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The impact of the collaborative workplace on the production system capacity: Simulation modelling vs. real-world application approach

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A B S T R A C T

In recent years, there have been more and more collaborative workplaces in different types of manufacturing systems. Although the introduction of collaborative workplaces can be cost-effective, there is still much uncertainty about how such workplaces affect the capacity of the rest of production system. The article presents the importance of introducing collaborative workplaces in manual assembly operations where the production capacities are already limited. With the simulation modelling method, the evaluation of the introduction impact of collaborative workplaces on manual assembly operations that represent bottlenecks in the production process is presented. The research presents two approaches to workplace performance evaluation, both simulation modelling and a real-world collaborative workplace example, as a basis of a detailed time study. The main findings are comparisons of simulation modelling results and a study of a real-world collaborative workplace, with graphically and numerically presented parameters describing the utilization of production capacities, their efficiency and financial justification. The research confirms the expediency of the collaborative workplaces use and emphasise the importance of further research in the field of their technological and sociological impacts.

A R T I C L E I N F O

Keywords:
Simulation modelling;
Production system capacity;
Industry 5.0;
Assembly line;
Human-robot collaboration;
Collaborative workplace

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1. Introduction

Optimization of production systems has been an attractive research field for many decades. Researchers are constantly wondering how to improve production system capacity or use it as efficiently as possible. In recent years, there have been an increasing number of collaborative machines that, together with workers, form high flexible, economically justified collaborative workplaces. Collaborative machines are to some extent already well studied, but their impact on the collaborative workplace, on workers and more broadly on the manufactured system is often unknown. Where is the turning point when a collaborative workplace is economically, socially and from a capacity standpoint justified? We want to answer this complex research question.

Researchers have been asking for years who is working with whom (human with robot, or vice versa) [1]. This issue, given the complexity of the social dimensions of the collaborative workplace and the security parameters, raises a lot of unanswered questions from the worker's point of view [2]. The findings show that we are talking about a hybrid research area, associated with a concept of Industry 5.0 [3, 4], where safety meets ergonomics, technological efficiency, and the unanswered question of the integrated impact of collaborative workplaces on the production system [5]. As we know, proper ergonomic analysis of workplaces significantly improves their productivity [6], but this is only proven in manual assembly workplaces; how different production parameters can affect the collaborative workplace is not known. Only general guidelines for the preparation and arrangement of the collaborative workplaces are given [7], where the authors still draw parallels with the manual assembly workplaces [8]. The shortcomings of such research are highlighted when we want to analyse in detail the impact of collaborative workplaces on the sustainable justification of the production system [9]. The authors cite limitations in terms of different time, cost and technological suitability of collaborative workplace parameters. Determining the appropriate "collaborative" parameters [10] is crucial in the use of efficient and safe (for worker and robot) workplaces [11]. Research work presents that states of safe parameters of speed and acceleration of collaborator robots in a common workspace [12], but how the change of parameters affects the efficiency of the collaborative workplace and other production capacities is hard to define [13]. Due to these limitations, researchers want to provide a general methodology for the introduction of collaborative workplaces [14], but when one of the general advantages is high flexibility of collaborative machines and associated production systems [15] in which we include them, the implementation is very demanding, most often made individually [16]. The answers to the questions about the feasibility of introducing collaborative workplaces must thus respond to an appropriate investment strategy [17] and the sustainable justification of such workplaces and their wider impact [9]. Correlations between these parameters [18] can be well represented by simulation modelling methods [19], where an integrated approach to planning and deployment of collaborative workplaces can be evaluated and the collaborative workplace constructed accordingly [20]. Recent research shows that it will be necessary to know the technological behaviour of the collaborating machine and, more importantly, its sociological impact on the co-worker [21]. The response that a co-worker may have to a collaborative workplace is complex and individual according to the employee's condition. More broadly, the impact of a collaborative workplace can significantly change production capacities and their efficiency. It should be emphasized that the collaborative workplace can be placed in different types of production systems, in different configurations, which represent an additional complexity of its optimization [22].

In our research work we want to answer the question of determining the collaborative workplace parameters (time study and financial norms) when introducing it into an existing production system. In doing so, we focus on the use of simulation modelling methods and the evaluation of a real-world collaborative workplace. Data from detailed time and costs analysis will enable the implementation and comparison of the broader impact of the collaborative workplace on the entire production system, where a comparison will be made between manual assembly and collaborative workplaces. The research is based on the study of the production system of assembly line and attempts to improve its limited production capacity.

2. Problem description

Optimizing an assembly production line system is a major challenge if the system is already at the minimum possible takt time and is no longer able to optimize assembly processing time for individual workplaces. Such an assembly line system, when orders increase, faces the inability to achieve the desired quantity of products with limited assembly capacities. In recent years, manual assembly workplaces have been automated and robotized, and such workplaces have some limitations as production capacity increases, investment costs increase, new equipment is introduced, and the size of such fully automated cells increases assembly line footprint. Given that the assembly line production system presented in Fig. 1 and the corresponding processing time data in Table 1 indicate assembly line constraints at manual assembly workplaces M_{as8} and M_{as9}, where the assembly processing time is equal to the line takt time. The question of the feasibility of introducing collaborative workplaces where the manual assembly is upgraded with the capacities of a collaborative robot, whose initial investment and introduction to an existing job is less demanding, is questionable.

2.1 Production system description

The research problem deals with the products assembly line with ten manual assembly workstations (M_{as}) and associated workstations processing times (work-element times) presented in Fig. 1 and Table 1 respectively. The assembly line production system has a certain line takt time of 54 s, a constant speed of the conveyor belt of 1.2 m/min, an additional mark-up coefficient of the conveyor belt length of 0.05. The assembly line is carried out in three shifts in five working days a week. Workers in the manual jobs of the assembly have a certain useful number of working hours in a shift, lasting 7.5 h. Transport to the initial station of the assembly line and shipment of finished products is carried out with the use of forklifts. Input semi-finished products and component assembly accessories are always available to the assembly workers.

Table 1 Assembly line manual workplaces processing times

Workplace	M_{as1}	M_{as2}	M_{as3}	M_{as4}	M_{as5}	M_{as6}	M_{as7}	M_{as8}	M_{as9}	M_{as10}
Processing time (s)	52	51	49	48	52	51	52	54	54	48

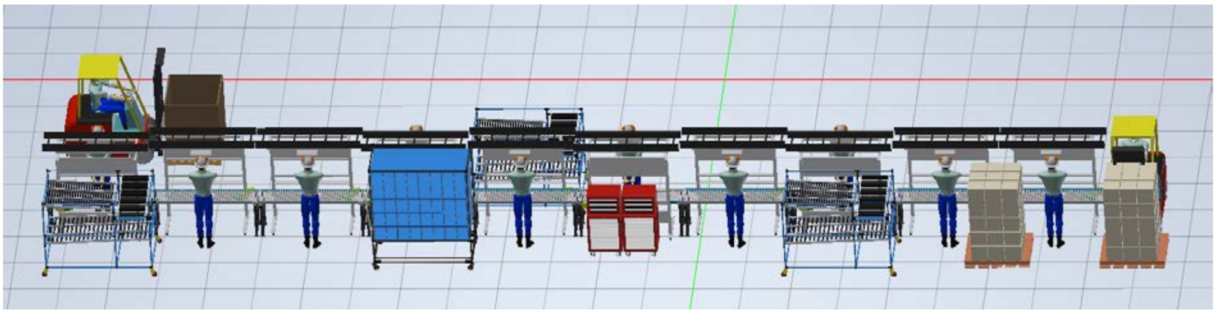


Fig. 1 Production system – manual assembly line with ten workplaces (3D model)

Eqs. 1 to 7 represent a numerical calculation of the assembly line characteristics. Numerically determined parameters are consistent with real-world production systems and serve as a basis for building a simulation model. For further calculations, next variables are defined:

$takt$	Takt time
U_c	Useful capacity
n_c	Useful number of working hours in one shift
n_s	Number of shifts
η_c	Worktime efficiency coefficient
η_l	Line efficiency coefficient
Q_e	Quantitative efficiency
M_d	Number of workplaces
l_c	Conveyor length
k_l	Mark-up coefficient for the conveyor length
v_c	Conveyor speed
d_w	Distance between workplaces
d_p	Distance between products on the conveyor
t_f	Product's flow time
t_1	Operation processing time
E	Additional number of products on the conveyor

Eq. 1 defines useful capacity of the assembly line per working day, including three shifts working schedule, 7.5 h of useful working hours and worktime efficiency coefficient of 0.92. High worktime efficiency coefficient is used in relation to assembly line characteristics.

$$U_c = n_s \cdot n_c \cdot \eta_c = 3 \cdot 7.5 \cdot 0.92 = 20.7 \frac{\mathrm{h}}{\mathrm{day}} \ \text{ or } \ 1242 \ \frac{\mathrm{min}}{\mathrm{day}} \tag{1}$$

In corelation to defined takt time of 0.9 min, which is minimum possible takt time for presented operations in Table 1, and defined line's useful capacity, quantitative efficiency is defined as presented in Eq. 2.

$$Q_e = \frac{U_c}{takt} = \frac{1242}{0.9} = 1380\,\frac{\text{pcs}}{\text{day}} \tag{2}$$

With the know number of workplaces (M_d = 10), takt time and total processing time the final assembly line theoretical efficiency is determinated by Eq. 3.

$$\eta_l = \frac{\sum t_1}{M_d \cdot takt} = \frac{509}{10 \cdot 54} = 0.943 \text{ or } 94.3\ \% \tag{3}$$

Defined number of workplaces, known distance between workplaces (d_w = 2.16 m) and proposed mark-up coefficient for the conveyor length (k_l = 0.05) the optimum conveyor length is defined by Eq. 4:

$$l_c = M_d \cdot d_w \cdot (1 + k_l) = 10 \cdot 2.16 \cdot (1 + 0.05) = 22.68 \text{ m} \tag{4}$$

Distance between products on the conveyor (d_p) is known when the speed of conveyor is defined (v_c = 1.2 m/min) and multiplied with the takt time of 0.9 min. Shown by the Eq. 5:

$$d_p = v_c \cdot takt = 1.2 \cdot 0.9 = 1.08 \text{ m} \tag{5}$$

An additional number of products on the conveyor is defined by the Eq. 6.

$$E = (M_d - 1) \cdot \frac{d_w}{d_p} = (10 - 1) \cdot \frac{2.16}{1.08} = 18 \tag{6}$$

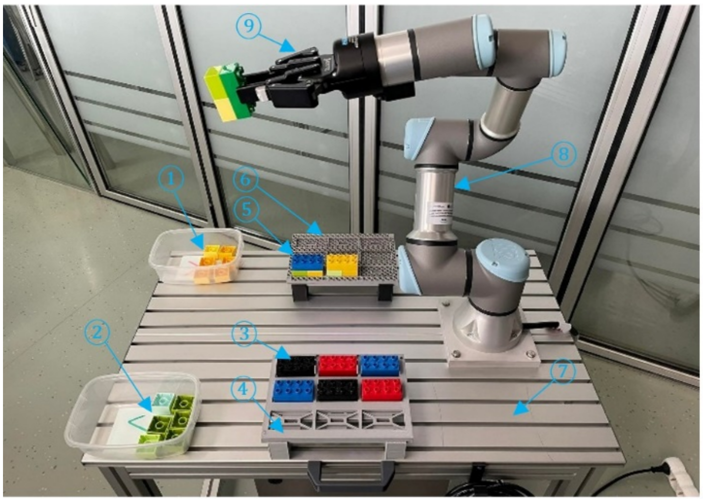
Knowing the number of workplaces, additional number of products on the conveyor, distance between workplaces and distance between products on the conveyor products' flow time can be defined by Eq. 7.

$$t_f = (M_d + E) \cdot takt = (10 + 18) \cdot 0.9 = 25.2 \text{ min} \tag{7}$$

2.2 Collaborative workplace (CW_{as}) description

Our own designed flexible collaborative workplace, in Fig. 2, consist of a worktable ⑦, a collaborative robot UR3e ⑧, a collaborative gripper Robotiq 2F-85 ⑨, a pallet of semi-finished products ④, pallet of finished products ⑤, and three types of semi-finished products need to be assembled (type one yellow brick ①, type two green brick ② and type three 4×2 brick ③).

To run simulation models and study the capacity of the assembly line production system, it was necessary to determine the processing time of collaborative assembly operation between worker and collaborative robot. To determine the most accurate processing times, we carried out the time study evaluation with different speeds and accelerations of the collaborative robot (Table 2), evaluating different workers, in sitting and standing positions.



Legend:
① semi-finished product (yellow brick)
② semi-finished product (green brick)
③ semi-finished product
④ pallet of semi-finished products
⑤ finished product
⑥ pallet of finished products
⑦ worktable
⑧ collaborative robot
⑨ collaborative gripper

Fig. 2 Layout of a collaborative workplace

Table 2 Collaborative robot speeds and acceleration data

Linear movement					Joint movement			
Speed (%)	(mm/s)	Acceleration (%)	(mm/s^2)	add	Speed (%)	(°/s)	Acceleration (%)	(°/s^2)
100	750	100	2000		100	180	100	360
80	600	80	1600		80	144	80	288
60	450	60	1200		60	108	60	216

By performing evaluation of the seventy-two iterations of the assembly operation, we were able to accurately determine the collaborative workplace's processing time, human operational time, optimal speed of the collaborative robot, and gain a better understanding of the collaborative robot influence on the worker.

The assembly operation consisted of simple assembling of three semi-finished products ①, ② and ③ into one finished product ⑤. In the initial stage, the collaborative robot picks up a semi-finished product ③ and move it to the assembly location (Fig. 2). At the assembly location, collaborative robot stops and waits for the worker to attach two semi-finished products ① and ②. At this stage of the assembly operation, the worker attaches two semi-finished products ① and ② to the semi-finished product ③, which is held in the collaborative gripper. The attachment position of the two semi-finished products ① and ② was determined, the green brick ① is always at the top, the yellow brick ② is always at the bottom, while the order of the composition is: first the yellow brick is attached followed by the green brick. After the three semi-finished products ①, ② and ③ were assembled into a finished product ⑤, the collaborative robot move and place the finished product on the pallet with the finished products. The working process is finished when the pallet of finished products ⑥ is filled. It should be noted that the work process was carried out in a laboratory environment, so the position of the semi-finished products pallet ④ was fixed, while in a real-world assembly line operation the pallet would be transported by a conveyor.

3. Simulation modelling

Given the presented line assembly production system and the problem of improving limited production system capacity by introducing collaborative workplaces, we used simulation modelling to build a simulation model of the assembly line production system and to analyse the collaborative workplace in detail. Initially, the input parameters of the assembly line production system presented in Section 2 were upgraded by numerical modelling of the manual and collaborative workplaces costs, further used to study individual workplaces financial justification.

For the simulation model, the workplaces cost calculation (M_{as} and worker-robot collaborative workplace CW_{as}) was performed. Table 3 presents the data and cost calculation of the workplaces provided for the results implementation into a discrete event simulation environment Simio. Obtained data provides the basis for the validation of the obtained results in Section 4.

Table 3 Workplaces cost calculation data

Cost calculation parameter	M_{as}	CW_{as}
Purchase value of the machine (€)	11,666	35,000
Machine power (kW)	0.1	0.1
Workplace area (m^2)	6	6
Depreciation period (year)	7	7
Useful capacity of the machine (h/year)	5216	5670
Machine write-off value (€/h)	0.32	0.88
Interest (€/h)	0.01	0.03
Maintenance costs (€/h)	0.02	0.06
Production system area costs (€/h)	0.12	0.11
Electrical energy consumption costs (€/h)	0.02	0.02
Machine operational costs (€/h)	0.49	1.1
Workplace total costs (€/h)	11.54	12.76
Workplace cost per item (€/piece)	0.173	0.185

3.1 Production system modelling

The assembly line production system was modelled in the Simio software environment. The simulation model shown in Fig. 3 represents the assembly line, where all ten workplaces are devoted to manual assembly stations. The input parameters of the assembly line are the same as presented in Section 2, in addition, the parameters of workplaces costs evaluation according to mathematical modelling in Section 3 are added. The simulation model operates in three shifts, five working days a week. The model assumes that input materials and semi-finished products are always available, the system operates at 94.3 % efficiency rate. There are no unknown failures during the assembly operation. The main purpose of the simulation model is to evaluate the possibility of introducing collaborative workplaces to existing manual assembly workplaces with limited capacity.

In the intermediate graphic presentation (Fig. 3) we can observe that in the manual assembly jobs M_As8 and M_As9 bottlenecks of the production system appear, potentially these two manual assembly workplaces represent the final capacity of the evaluated assembly line. Since these two workplaces are about equalizing the time of the assembly cycle and the time of the assembly line takt time, it is advisable to optimize these two workplaces to raise production system capacity.

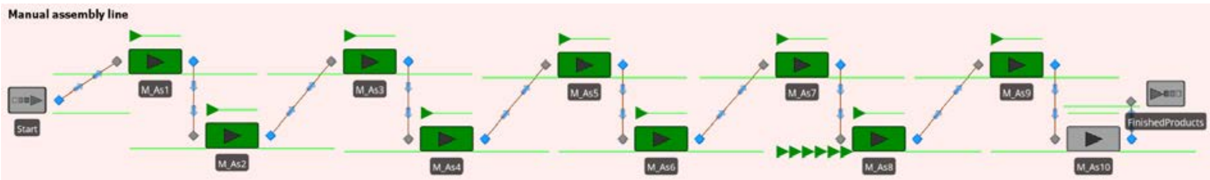


Fig. 3 Simulation model of the manual workplace's assembly line (2D model)

As a proposal to increase the production system capacity, the assembly line in Fig. 4 represents the introduction of one collaborative workplace, where one worker serves two collaborative robots. Fig. 4 shows this workplace with one AsCw1 worker workplace and two collaborative robots in AsCr1 and AsCr2 workplace. As shown, instead of ten workers in production, we now have only nine workers. In consideration, we have eight manual assembly workplaces and one collaborative workplace including worker and two robots. With the input parameters of the production system, all parameters of manual assembly workplaces remain unchanged. We added the input data for the collaborative workplace. The preliminary phase of graphic presentation of the simulation model shows the elimination of previous (Fig. 3) bottlenecks and the potential increase in the production system characteristics.

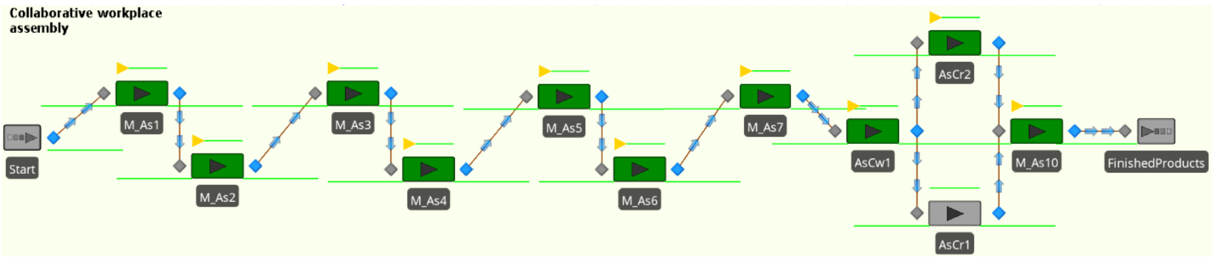


Fig. 4 Simulation model of the proposed collaborative workplaces assembly line

3.2 Collaborative workplace modelling

Collaborative workplace design and collaborative assembly operation were modelled in Siemens Process Simulate environment. The Process Simulate software environment allows us to model different systems or scenarios, simulate operations (machine or human), analyse human movements, optimize the production system, create robot programs, etc.

We have started by modelling the collaborative workplace and added all the necessary components for the collaborative work process, as shown in Fig. 5a. To perform the actual simulation, we first had to define the correct kinematics of the collaborative robot and the collaborative gripper. Properly defined kinematics is crucial to the functionality of the simulation model, as the same program of collaborative robot is running inside the simulation model as in the real-world application. After defining the exact locations of components, we have started to create the program for collaborative robot. In the program, we adjusted the movement of collaborative robot according to the range, kinematics, speed, type of movement and human safety. After completing the program in Process Simulate environment, we have transferred the program from the virtual to the real-world collaborative robot, through an integrated interface, where we only checked proper functioning and safety of the program.

After ensuring the relevance of the collaborative robot and the human-robot collaboration, the collaborative operation was simulated (Fig. 5b). The goal of simulating human work was to compare the simulation processing time against a real-world study human processing time.

Table 4 shows the results of the real-world collaborative workplace time study evaluation, in which we conducted a time study of four workers with different ages (between 25 and 45 years). Workers were instructed for the correct assembly operation order and needed collaborative workplace knowledge. When performing time study, we have unknowingly changed the speed of the robot for the workers and automatically measured and recorded the assembly process processing time. We performed seventy-two iterations to study the time of the collaborative assembly operation. The results in Table 4 represent the average results of these iterations for an individual worker and total average assembly processing time with respect to the robot speed and acceleration. The total average processing time of collaborative assembly was used in both the simulation model of the production system, in Simio, and the collaborative workplace, in Process Simulate.

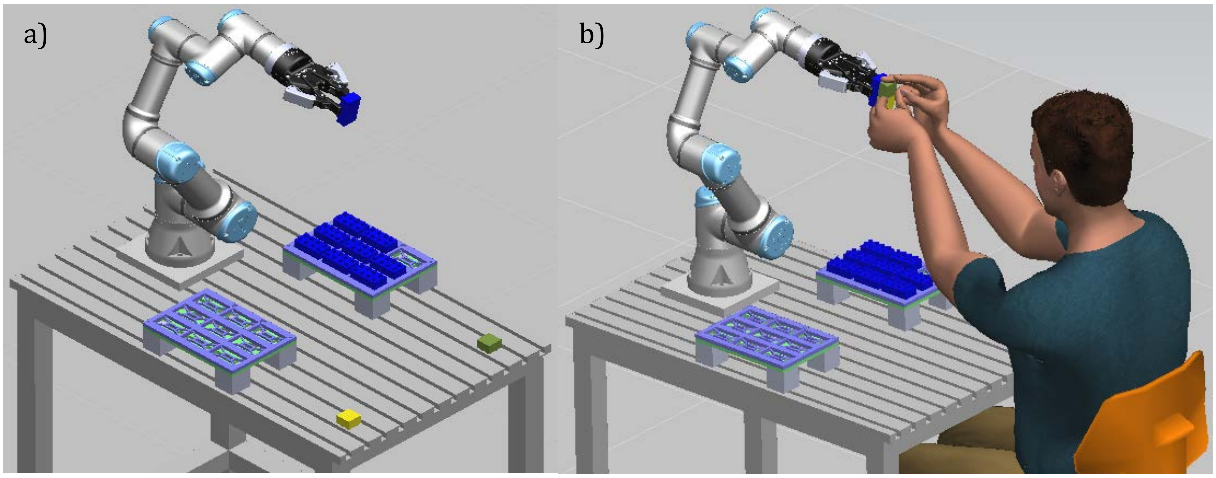


Fig. 5 Simulation model of human-robot collaboration

Table 4 Real-world evaluated workers (W_i) collaborative workplaces processing times

	Workers processing time (s)				
Robot speed/acceleration (%)	W_1	W_2	W_3	W_4	Average
60	90.146	89.796	86.950	86.566	88.36
80	81.038	75.234	68.444	67.434	73.04
100	64.544	62.108	59.286	63.318	62.31

4. Results and discussion

The results in Table 5 show the simulation modelling results of the costs and the utilization rate of an individual manual assembly workplaces. The workplaces cost depends on the number of processed products in the simulation time of five working days, working in three shifts. According to the determination of the assembly line production cost per individual piece and the type of workplace (data presented in Table 3), we can see how the costs affect the number of production pieces on the assembly line. More important is the parameter of workplace utilization, for which the utilization of the first workplace M_{as1} is not relevant, since the simulation model assumes a constant supply of semi-finished products to the first assembly workplace. However, we can see that the highest utilization rate is in the workplaces M_{as5}, M_{as7}, M_{as8} and M_{as9}. Based on a detailed analysis (throughput time, average time in station and number of entered/exited products) of the results, we find that the bottleneck of the production system is represented by the workplaces M_{as8} and M_{as9}, where the assembly processing time is equal to the assembly line takt time. Workplaces M_{as8} and M_{as9} are at the maximum of their capacity and prevent smooth flow of products through other workplaces. As we can see, the numerical results confirm the preliminary graphical representations of the simulation model and suggest the importance of optimizing these two workplaces.

When introducing a collaborative workplace (replacement of the M_{as8} and M_{as9}), which contains one CW_{as1} robot collaborative workplace and two CR_1 and CR_2 collaborative robots, the simulation results in Table 6 prove the feasibility of introducing such workplaces at evaluated assembly line. Table 6 shows the simulation results according to three different speed levels of collaborative robots. The results, as in Table 5, show the values of job costs according to the number of assembled products and associated to workplace utilization rate. As we can see, at 60 % of the robot's speed, the bottleneck in the assembly line workplace is already eliminated, in which case the collaborative worker and the robot are equally utilized (CW_{as1}: 92.2 %, CR_1: 84.14 % and CR_2: 85.45 %). The results of utilization rate prove a consistency of other manual assembly workplaces, which, however, approach the maximum capacity according to the results. Given the value of the cost per piece, we see a huge reduction in the cost of collaborative compared to manual assembly workplaces. Reducing costs is essential, as two collaborative robots represent significantly lower costs than one additional worker.

As the speed of the robots increases, their occupancy decreases (robots have more capacity to be used), but this does not significantly affect the rest of the assembly line workplaces, as the operator needs his/her time to properly assemble the parts on the collaborative robot. The cost of a collaborative workplace does not change, at all different speeds, the collaborative workplace enables the production of all available semi-finished products to be assembled. Based on the results, we can conclude that the production capacities are increased but the other workplaces' capacity is limited, potentially appearing new production line bottlenecks.

Table 5 Simulation model manual assembly line results

WP type	M_{as1}	M_{as2}	M_{as3}	M_{as4}	M_{as5}	M_{as6}	M_{as7}	M_{as8}	M_{as9}	M_{as10}
Cost (€)	939.39	939.23	939.06	939.06	938.74	938.57	938.41	903.48	903.31	903.15
Utilization (%)	100	98.06	94.2	92.26	99.93	97.99	99.9	99.88	99.86	88.75

Table 6 Simulation model collaborative workplace assembly line results

CR_1 and CR_2 speed and acceleration 60%						Average CW_{as1} processing time 88.36 s					
WP type	M_{as1}	M_{as2}	M_{as3}	M_{as4}	M_{as5}	M_{as6}	M_{as7}	CW_{as1}	CR_1	CR2	M_{as10}
Cost (€)	939.39	939.23	939.06	939.06	938.9	938.57	938.41	938.244	29.78	30.25	937.26
Utilization (%)	100	98.06	94.2	92.26	99.93	97.99	99.9	92.2	84.14	85.45	92.1
CR_1 and CR_2 speed and acceleration 80%						Average CW_{as1} processing time 73.04 s					
WP type	M_{as1}	M_{as2}	M_{as3}	M_{as4}	M_{as5}	M_{as6}	M_{as7}	CW_{as1}	CR_1	CR2	M_{as10}
Cost (€)	939.39	939.23	939.06	939.06	938.74	938.57	938.41	938.24	29.78	30.27	937.75
Utilization (%)	100	98.06	94.2	92.26	99.93	97.99	99.9	92.2	69.55	70.7	92.14
CR_1 and CR_2 speed and acceleration 100%						Average CW_{as1} processing time 62.31 s					
WP type	M_{as1}	M_{as2}	M_{as3}	M_{as4}	M_{as5}	M_{as6}	M_{as7}	CW_{as1}	CR_1	CR2	M_{as10}
Cost (€)	939.39	939.23	939.06	938.9	938.74	938.57	938.41	938.24	29.78	30.28	937.91
Utilization (%)	100	98.06	94.2	92.26	99.93	97.99	99.9	92.2	59.33	60.33	92.16

Table 7 and Fig. 6 show the comparative average simulation results on which we find that the assembly line total cost in comparison with manual assembly workplace costs and the introduction of one collaborative workplace are reduced by 8.34 %. The reduction of the average workplaces utilization is minor, as collaborative robots are at any speed fully occupied. We can see that just one collaborative robot would be too few. In this case, the worker in the collaborative workplace would have to wait a long time for the next assembly operation to be performed, that time is significantly less justified in terms of cost and capacity than serving a pair of collaborative robots. Given the number of finished products, we can assume that the average number of finished products increases by 3.83 %, when introducing a collaborative workplace, at this state the number of finished products approaches the theoretical capacity of the production system. The theoretical assembly line capacity is limited by the longest processing time of the individual workplace.

In current state it is represented by the workplaces M_{as5} and M_{as7}, with a processing time of 52 s. An interesting fact is the number of unfinished products in the production system (remaining products in system RP_{is}), which represents the size of intermediate stocks. Considering that there were bottlenecks in the manual assembly line, we can see that this number is reduced by as much as 93.67 % in the introduction of the collaborative workplaces. This result demonstrates how the elimination of bottlenecks has a positive impact on production capacity and its justification.

Fig. 7 shows a simulation model of the product assembly process and time study of needed worker time to assembly one product. With the help of a simulation model, we can accurately determine the phases of assembly, the needs of the worker movement and the robot operations. The simulation model itself assumes the optimal speeds of such a collaborative workplace in core-lation to the input parameters. Created simulation model assumes the assembly of one product, which includes three semi-finished products. The assembly phase is divided into five sub-phases (phase a – starting position, phase b – preparation of yellow and green semi-finished product, phase c – placement of yellow semi-finished product on a semi-finished product in robot gripper, phase d – placement of green semi-finished on a semi-finished product in robot gripper and phase e – final worker position). The initial assembly time is represented by the variable t_s = 0 s and the final time of the worker assembly phase by the variable t_f. The results prove that the simulation model predicted the working time of the worker assembly per product it would be 2.04 s, which is on average equivalent to 80 % of the robot speed criteria compared to the results in Table 8 where the four-worker real-world time study was performed.

Four evaluated workers have assembled nine consecutive products during the study. In Table 8, the results of the individual assembly processing times are captured between t_1 and t_9. Workers assembled the product in a sitting position at three different robot speeds, unaware of the real speed of the robot. Presented results prove that different workers, and their working abilities can affect the assembly operation processing time, as shown in a simulation model, an average assem-bly processing time can be used for variety of workers. The results prove the expediency of eval-uating the collaborative workplace in both real and simulation environments.

Table 7 Manual vs. collaborative workplace comparison results

AL Type	M_{as}	CR speed 60 %	CR speed 80 %	CR speed 100 %
Total AL costs (€)	9282.4	8508.2	8508.5	8508.5
Average utilization (%)	97.1	94.2	91.5	89.7
Throughputs (pcs)	5507	5714	5717	5718
RP_{is} (pcs)	221	14	11	10

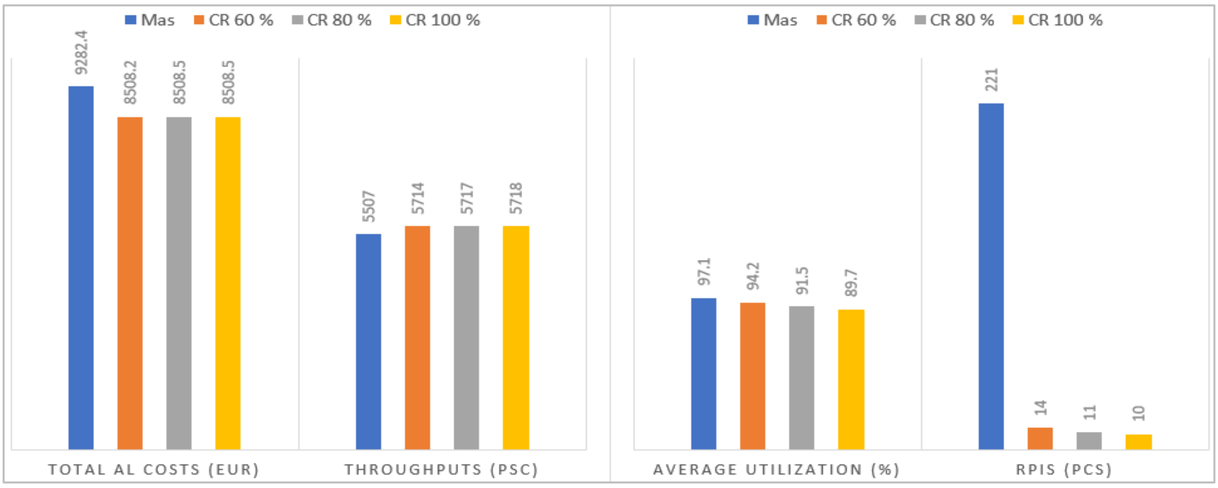


Fig. 6 Workplace comparison results

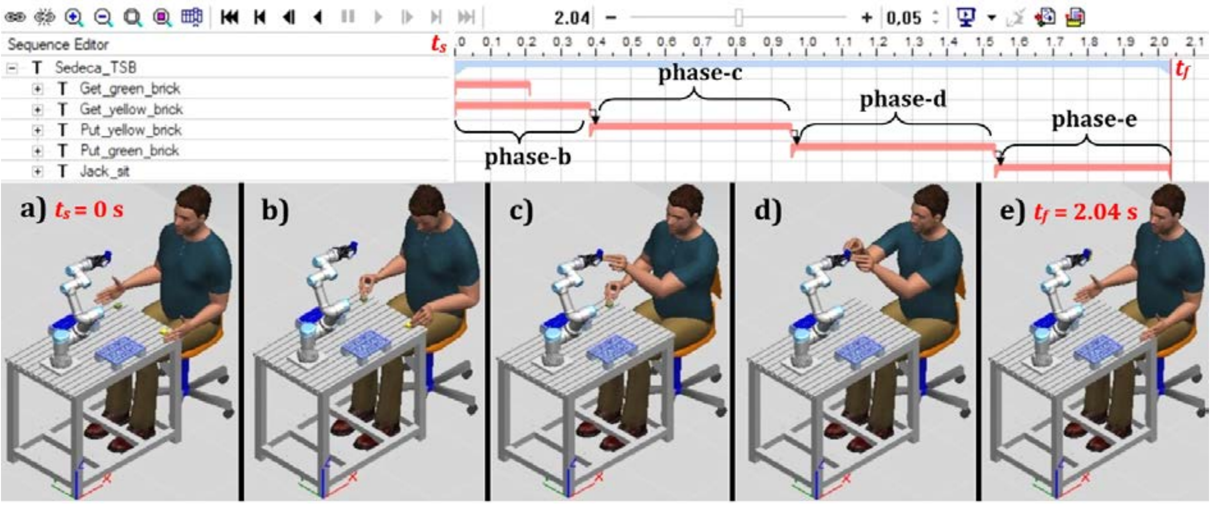


Fig. 7 Collaborative workplace simulation model – product assembly phases

Table 8 Real-world collaborative workplace worker product assembly processing time study

	Worker 1, age of 46 years								
CR speed (%)	Workers assembly processing time by product (s)								
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9
60	1.956	2.056	2.008	1.900	2.536	2.264	3.122	2.082	2.616
80	1.898	2.184	2.124	1.982	1.084	2.076	1.830	1.922	1.944
100	2.044	2.192	2.012	1.958	2.460	1.940	2.338	1.754	2.356
	Worker 2, age of 27 years								
CR speed (%)	Workers assembly processing time by product (s)								
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9
60	2.262	1.496	1.700	1.684	3.506	1.594	1.624	1.628	1.966
80	1.984	2.672	1.602	1.660	1.558	1.860	1.862	2.066	1.824
100	2.056	4.380	1.960	1.722	1.914	1.884	1.449	2.178	2.048
	Worker 3, age of 29 years								
CR speed (%)	Workers assembly processing time by product (s)								
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9
60	1.674	1.474	1.358	1.254	1.230	1.454	1.118	1.370	1.184
80	1.416	1.460	1.366	1.330	1.350	1.758	1.306	1.454	1.288
100	1.400	1.314	1.414	1.406	1.468	1.226	1.422	1.448	1.118
	Worker 4, age of 25 years								
CR speed (%)	Workers assembly processing time by product (s)								
	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9
60	1.406	1.922	1.242	1.358	1.366	1.240	1.594	1.380	1.700
80	1.126	1.552	1.196	1.016	1.698	1.152	1.362	1.336	1.164
100	1.770	1.566	1.644	1.106	1.682	1.658	1.478	1.222	1.222

The obtained results prove the expediency of introducing collaborative workplaces in the positions of manual workplaces with limited capacities. The positive impact of collaborative workplaces is reflected in the entire production system capacity increase.

Presented simulation results of manual workplaces prove that they can identify bottlenecks in the production system, which need to be eliminated to achieve higher production capacities. Described graphical and numerical results accurately describe the place where the introduction of a collaborative workplaces is appropriate. In the present case, this is the M_{as8} and M_{as9} workplaces, where the workplaces processing time is equal to the line takt time.

With the help of simulation modelling, we have introduced a collaborative workplace to this assembly line station, where one worker serves two collaborative robots. The collaborative robot operates in three different modes of speed and acceleration. Based on the results, we find that the correct setting of the speed of the collaborative robot is key to achieving full utilization of capacities of the collaborative workplace. It should be noted that exceeding the optimal speed of a collaborating robot may have a negative impact on the worker, as excessive speed and acceleration cause discomfort to the worker and longer waiting times for the robot to proceed with the next operation. At too high robot speeds and inability to achieve shorter assembly times on the side of the worker, congestion can occur due to poorly performed work of the worker. The correct choice of robot speed and the corresponding optimal process time of robot service is crucial, as evidenced by the simulation results of the collaborative workplace impact on the production system, where we see that the increasing robot speed beyond the robot service limit has no positive effect on the collaborative workplace production system. In general, we can see that elimination bottleneck in the manual assembly workstation can be eliminated by introducing collaborative workplace. In the evaluated case the costs of workplaces of entire production system have reduced by 8.34 %, the number of finished products has increased by 3.83 %, elimination of production system bottleneck decreased the remaining product in system by 93.67 %.

A detailed time study of the collaborative workplace confirms that all workers have an associated work rhythm that is not necessarily always the same for all workers. Since, we are talking about a collaborative workplace, where the robot cooperates directly with the workers, adjusting the processing time of the collaborative operation makes sense if this time is within the estimated time of the workplace, and it does not negatively affect the rest of the system utilization. It should be added that each worker has his own preferences regarding of the assembly position, both the worker and the robot (ergonomics and positions studies). Different workers feel more comfortable at different robot speeds. It makes sense to take all technological and sociological influences into account as much as possible when planning collaborative workplaces, thus ensuring maximum production system capacities.

5. Conclusion

In our research work, we have focused on presenting the impact of collaborative workplaces on the entire production process capacity, which is positive with the presented results. We presented various simulation models, both manual assembly workplaces, and the introduction and impact of collaborative workplaces on production capacity. A detailed time study of the assembly time impact of both the real-world collaborative workplace and the simulation model was presented. The presented results showed a positive degree of correlations and the specificity of the use of both approaches to achieve effective capacity planning. Of course, the results and findings, along with positive answers to the initial research question, raised many questions about how to optimally construct and prepare a collaborative workplace that could fully utilize both worker and robot capacities and effectively consider both technological and sociological aspects. In the future research work, we will focus on a detailed study of the technological and sociological aspects of collaborative workplaces and their correlation. Even though the presented research work deals with assembly line production, collaborative workplaces, with their great flexibility, can be used in different types of production at different workplaces. However, as can be seen from the results, their justification in relation to capacity utilization needs to be studied in detail in future.

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