phase 4.

Table 1 Structure of the experiment

Phase No.	Time length (min)	Description
Phase 1	5	Manual assembly operation
Phase 2	10	Collaborative assembly operation (CR speed and acceleration 60 %)
Phase 3	5	Manual assembly operation
Phase 4	10	Collaborative assembly operation (CR speed and acceleration 100 %)

Table 2 Cobot speeds and accelerations

Linear movements					Joint movements			
Speed (%)	(mm/s)	Acceleration (%)	(mm/s^2)	add	Speed (%)	(°/s)	Acceleration (%)	(°/s^2)
60	600	60	1500		60	206	60	310
100	1000	100	2500		100	344	100	516

4. Results

The experiment involved nine participants, both men's and women's, aged from 20 to 50 years. Until the end of experiment participants did not know the real goal of the experiment. With unknown, research goal (caning speeds and accelerations of the Cobot), we provided that they could not had an impact on their assembly task. The results in Table 3 show the average assembly time and number of finished products of each participant in two different scenarios corelated to phase 2 and phase 4. In both scenarios, the worker collaborated with the Cobot, but in scenario 1 (S1) the Cobot parameters were set to 60 % meanwhile in scenario 2 (S2) the parameters were set to 100 % of the specified speed and acceleration. Throughout the experiment we focus on next optimization parameters: worker average assembly times, number of finished products and Cobot and worker occupancy. Each worker average assembly times were saved to the time variable of the Cobot data collecting unit. According to the number of finished products and stored assembly times in the time variable, the average assembly time for each scenario was calculated.

4.1 Results of average assembly times and number of finished products

From the results seen in Table 3 and Fig. 5, it is clear that with increased Cobot parameters assembly times did shorten. Although the number of participants in our experiment was low, we did not perceive a single longer assembly time while the parameters of the Cobot were increased in comparison with the S1, where Cobot parameters were lower. The average assembly time in S1 was 3.4 s with a standard deviation of 0.81. The number of participants in which the average assembly time was below average was 5 out of 9 participants. In scenario S2, where the speed of the robot was increased to 100 %, the average assembly time decreased to 2.6 s, in this case the standard deviation is lower at 0.66. In S2, 6 out of 9 participants had a shorter average assembly time than the average total time.

Increasing the parameters of the Cobot from 60 % to 100 % contributed to the 23.4 % decrease in average assembly time of the worker. The minimum decrease in average assembly time that occurred in our experiment was 8.70 %, while the maximum decrease was 36.90 %.

The presented results of the experiment confirm our prediction. Higher define parameters of the Cobot had an impact on the worker and resulted in a higher working speed. Due to the higher working speed, the average assembly time is shorter, and we are able to deliver a higher number of finished products. Using the number of finished products parameters, we see that the total number of products produced in S1 is 497 pieces for nine participants in total. On average, each participant assembled 55.2 pieces in 10 minutes, with a standard deviation of 3.9. A significantly higher number of finished products is seen in S2, where participants assembled a total of 761 pieces in 10 minutes, while each worker assembled an average of 85.5 pieces with a standard deviation of 7.6, as shown in Fig. 6.

Table 3 Average assembly times and Number of finished products per participant in S1 and S2

Participants	Average assembly time (s) – S1	Number of finished products (pcs) – S1	Average assembly time (s) – S2	Number of finished products (pcs) – S2
1	2.82	58	2.34	87
2	3.00	57	2.42	86
3	2.82	58	1.97	92
4	2.65	59	2.27	88
5	2.48	60	1.70	96
6	3.59	54	2.27	88
7	4.98	48	3.34	76
8	4.24	51	3.45	75
9	4.02	52	3.67	73

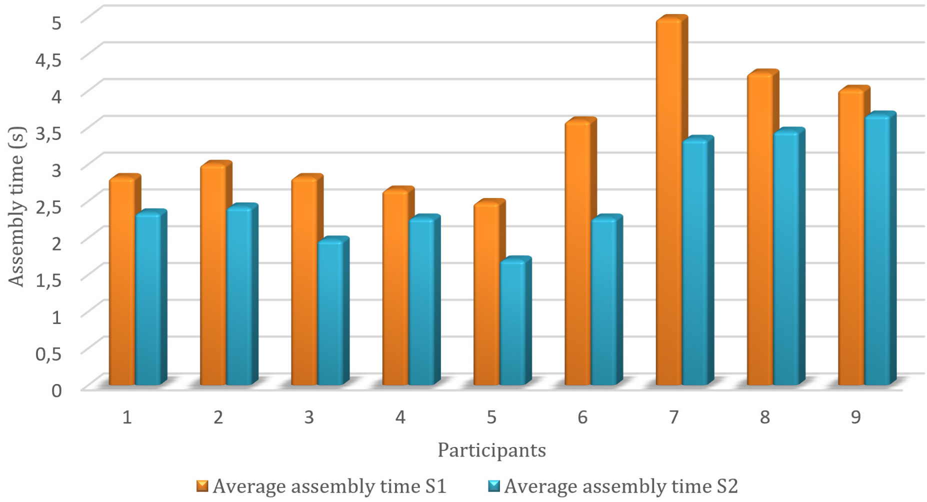

Fig. 5 Average assembly times, results comparison (S1 vs S2)

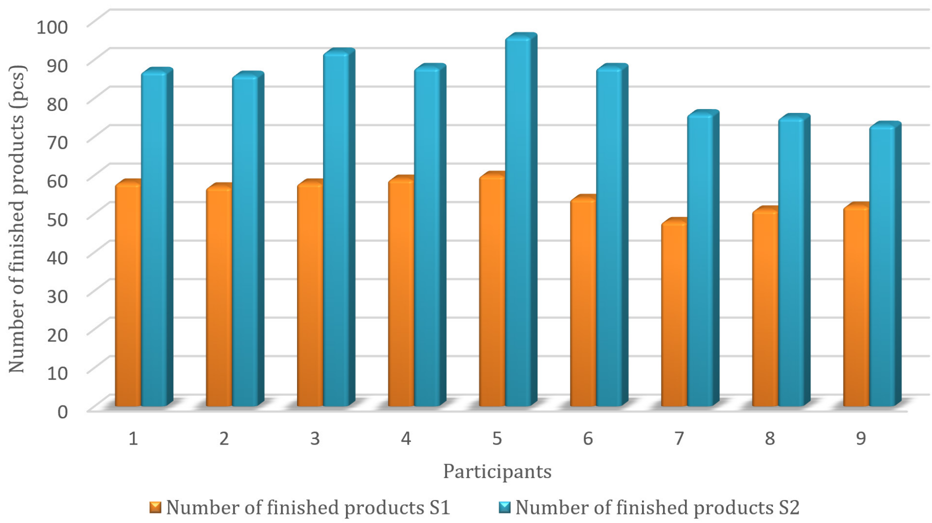

Fig. 6 Number of finished products, results comparison (S1 vs S2)

4.2 Results of Cobot and worker occupancy

Table 4 shows the occupancy of the collaborative workspace (Cobot and worker time occupancy), where the values are evaluated according to the total assembly time, which is in total 10 minutes for the individual scenario. The results show the three optimization parameters, where the Cobot occupancy indicates the total operating time of the Cobot. The worker occupancy is divided into the assembly and setup time parameters. Notice: the worker's assembly setup time is performed when the robot performs its operations.

Table 4 Cobot and worker occupancy in S1 and S2

Participants	Cobot occupancy (min) – S1	Worker occupancy (min) – S1		Cobot occupancy (min) – S2	Worker occupancy (min) – S2	
		Assembly time	Setup time		Assembly time	Setup time
1	7.27/10	2.73/10	1.87/10	6.60/10	4.40/10	3.19/10
2	7.15/10	2.85/10	1.95/10	6.53/10	3.47/10	2.52/10
3	7.27/10	2.73/10	1.87/10	6.98/10	3.02/10	2.19/10
4	7.40/10	2.60/10	1.78/10	6.68/10	3.32/10	2.41/10
5	7.52/10	2.48/10	1.70/10	7.28/10	2.72/10	1.97/10
6	6.77/10	3.23/10	2.21/10	6.68/10	3.32/10	2.41/10
7	6.02/10	3.98/10	2.72/10	5.77/10	4.43/10	3.22/10
8	6.39/10	3.61/10	2.47/10	5.69/10	4.31/10	3.13/10
9	6.52/10	3.48/10	2.38/10	5.54/10	4.46/10	3.24/10

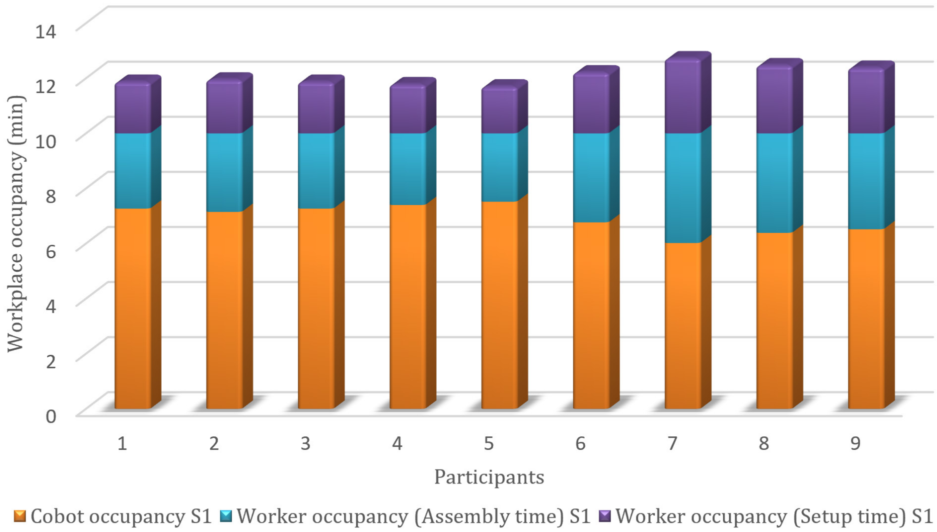

Fig. 7 Workplace occupancy in S1

Fig. 7 and the results in Table 4 show that in S1, the participating robot is occupied on average 6.92 minutes of the available 10 min total time. The standard deviation of average Cobot occupancy is 4.9. A worker at a collaborative workstation is engaged in assembling operation for an average of 3.08 minutes while spending another 2.11 minutes preparing the parts to be assembled, giving a total time occupancy of 5.18 in the available time of 10 min, where the standard deviation is 4.9.

Results of the S2 in Fig. 8 shows, that the Cobot works an average of 6.42 min of the available 10 min. With the parameters S2, the worker is occupied for 3.71 min for the assembly operation and 2.69 min for the setup time, which totals 6.40 min of the available 10 min workplace operation time. For parameters S2, the standard deviation of the Cobot occupancy is 5.7 and for the worker it is 6.3.

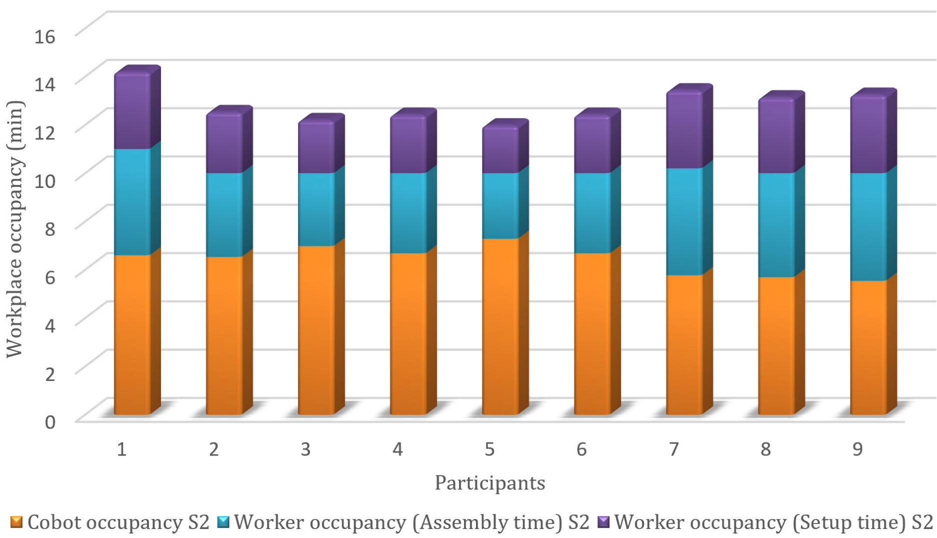

Fig. 8 Workplace occupancy in S2

5. Discussion

Based on the results shown, we conclude that in total 264 more pieces are produced in S2 at the collaborative workplace than with the parameters representing scenario S1. The average number of finished products at the collaborative workplace in scenario S2 increases by 54.9 %, which significantly increases the number of manufactured products. At the same time, the standard deviation results, which are 3.7 higher for S2, indicate a higher probability of non-constant operation of the collaborative workplace assembly operations when repeated operations are performed in several shifts with several different workers. The results presented indicate that worker workload increases at higher speeds and accelerations of the Cobot. Based on the evaluated optimization parameter of the average assembly time, we find that it is 23.5 % shorter in scenario S2, which is an interesting observation from the justifying the collaborative workplace point of view. The worker changed the work speed (assembling operation) when the Cobot mode of operation changed (the transition of the Cobot parameters from S1 to S2). Obviously, the visual and audio effects presences (perception of the Cobot) had a positive effect on the shorter average assembly time, even though the worker had exactly the same time to assemble the product in both evaluated scenarios (S1 and S2).

It is also interesting to analyse the occupancy of the participants (Cobot and worker) in the collaborative workplace. The results show that the occupancy of the Cobot in the S2 scenario decreased by 7.2 % compared to the time occupancy in the S1 scenario. The results prove that the Cobot is able to perform multiple activities simultaneously and possibly participate in more complex activities or collaborate in a workplace with two workers when the operating parameters are increased. In this case, it is useful to study the utilization of the Cobot in detail, because only with a detailed analysis we can ensure the justification for the introduction of such a machine in existing or newly proposed production system. In contrast to the decrease in the time occupancy of the Cobot in S2, the occupancy of the worker in S2 increases, by 23.6 %, the occupancy is higher both during assembly and setup time. With respect to the time occupancy parameter, we find that the importance of consistent collaborative workplace occupancy is critical to the economic and social justification of a collaborative workplace. When introducing new collaborative workstations, the use of simulation techniques is highly justified, assuming that they represent the minimum cost of the initial investment and reduce the risk that the new investment is not justified.

As mentioned in the introduction, usually companies start to increase the parameters (speeds and accelerations) of the Cobot to reduce the cycle time of the machine operations to provide enough collaborative workplace capacity. But as our results show, the integrators probably also affect the worker's working speed unconsciously. It is difficult to fully determine the reason for the increased worker operating speed, but a few options emerged during the experiment that may be important contributors. Different speeds and accelerations of the Cobot provide different volumes of noise. The loudness of electro motors in joints could be a factor for faster movements and greater willingness of the worker. The other aspect that should be considered is visualization. In collaborative operation, the worker is constantly in "contact" with the Cobot, as with assembling the products together as at observing the robot's movements. With defined and constant parameters of the Cobot, workers get to use of work sequence and begin to memorize specific positions of the Cobot at specific time frames. If the remembered positions start to differ from previously remembered start to deviate from previous memorized positions, this could trigger some kind of alarm in the worker, whose spontaneous reaction could be an increased working speed.

According to the existing literature [19, 21], the presented work highlights the importance of a detailed study of the feasibility of introducing collaborative workplaces, where the setting parameters of the collaborative machine can significantly affect the efficiency of such a workplace. Proper integration of a Cobot affects both economic, time and social justification. The main contribution of the presented work is evident in the results that highlight the study of the importance of the visual and acoustic impact on the worker and consequently on its use. Considering the number of participants considered, the trend of results shown allows further work and extension of the experiment, which must be transferred to a real-world environment where the working hours of the collaborative workplace would be longer. With longer working hours and the evaluation of the collaborative workplace efficiency, the speed and acceleration of the Cobot would have a significant impact on the worker's workload, concentration, and therefore on the quality of the work performed.

6. Conclusions

In the research paper, the importance of Cobot parameters on worker productivity is presented. The results of the study provide useful and interesting answers to our research question, but new doubts have also been raised. The results show that the parameters of the Cobot have an impact on the assembly times of the workers. Higher speed and acceleration of the Cobot contribute to a higher working speed of the worker, which leads to shorter assembly times in our study. Despite the positive results, the limit of the Cobot parameters must be considered at different collaborative work operations. The speed and acceleration limit should be set in such a way that it does not affect the correct performance of the Cobot and, most importantly, it does not negatively affect the worker (performance, physical health, mental health, etc.).

Future research will focus on the analysis of more participants, different ages, educations and genders. We will focus our research on studying the mental and physical health of workers working with Cobot. Favourable research results will lead to the transfer of the laboratory experiment to a real-world production environment, where the speed and acceleration of the Cobot will have a longer-term effect on the efficiency of the worker and the entire collaborative workplace. When evaluated in a real-world environment, the challenges will enable a more detailed and practical application value of the presented research work, which is crucial in the era of Industry 4.0 and the arrival of new technologies. Cost, time and social justified of the collaborative workplaces certainly represent one of the more attractive research areas from the manufacturing efficiency point of view.

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