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The Impact of Collaborative Robot on Production Line Efficiency and Sustainability

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Abstract: The global production tends towards more sustainable manufacturing, which forces manufacturers to constantly change and adapt. In our case, we are considering the FESTO CP LAB 400 production line, primarily designed for the training of personnel in the field of automation, which is essential for maintaining competitiveness in today's world. The production line consists of seven fully automated workstations and one manual assembly workstation, which represents the bottleneck of the production system. The paper presents a comparative study of the lines (human assembly vs. collaborative robot assembly) with an emphasis on economic and environmental aspects. The input parameters of the production line were obtained based on real-world measurements, while the assembly time of the collaborative robot was determined through simulation studies. The results of the study are presented graphically and numerically and confirm the contribution of the introduction of a collaborative robot to the assembly workstation in both financial and environmental terms.

Keywords: cobot; collaborative robot; manufacturing efficiency; production line; simulation modelling; sustainability

1 INTRODUCTION

The trend of the market has started shifting from mass production of identical products to mass-customization (low volumes and high variety). In order to maintain global competitiveness, companies strive for efficient and flexible systems that enable them to meet market demands [1]. Originally, line production was designed for mass production of standardized products, but with the emergence of new technologies and recent developments at automation and flexibility field, its use has expanded. The high cost of implementation, potential changes, and operation represent an important topic of discussion. Researchers have developed optimization models and methods to help manufacturers to achieve more effective systems. Despite the efforts of researchers, there is still a gap between real-world problems and the state of research [2]. The biggest problem in line production is bottlenecks, which determine product flow respectively system capacities. Fast and adequate identification of bottlenecks is essential to ensure adequate productivity of the system [3]. Therefore, engineers use both analytical and numerical approaches to identify bottlenecks. As the complexity of systems increases, human capabilities decrease. To cope with the complexity of the systems, the use of advanced computing environments is inevitable. The use of simulation tools allows us to model and analyse the system [4], and with the development of optimization methods and computer technology, it is now an important support and decision-making tool [5]. By using simulation, we can check the efficiency of system operation and the contribution of planned changes in a relatively short time and identify or analyse potential problem areas without interfering with the real system [6, 7]. The era of Industry 4.0 and the development of advanced technologies (IoT, Big Data, AI, remote monitoring, cloud computing) have contributed to the development of simulations. Researchers are particularly interested in the establishment of digital twins. The establishment of a digital twin not only helps to optimize operations, but also can help us in planning, maintenance, and sales by using advanced technologies [8]. The challenge of current globalization is to meet the needs of the market while ensuring all three aspects of sustainability: economic, environmental and social. The progress and development of Industry 4.0 provide various opportunities to introduce and implement sustainable manufacturing [9]. Research mentions various concepts, methods, and tools that contribute to a comprehensive treatment of sustainable manufacturing [10]. Increasingly, the development of standardized metrics for sustainable manufacturing is also being considered, which would enable different manufacturers to adopt a consistent approach [11]. To ensure efficient production and sustainable aspects at the same time, manufacturers must strive for changes at both the organizational and process levels. In recent years, the need for more flexible and efficient production systems has contributed to the increased interest in collaborative robots and their use in production processes. Collaborative robots differ from traditional industrial robots primarily in their ability to work with humans. There are also other differences between them, such as programming, manual guidance, shape, etc., but the collaboration allowed is the most important one [12]. Despite their ability to work with humans at the same time in the same space without safety barriers, collaborative robots still offer advantages such as speed, precision, and consistency [13]. The topic of collaborative robots is still relatively young, as the rise of the technology began with the development of Industry 4.0, so there is still much to explore in the world of research. However, there are already academic papers in research that showcase their contribution to efficiency and sustainability of the systems. Researchers cite various contributions of the implementation of collaborative robots into the production system and emphasize the importance of appropriate parameter settings to ensure optimal results [14]. Better support based on productivity analysis is needed for decisions on the acquisition and deployment of cobots (for single workstations and assembly lines) [15]. The role of system integrators could change in implementation projects for industrial collaborative robot applications [16]. The main challenges are in the areas of safety, knowledge, and functionality. Collaboration with a cobot that adapts to human variability is possible and could lead to better performance and improve certain dimensions of the system's usability [17]. There is a lack of models that can evaluate the use of cobots and lead decision makers to choose the most cost-effective configuration [18]. In assembly systems, task allocation is fundamental to properly assign the available resources. It is fundamental to ensure the safety of the human operator while working with the cobot [19]. Studies show that workers are more likely to assign manual tasks to the cobot than cognitive tasks [20]. Proper implementation and parameter setting of the collaborative robot contributes to the elimination of bottlenecks, more efficient system operation [21], and system sustainability [22]. The introduction of collaborative robots also affects the social aspect, as the proximity of a collaborative robot affects both the mental and physical health of workers [23]. In particular, the use of a cobot is proposed to reduce ergonomic risks for workers assembling, for example, cable harnesses [24]. However, more and more positive aspects can be seen, as the collaborative robot takes on heavier tasks and workloads, which relieves the worker and has a positive impact on their health [25]. Due to their versatility and advantages, the use of collaborative robots is becoming more and more common.

The main goal of this paper is to compare production lines with manual assembly workstations and with collaborative assembly workstations. We wanted to show the readers how easily we can improve our production system (cost reduction, energy reduction, increase the number of finished products, etc.), even if the implementation of the cobot seems extremely expensive at the initial stage.

In this study, we aim to investigate in detail the impact of a collaborative robot on the efficiency and sustainability of the FESTO CP LAB 400 production line. With the use of real process times and simulation modelling methods, a comparative study of production lines, a line with a manual assembly workstation and a line with a collaborative robot introduced into the assembly workstation will be conducted. The results of the study will focus on the economic and environmental aspects of sustainable production.

2 PROBLEM DESCRIPTION

Ensuring efficient operations and sustainability are among the most important aspects of today's world. Companies with constant improvements strive to perfect their systems and ensure these aspects, which ultimately reflects in profit.

In this work we study the production line FESTO CP LAB 400, which is designed for training personnel in the field of automation. The line is almost completely automated, so there are few opportunities for improvement. However, despite all the automation, the line contains a manual assembly workstation that is a bottleneck in the system. The manual workstation among the fully automated workstations has a major impact on the efficiency of the line, so it makes sense to optimize the assembly workstation. The proposed optimization step is to introduce a collaborative robot to the existing manual assembly workstation.

In the research work, we first conduct a study of the existing line, in which we confirm the existence of a bottleneck (manual assembly workstation) using simulation methods. Then, with the proposed optimization step (introduction of a collaborative robot) a study of the newly created production line is performed. The result of the work is a comparative study of production lines focusing on efficiency and sustainability.

2.1 Production System Description

FESTO CP LAB 400 production line consists of 8 workstations (Fig. 1). Seven of them (①, ②, ③, ⑤, ⑥, ⑦, ⑧) are fully automated and one (④) is a manual workstation. The working process includes operations such as: inserting the front cover, measuring the height of the cover, drilling holes, assembly (inserting the circuit board and two fuses), inserting the back cover, pressing the covers, labelling and sorting the finished products.

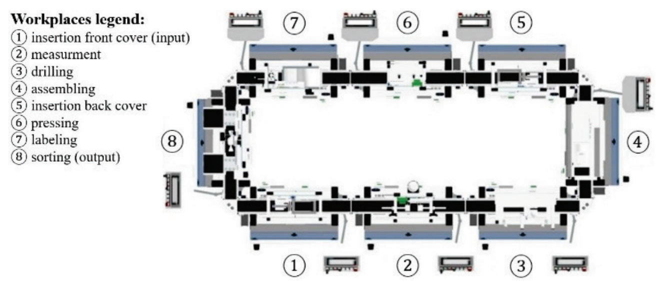

Figure 1 FESTO CP LAB 400 layout [26]

The final product is a "telephone", consisting of a front cover, a circuit board, two fuses, a back cover and a label (Fig. 2). It should be noted that the line FESTO CP LAB 400 is designed for training personnel in the field of automation, so the product complexity is low.

Figure 2 A set of components for the finished product

2.2 Sustainable Manufacturing

Ensuring aspects of sustainable manufacturing is an increasingly used concept in today's manufacturing. Sustainable manufacturing aims to improve the system in terms of environmental, economic and social aspects. All three aspects are equally important and together form a whole that allows companies to grow and have an advantage over their competitors. By ensuring sustainable manufacturing, companies strive to reduce their negative impact on the environment, improve their financial situation, and improve their social impact on people. The most common steps of sustainable manufacturing are to improve the efficiency of resources, to introduce the use of renewable resources, to implement a circular economy, to reduce excess materials, to reduce the use of hazardous substances, and to reduce the use of energy. The mentioned steps not only address one aspect of sustainable manufacturing, but also have a significant impact on the other two aspects. Reducing energy consumption not only helps to protect the environment, but also allows companies to improve their financial situation. Reducing the use of hazardous substances not only helps preserve the environment, but also makes it more humane and less harmful to people. The introduction of modern technologies enables more efficient operation of workplaces and processes, which affects both the financial situation of the company and the well-being of its employees. There are still many steps and contributions to be made, but it must be recognized that in today's world companies need to develop in this direction to provide a better future for all of us.

There are three reasons why we decided to use a cobot rather than a robot. The first reason was safety. The FESTO CP LAB 400 production line is designed to train personnel in automation. The learning groups consist of several people and during the lessons it is difficult to observe/control all participants, so using a cobot was a safer option. The second reason is the open access to the cobot. Without a protective fence or additional safety sensors, participants can observe the operation up close and explore the functions of the FESTO CP LAB 400 in the middle of the process. The third reason is that FESTO CP LAB 400 enables the production of different products. By using the cobot, we gain flexibility. We are able to change applications quickly and easily.

3 SIMULATION MODELLING APPROACH

The research work includes two studies. The SIMIO simulation environment was used to model and simulate both scenarios. The first study examines the existing assembly line with a manual workstation, while the second study examines a newly created assembly line with a proposed collaborative robot at the assembly workstation. Real process times were used to conduct the studies. The assembly time of the worker was determined based on multiple repetitions, while the assembly time of the collaborative robot was determined using the simulation environment. The presence of a worker in the production line leads to variations in the assembly time, so based on the obtained measurements of the assembly time, a random triangular distribution (± 10 %) was proposed for the assembly time of the worker for the purpose of the simulations**.**

The simulation scenarios include the following assumptions:

- The simulation lasts one working day, three shifts.
- Semi-finished products are always available.
- The products are delivered in batches of 500 pieces.
- The size of the buffer is unlimited.
- The transfer time between workstations is 9 seconds.
- The simulation results are based on the average values of ten replications of the simulation model.
- The electricity price is 0.2 €/kWh.

To perform the simulation studies, it was necessary to define the cost of the workstations [27]. In previous cases the same method has given us accurate results. Tab. 1 contains only the cost analysis of the manual assembly workstation (MA) and the collaborative robot assembly workstation (CA). The other workstations remained unchanged during the simulation studies, so they are not shown in detail.

Table 1 Workstations cost calculation data

Cost calculation parameter	MA	CA
Purchase value of the machine (€)	31250	61250
Machine power (W)	97	143
Workplace area (m²)	1.72	1.07
Depreciation period (year)	5	5
Useful capacity of the machine (h/year)	5049	5814
Machine write-off value (€/h)	1.238	2.11
Interest (€/h)	0.031	0.053
Maintenance costs (€/h)	0.062	0.105
Production system area costs (€/h)	0.041	0.022
Electrical energy consumption costs (€/h)	0.019	0.029
Machine operational costs (€/h)	1.238	2.319
Workplace total costs (€/h)	16.238	2.319
Workplace cost per batch (€/batch)	63.15	3.93

3.1 Production System Modelling

The MA workstation simulation model of the FESTO CP LAB 400 production line with an existing manual assembly workstation ④ is shown in Fig. 3. For the simulation study, the data from Tab. 2 and the assumptions from Section 3 were used. The simulation model simulated the operation of the production line of one working day, three shifts, with a useful operating time of 7.5 hours per shift, since the line had to be stopped during the lunch break. In the model itself, a utilization coefficient of 95 % was considered for fully automated workstations, while a utilization coefficient of 88 % was assumed for manual workstation due to the presence of a human.

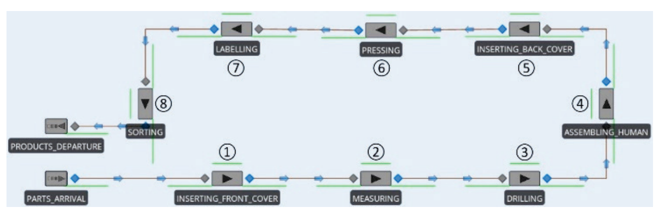

Figure 3 MA – simulation model of the production line with the manual assembly workstation

Table 2 Manual assembly-modelling parameters

Workplace	①	②	③	④	⑤	⑥	⑦	⑧
Process time (s)	1	3	4	T (25/28/31)	1	10	6	6
Operating costs (€/h)	1.27	1.27	1.27	16.24	1.27	1.27	1.27	1.27
Idle costs (€/h)	0.42	0.42	0.42	5.41	0.42	0.42	0.42	0.42
Energy consumption (W/h)	97	97	97	97	97	97	97	97

The process times in Tab. 2 were determined based on real measurements. The assembly time of the worker is the average value from several measurements. To obtain high quality results from the simulation model, a triangular random distribution was assumed for the assembly time of the worker. The other data in Tab. 2 come from the characteristics provided by the equipment manufacturer and the assumptions made for research purposes.

The manual assembly workstation ④ represents the bottleneck of the production line, which is confirmed numerically in Section 4. The introduction of a collaborative robot was proposed as an optimization step. Fig. 4 shows the CA workstation simulation model of the newly proposed production line with the introduced collaborative robot at the assembly workstation ❹. The simulation model used the data from Tab. 3 and the same assumptions as the previous model. With the introduction of the collaborative robot, the production line became fully automated, so a utilization coefficient of 95 % and a useful operating time of 8 hours per shift were assumed for all workstations. Again, a working day with three shifts was simulated.

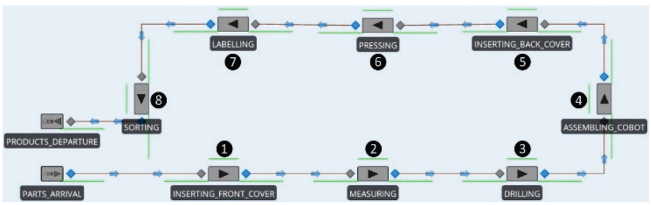

Figure 4 CA – simulation model of the production line with the collaborative robot assembly workstation

Tab. 3 shows the process times, operating and idle costs and energy consumption of each operation. Except for the process time of the assembly workstation ❹, process times of remain workstations did not change. Despite the introduction of a collaborative robot, the assembly workstation still represents the bottleneck of the line.

Table 3 Collaborative robot assembly-modelling parameters

Workplace	❶	❷	❸	❹	❺	❻	❼	❽
Process time (s)	1	3	4	12.2	1	10	6	6
Operating costs (€/h)	1.19	1.19	1.19	2.32	1.19	1.19	1.19	1.19
Idle costs (€/h)	0.40	0.40	0.40	0.77	0.40	0.40	0.40	0.40
Energy consumption (W/h)	97	97	97	143	97	97	97	97

3.2 Collaborative Workplace Modelling

To determine the assembly time of the collaborative robot, it was necessary to model the assembly workstation with the collaborative robot. The model of the collaborative robot workstation and the assembly simulation were created in Siemens Tecnomatix Process Simulate. The simulation model included the UR3e collaborative robot, the Robotiq 2F-85 collaborative gripper, a worktable, a conveyor belt, and the components required for assembly (front cover, circuit board, fuses), as shown in Fig. 5.

The collaborative robot assembly operation was performed in the same order as the manual assembly operation. In the initial stage, the collaborative robot (I) waited for a signal that the front cover (V) had arrived at the assembly location. The arrival of the front cover (V) at the specified position triggered a signal to start the assembly process. The collaborative robot (I) first inserted the circuit board (VI) into the front cover (V) and then placed two fuses (VII) on the circuit board (VI). After the assembly was completed, the collaborative robot triggered the continuation of the process.

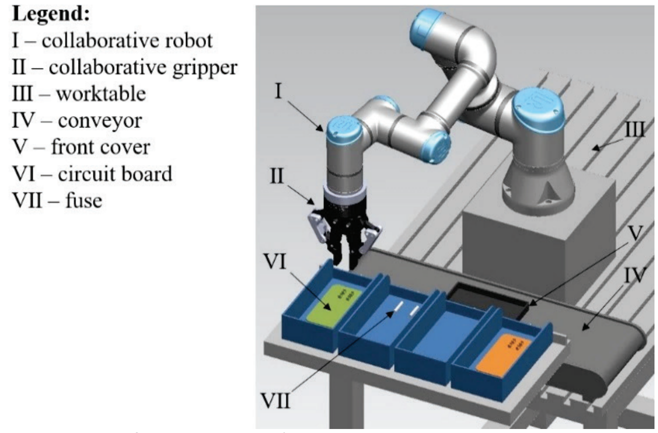

Figure 5 Simulation model of collaborative robot assembly workstation

In the simulation, the speed and acceleration of the collaborative robot from Tab. 4 were used. Move L is used to move the tool centre point linearly to a given destination at a certain speed and acceleration. All cobot joints will rotate as needed, to ensure the tool centre point stays on path with a consistent orientation. Move J is similar to Move L with the exception that the tool centre point does not move along a straight path. The cobot (tool centre point) will move to the destination along a non-linear path. The defined speed and acceleration correspond to 1/3 of the maximum value specified by the manufacturer (Universal Robots) for safety reasons. If the study were not purely academic, higher values would be used for research, but these values should be tested on a real collaborative robot to ensure proper and safe operation. Higher speed is not recommended for training.

Table 4 Collaborative robot speed and acceleration data

	Move L	Move J
Speed	333 mm/s	120 °/s
Acceleration	833 mm/s^2	267 °/s^2

4 RESULTS

In this section, the results of the MA and CA workstations scenarios are presented numerically and graphically. First, the results of each study are explained individually then a comparative study between the scenarios MA and CA is conducted. In a comparative study, we analyse the utilization of the workstations, the number of finished products, the cost per batch, and the energy consumption.

4.1 Manual Assembly

Tab. 5 shows the results of the production line (MA). Workstations ①, ②, ③ and ④ are fully utilized. Workstation ① is 100 % utilized because the study assumes that the input components are always available. Workstations ② and ③ are almost 100 % utilized, which is due to the short processing times of the previous operation. Workstation

④ represents a bottleneck of the line, which is evident from the results, as the utilization of the line from workstation ④ to workstation ⑤ drops from almost 100 % to 3.57 %, which corresponds to only 0.8 hours of operation time out of a possible 22.5 hours. The utilization of the subsequent workstations is relatively low, which is of course a consequence of the bottleneck and a low further input quantity of components. Simulation results based on ten replications of the scenario predict that the line will produce 2890 finished products and consume 12831 W of electrical power in a working day with a useful time of 22.5 hours. The cost of the batch is 71.4 €, and 2220 W of electrical energy is used to produce 500 finished products.

Table 5 Results of production line with manual assembly workstation

Workplace	①	②	③	④	⑤	⑥	⑦	⑧
Utilization (%)	100	99.99	99.97	99.96	3.57	35.70	21.42	21.41
Time processing (h)	22.50	22.50	22.49	22.49	0.80	8.03	4.82	4.82
Operating costs (€)	28.60	28.59	28.59	365.20	1.02	10.21	6.12	6.12
Idle costs (€)	0	0.001	0.003	0.05	9.20	6.13	7.50	7.50
Cost per batch (€)	0.2	0.5	0.5	65	0.2	2	1	1
Energy consumption (W)	2183	2182	2182	2182	779	1247	1039	1038

4.2 Collaborative Assembly

The introduction of a collaborative robot has contributed to the complete automation of the production line. With a fully automated line, we were able to increase the number of useful hours to 24 hours per working day. The utilization of workstations ❶, ❷, ❸ and ❹ remains unchanged compared to the previous scenario (MA), while the utilization of the other workstations in the line has increased. However, despite the introduction of the collaborative robot, the assembly workstation ❹ remains a bottleneck in the line as it is still fully utilized, followed by a significant decrease in the utilization of workstation ❺, which illustrates a lack of input semi-finished products compared to the available capacity of workstation ❺. In Tab. 6, we see that the utilization of workstation ❺ increased from 3.57 % to 8.19 % compared to workstation ⑤, which contributed to an increase in the number of finished products to 7074. The power consumption of the production line in a working day is 16467 W, which is higher than in the previous scenario (MA), since the presence of the collaborative robot must be considered. Based on the quantity of finished products, the cost of the batch is 9.05 € and 1164 W of electrical energy is consumed.

Table 6 Results of production line with collaborative robot assembly workstation

Workplace	❶	❷	❸	❹	❺	❻	❼	❽
Utilization (%)	100	99.99	99.98	99.96	8.19	81.91	49.13	49.13
Time processing (h)	24	24	24	24	1.97	19.66	11.79	11.79
Operating costs (€)	28.44	28.44	28.43	55.63	2.33	23.29	13.97	13.97
Idle costs (€)	0	0.001	0.002	0.008	8.70	1.72	4.82	4.82
Cost per batch (€)	0.15	0.5	0.5	4	0.15	1.5	1	1
Energy consumption (W)	2328	2328	2355	3431	902	2047	1538	1538

4.3 Results Comparison

Fig. 6 graphically shows the utilization of workstations in MA and CA scenarios. By introducing a cobot into the production line (CA), we were able to increase the line utilization by 13.3 % compared to the production line (MA) with the existing manual assembly workstation. However, despite the introduction of a cobot, the assembly workstation remains a bottleneck. The capacity of the cobot assembly workstation is still insufficient, considering the process times of previous operations. As shown in Fig. 6, by reducing the assembly time in the CA scenario, the utilization of the workstation ❻ increases rapidly, which would become a new bottleneck after further optimization of the cobot assembly workstation and ensuring an assembly time of less than 10 seconds.

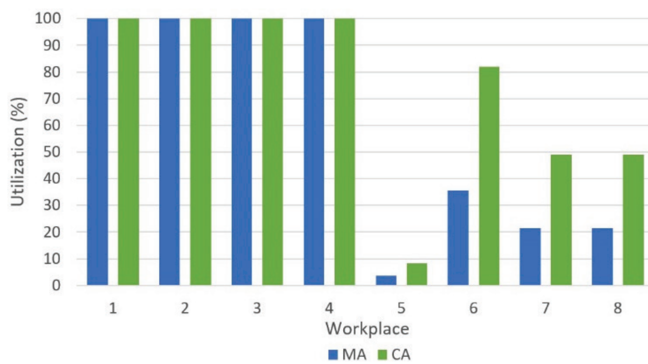

Figure 6 Utilization MA vs CA workstation

The introduction of a cobot enabled 7074 finished products in a working day, which is 144.8 % more than can be produced with the MA production line (Fig. 7).

Figure 7 Finished products MA vs CA workstation

The cost per batch comparison is shown in Fig. 8 and is extremely interesting as costs drops rapidly. With the introduction of the cobot, we were able to reduce the batch cost by 87.3 %, which is difficult to imagine before running simulations given the high investment costs associated with the introduction of a cobot.

In today's world, companies are looking to reduce energy consumption as it relates to both financial and environmental aspect. The energy consumption of the collaborative robot was 3431 W per working day (Tab. 6), while the energy consumption of the manual assembly workstation was only 2182 W (Tab. 5). However, conclusions cannot be made immediately, it is important to consider the useful number of hours per day for each production line and the number of finished products. Fig. 9 shows the energy consumption per batch. Based on further calculations, the comparison of the lines shows that the energy consumption per batch with the use of the cobot is 47.6 % lower than the energy consumption of the MA production line.

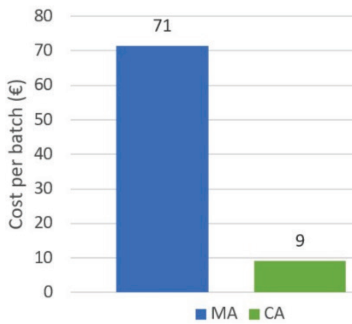

Figure 8 Cost per batch MA vs CA workstation

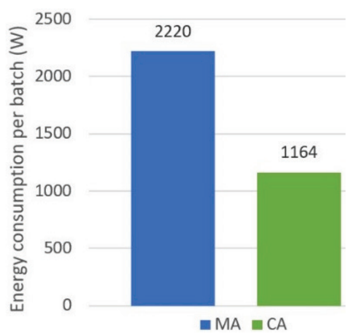

Figure 9 Energy consumption per batch CA vs MA workstation

5 CONCLUSIONS

In the research work, we study the production line FESTO CP LAB 400 using simulation modelling methods. In this study, we focus on the efficiency of the production line and aspects of sustainable manufacturing. The FESTO production line was developed to train staff in automation and to demonstrate the values of Industry 4.0. Automation of production is becoming increasingly widespread as companies try to achieve global competitiveness, which is difficult to achieve in today's world. The featured line demonstrates modern automation approaches very well, as it contains seven fully automated workstations and only one manual assembly workstation. Manual workstations are usually a problem in well-automated production lines, as human skills are not comparable machines.

A simulation study of the existing production line showed that the manual assembly workstation was a bottleneck in the line. The introduction of a collaborative robot at the assembly workstation was proposed as an improvement. The results of the comparative study showed that the introduction of a collaborative robot has a positive impact on the production line. With the help of a collaborative robot, the overall line utilization was increased by 13.3 %, productivity increased by 144.8 %, which meant 4182 more finished products at the same time, operating costs and batch costs decreased, and the negative environmental impact in the form of electricity consumption was reduced by 47.6 %.

Many questions remain open for further research. From the viewpoint of sustainability, the social aspect should be studied. The social aspect is definitely present due to the introduction of a collaborative robot at the worker's workplace and the removal of the worker. From the point of view of the efficiency of the production line, the parameters of the collaborative robot need to be optimally defined and not only based on the assumptions of the manufacturer of the collaborative robot.

Although the research study was only informative and based on assumptions that real production systems cannot provide, it can be concluded that the proper implementation of a collaborative robot and the adjusted parameters help to eliminate bottlenecks and have a positive impact on the efficiency of the production line FESTO CP LAB 400 and the considered aspects of the sustainable manufacturing.

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