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IMPORTANCE OF SUSTAINABLE COLLABORATIVE WORKPLACES – SIMULATION MODELLING APPROACH

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Abstract
The paper presents the use of simulation modelling methods to evaluate the impact of the collaborative workplaces (human-robot collaboration) importance in correlation to the sustainable manufacturing. Based on an example, numerical simulation results of an existing manual assembly workplace and a newly proposed collaborative workplace are presented using production parameters that describe all three key aspects of sustainable manufacturing: economic, social and environmental aspect. A data-driven simulation model was used, mainly using the input parameters of the real-world production system and numerical assumptions obtained from the literature, with the main objective of detailing the impact on the sustainable orientation of the production process. The results presented in the paper demonstrate the high suitability of simulation modelling methods in the evaluation of existing and newly proposed technologies from the sustainable manufacturing point of view. The results demonstrate that collaborative workplaces, if implemented appropriately and using correct input data, are a possible solution that can cope with limited human resources and ensure high production efficiency.
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Key Words: Sustainable Manufacturing, Manufacturing Efficiency, Collaborative Workplace, Collaborative Robot, Cobot, Simulation Modelling

1. INTRODUCTION

At a time when the need for optimized production systems is growing, the question of their sustainable justification is increasingly raised in the global environment. The global need for efficient use of natural resources, aligned with high efficiency of production systems and acceptable from a social point of view for production and service companies, is an optimization challenge that needs to be thoroughly investigated in the era of Industry 4.0 and in the future [1]. The use of different optimization methods that have been well applied/used so far [2] and new approaches that focus on the use of social resources [3] allow the implementation of new multicriteria optimization methods supported by artificial intelligence methods [4]. The importance of a sustainable approach applies not only to manufacturing environments but is also increasingly present in service processes [5], where the dynamics of the market and the adaptability of the company play a key role in achieving global competitiveness [6]. According to current forecasts, urgent constraints on energy consumption [7] are predicted for the European economy (even widely), which will certainly be reflected in the process of developing new sustainable products [8] and the competitiveness of European companies in the global market. When using predictive models, data-driven optimization methods [9] are crucial to achieve efficient and reliable results. Data processing [10] enables the optimization of production systems in various fields [11, 12], which expresses the need for the introduction of new production technologies with the increasing global demand for efficient, sustainable production systems. In the era of Industry 4.0 and the transition to the introduction of collaborative machines (human-robot collaboration), which enable high adaptability and satisfactory efficiency, the question of their sustainable justification is a challenge to be investigated [13]. Collaborative robots, in addition to their advantages that enable an increase in production capacity, pose a challenge to the technical staff that introduces them to the work process [14]. The appropriate configuration in the different application areas is the key to achieve their effectiveness [15]. It should be emphasized that inefficiently used capacities of a collaborative robot can negatively affect the underutilization of other collaborative operations of the work process [16]. Considering the high job dynamics and the degree of flexibility that collaborative robots enable [17], studying their effectiveness is crucial for a sustainable manufacturing justification [18]. Ergonomically designed workplaces significantly influence the satisfaction of workers in a way to achieve efficient production systems and their sustainable justification [19]. The methods that have proven effective are simulation modelling methods [20], but so far researchers have not been able to link the importance of collaborative workplaces to the sustainable orientation of the production process [21, 22]. The issue of sustainable orientation primarily touches on the environmental significance of introducing new machines into the production environment [23], but at the same time it also touches on the social aspect of workers [24]. In most cases, when evaluating the environmental and social perspectives of the sustainable justification of production systems, the evaluation of the production costs and initial investments required for the introduction of collaborative workplaces is of primary importance to companies [25]. Due to the lack of a comprehensive valuational approach of simulation modelling in evaluating collaborative workplaces from the perspective of sustainable production [26], we show the importance of studying the sustainable justification of collaborative workplaces in this research. Efficient operation of collaborative workplaces could be additionally facilitated with digital production control based on the Internet of Things [27].

Fig. 1 shows a block diagram that we use to propose the introduction of simulation modelling methods in the evaluation of collaborative workplaces (human-robot collaboration), focusing on all three key aspects of sustainable manufacturing. The parameters of the three sustainable manufacturing aspects are discussed and presented in three blocks indicating the economic, environmental, and social aspects that are evaluated in this research. Given the research question of whether collaborative workplaces are the key to global competitiveness in the face of increasing demand and limited human resources, we aim to answer this question with a developed simulation model that encompasses all aspects and effectively represents the link between the simulation model and implementation in a real-world production environment.

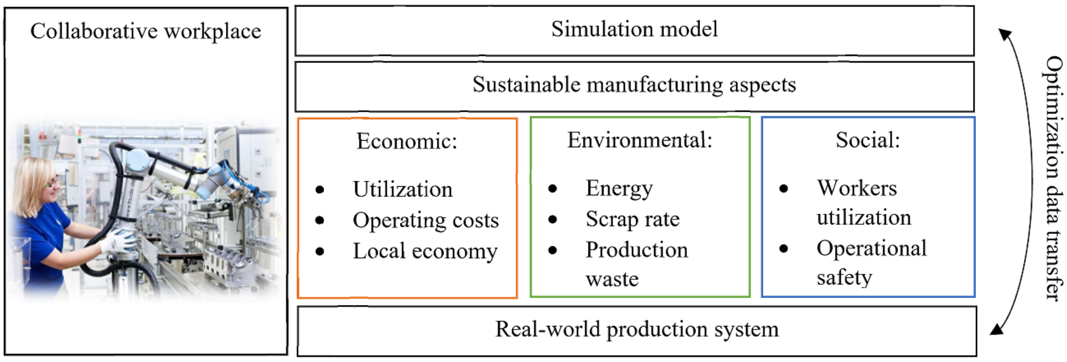

Figure 1: Research proposal block diagram.

2. PROBLEM DESCRIPTION

The discussed investigation problem represents a problem that is common in the everyday production environment. Production companies usually have predetermined production goals that they set based on production technology and available capacity. However, due to various losses (mostly time and available production capacity), the actual number of produced quantities is lower than expected. The main problem is the evaluation approach that companies (especially small and medium enterprises) use to increase the efficiency of their production capacities. The problem discussed shows the evaluation of a production system in which two workers assemble products in six operations. The company wants to produce 1000 products in one shift, but despite all efforts, they fail. In the conducted research, we focused on two optimization steps using simulation modelling methods, in which we evaluate the current actual situation and the proposed improvement using a collaborative robot. The main added value of the research work is the evaluation of the assembly production system efficiency parameters describing the manufacturing system sustainability justification.

2.1 Sustainable manufacturing

A growing number of companies are considering sustainable manufacturing as a key objective in their strategy and operations to drive growth and global competitiveness. Sustainable manufacturing is the production of products using a process that minimises negative impacts on the environment, conserves energy and natural resources, and is safe for employees, communities, and consumers. The overall goal of sustainable manufacturing is to look at the entire product cycle and optimise the life cycle of manufacturing systems, products and services. Sustainable manufacturing not only produces more sustainable products, but manufacturing processes also become more sustainable, increasing a company's overall benefit to society and the environment.

Fig. 2 shows a block diagram of the elements that describe sustainable manufacturing. The elements comprehensively deal with an effective approach to manufacturing optimization, where the main problem is precisely the ability to evaluate the current situation using collected and existing operational data, and to propose improvements that positively affect a larger number of optimization parameters of sustainable manufacturing. In the present research work we focus on all three main areas describing the economic, environmental and social aspects. We focus on the parameters of production capacity utilization, operating and idle costs, electricity consumption, number of pieces produced and condition of process scrap rate. The work emphasizes the importance of the social aspect from employee utilization and occupational safety.

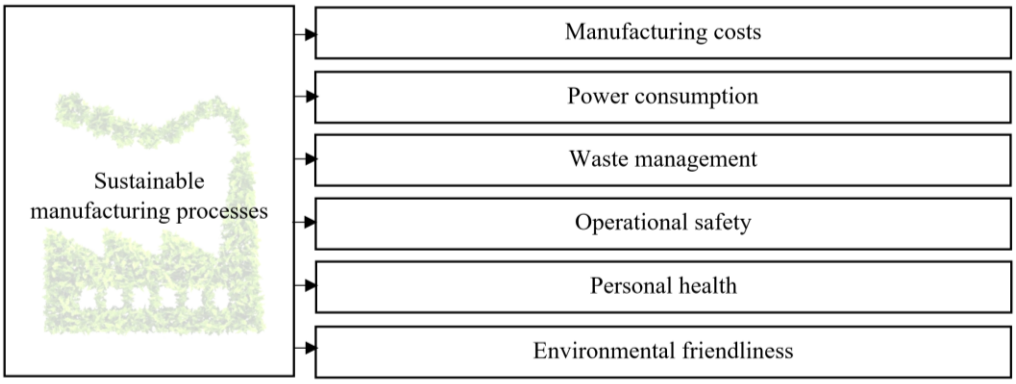

Figure 2: Elements of sustainable manufacturing.

2.2 Collaborative workplace

Collaborative workplace is a work style that helps employees work together to achieve a common goal that benefits a production or service companies and its employees. In our case we evaluate collaborative workplace between employee and collaborative robot (Cobot). In this research, we present a simulation modelling method in which the collaborative workplace of two workers is replaced by a collaborative workplace between a Cobot and a worker. Fig. 3 shows the advantages and limitations of a Cobot designed to collaborate directly with a worker. In this case, the Cobot enables an increase in production efficiency, allows flexibility, and is relatively easy to operate and adapt to a new workspace (work process) compared to industrial robots. Given the known characteristics of robots, the Cobot enables a higher level of quality with a corresponding level of repeatability and robustness. When introducing a Cobot, the question of replacing or removing a worker from the robot's workspace arises. In addition, the exact impact of the collaborative machine on the worker interacting with it is unknown. Also questionable for manufacturing companies is the initial investment cost, which is generally lower than purchasing an industrial robot, but still higher than the cost of human labour in developing or less developed countries. In developed world countries with labour shortages, Cobot can fill the gap of missing personnel in monotonous, dangerous or toxic operations. However, the investment cost is decreasing year by year as new technologies are developed and Cobots become more widespread. In addition, the company must provide trained technical personnel to enable smooth operation of the robot, expand the range of their flexibility, and ensure optimized (utilized) capacity.

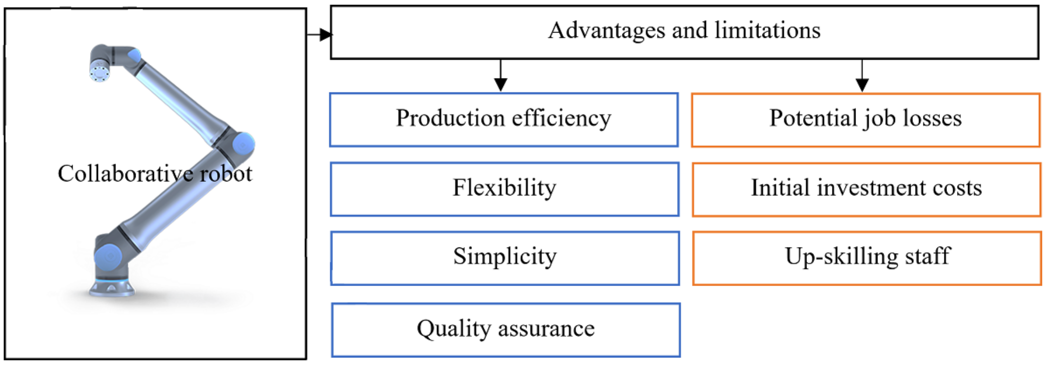

Figure 3: Collaborative robot’s advantages and limitations.

3. SIMULATION MODELLING APPROACH

The research work is based on the use of the data-driven simulation modelling method. The Simio software environment was used, in which a model of a real-world production system was modelled and a comparative model in which a collaborative workplace was assumed. The method used allows taking into account a 15 % variation of production parameters (process time of individual operations) using two random distributions (triangular and uniform). The simulation model takes into account following assumptions and constraints:

- The shift time is 7.5 hours.
- The simulation experiment assumes a 2-hour warm-up period.
- The simulation results are based on the average values of ten repetitions of the simulation model runs.
- New parts arrivals are constant relative to the real-world situation and appear in the system every 13.5 seconds.
- Semi-finished products and components are always available.
- There are no interruptions when the operation starts.
- During each operation, the transfer time is zero.

3.1 Manufacturing system

The production system represents a manual assembly workstation, assembling products in six operations performed by two workers. The operations are: Preparation assembly parts, Insertion of parts 1, Screwing, Insertion of parts 2, Covers assembly and Finishing and packaging. The workplace model is shown in Fig. 4. The workers help each other to perform the operations in as short as possible time and there are no fixed operations that are performed exclusively by one worker. The company assumes that two workers can assemble 1000 parts per shift.

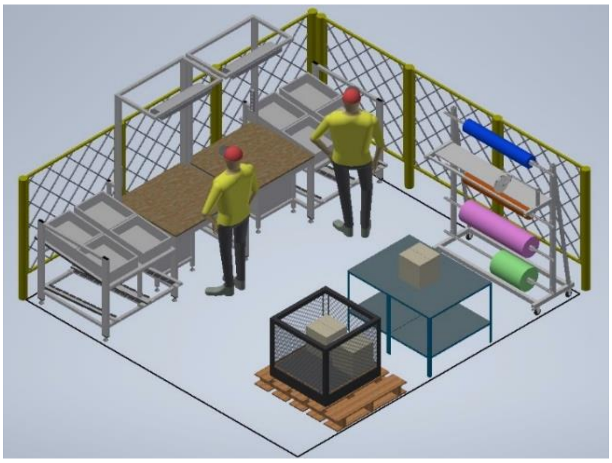

Figure 4: Manual assembly workplace – 3D model.

Table I shows the process times of each operation, which were determined using the normative times assumed by the company and the process times determined from the production system workplaces time study. We have found that it is necessary to use random distributions when building a simulation model because the normative times are not constant due to the nature of manual assembly tasks. We have used two distribution types, depending on times nature. In the paper triangular distribution is labelled with T (min, mode, max) and uniform distribution is labelled with U (min, max).

Table I: Manual assembly process times.

Operation	Preparing parts	Inserting parts 1	Screwing	Inserting parts 2	Inserting covers	Finishing & packaging
Process time (s)	T (7.65, 9, 10.35)	T (11.05, 13, 14.95)	U (25, 29.1)	T (15.3, 18, 20.7)	T (10.2, 12, 13.8)	T (12.75, 15, 17.25)

3.2 Manufacturing sustainability

In modelling the sustainability of assembly operation, we focused on the three main areas that sustainable manufacturing tracks: economic, environmental, and social. In modelling the economics of operations, we focused on modelling operational and idle costs for the operation to be performed. As shown in Table II, based on the literature [6] and real-world production parameters, we assumed the specified operating and idle costs for the work. When modelling the environmental justification of the manual assembly workplace, we focused on the currently very important area of optimized electrical power consumption [7], which is described by the parameter energy consumption in Table II. The given parameters and the process time parameter listed in Table I allow us to monitor the utilization rate of employees, which can be classified as a social area in the field of sustainable manufacturing.

Table II: Manual assembly modelling parameters.

Operation	Preparing parts	Inserting parts 1	Screwing	Inserting parts 2	Inserting covers	Finishing & packaging
Operating costs (EUR/h)	35	36	31	35	37	33
Idle costs (EUR/h)	14	14.4	12.4	14	14.8	13.2
Power consumption (W)	1150	950	1800	950	950	1370

Fig. 5 shows the data-driven simulation model, which includes the data listed in Table I, Table II and the assumptions and constrains from the beginning of section 3. In addition, in environmental suitability workplace modelling, the model takes into account process scrap rate (environmental waste aspect), which is in averages 12 % for manual assembly, where the model assumes a random triangular distribution T (10, 12, 14).

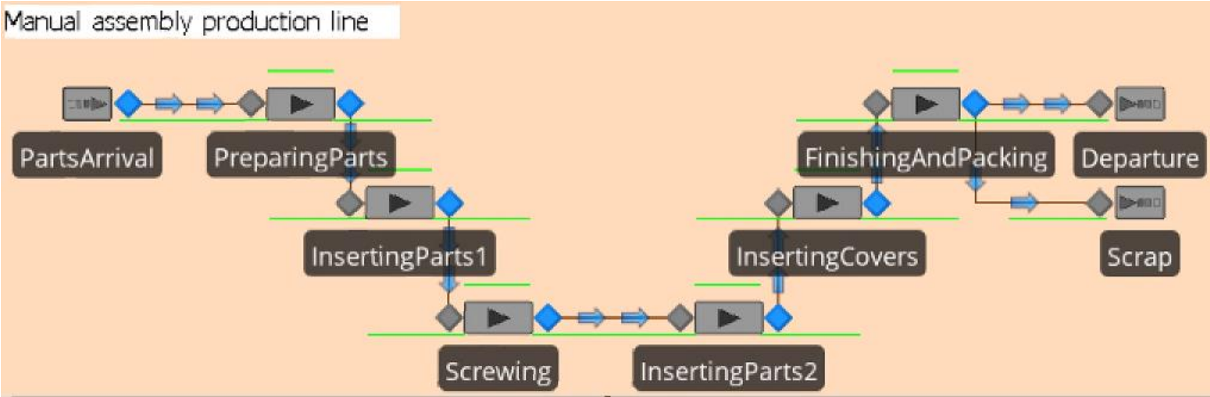

Figure 5: Simulation model of the manual assembly production line.

3.3 Collaborative workplace modelling

Being aware of the bottleneck in the two operations of Inserting parts 1 and Screws (the constraints of these two operations were indicated by the input data of the simulation model), we decided to perform a simulation analysis of the introducing a collaborative workplace feasibility (collaboration between workers and a Cobot). In the collaborative operations, the Cobot performs two operations: Inserting parts 1 and Screwing; we added the note 'Robot' to these two operations in the Table III. The worker performs all other operations. Compared to the previous situation where we had two workers, the operations are now performed by one worker and one Cobot. The process times of the worker assembly operations did not change but based on the properties of the selected Cobot (UR 3e), we assumed constant process times for two collaborative operations. As mentioned in section 3.2, we also modelled the sustainable justification of a collaborative workplace, using literature [13] and assumptions to adequately describe the economic, environmental, and social impact parameters of a collaborative workplace.

Table III: Collaborative workplace modelling parameters.

Operation	Preparing parts	Inserting parts 1 (Robot)	Screwing (Robot)	Inserting parts 2	Inserting covers	Finishing & packaging
Process time	T (7.65, 9, 10.35)	11.2	31	T (15.3, 18, 20.7)	T (10.2, 12, 13.8)	T (12.75, 15, 17.25)
Operating costs (EUR/h)	35	41	41	35	37	33
Idle costs (EUR/h)	14	20.5	20.5	14	14.8	13.2
Power consumption (W)	1150	1230	1230	950	950	1370

In Fig. 6, the red coloured rectangle shows the assembly operations performed by the Cobot. In contrast to the simulation model, where the process scrap rate was considered to be 15 % on average, we have now assumed an average value of 4 % with the random distribution T (3, 4, 5) used, following the literature [28]. The significantly lower process scrap is due to the more constant execution of the assembly operations by the Cobot, which enables a more consistent and reliable operation of the assembly line due to its constancy and robustness.

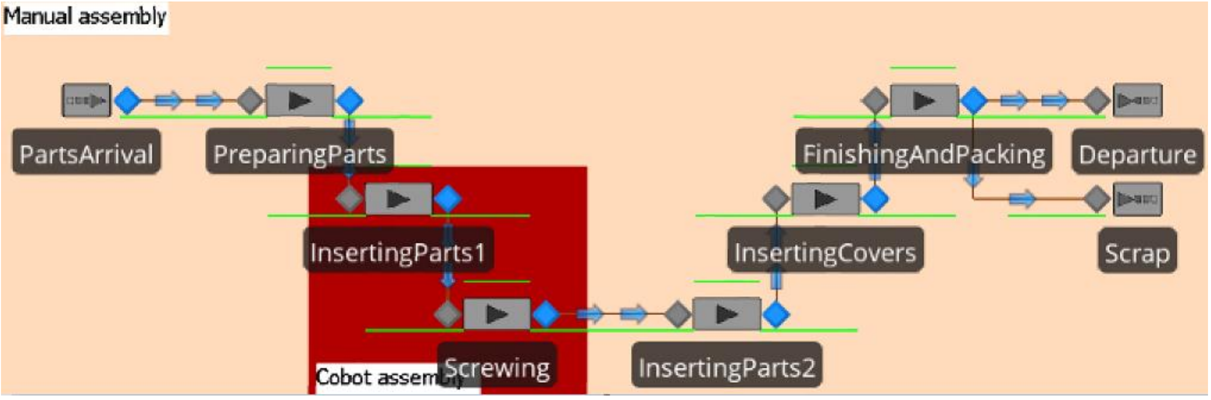

Figure 6: Simulation model of the collaborative workplace assembly production line.

4. RESULTS

In this section we present the numerical and graphical results of the manual vs. collaborative workplace manufacturing sustainable eligibility. When evaluating the manual assembly workplace, we focus on the specific operations bottleneck evaluation, based on which we propose the introduction of a collaborative workplace, Cobot that would replace a worker in determinate critical operations. In presenting the results, we focus on the study of seven optimization criteria that describe the sustainable justification of the studied workplaces comparison from an economic, environmental, and social perspective. In the results, MW stands for manual assembly and CW for collaborative workstation operation.

4.1 Manual assembly

Table IV shows the numerical results of the MW evaluation regarding manufacturing sustainability parameters. Studying the parameter of utilization of two workers performing assembly activities, we see a bottleneck in the two activities of Inserting parts 1 and Screwing, which lead to a decrease in the total production capacity, although the two workers are on average 70.97 % utilized when performing the operations. Due to the turnover and uneven utilization in manual assembly operations, the standard deviation is high at 20.87. The uneven distribution in the execution of assembly operations is also evident in the Time processing parameter, which also clearly shows the bottlenecks in the assembly process, based on which we propose the implementation of the collaborative machine (Cobot) performing these two operations. With the help of the literature [6], we have also performed a detailed analysis of the Operating and Idle costs, finding that the assembly cost for a MW totals 1562.87 EUR or 1.82 EUR per piece. Based on the evaluation of idle times, we have numerically determined the parameter of Idle costs (that significantly increase in case of bottlenecks), which in the case of manual assembly workplace is 183.8 EUR or 0.21 EUR per piece. It should be emphasized that idle costs cannot be allocated to the final selling price of the product but represent an irreparable burden for the company. In the present case, these costs amount up to 11.5 % of the product production value. Considering the current issue of energy consumption, where the EU imposes certain restrictions on companies, an assessment was made of the electrical energy consumption, which in the present case amounts to 39.3 kWh, which, given the number of products produced per shift, amounts to 48.8 Wh per piece. According to the insulted quantity of assembled products in a shift, indicated by the company, which is desired 1000 pieces, we note that with the evaluated system the quantity produced falls short and is 857 pieces. Considering this value and the value of the process waste, which amounts to 130 pieces, we conclude that the optimization of the MW is the key to achieving the desired production values and a sustainable justified manufacturing process.

Table IV: Manual assembly workplace results.

Operation	Preparing parts	Inserting parts 1	Screwing	Inserting parts 2	Inserting covers	Finishing & packaging
Utilization (%)	66.40	96.86	99.86	65.54	43.27	53.89
Time processing (h)	4.98	7.26	7.49	4.91	3.25	4.04
Operating costs (EUR)	174.31	261.53	696.58	176.98	120.09	133.38
Idle costs (EUR)	35.28	3.38	0.37	36.17	62.96	45.64
Energy consumption (Wh)	5727	6897	13482	4664.5	3087.5	5534.8
∑ **Number of finished products** (pcs)				857		
∑ **Scrap** (pcs)				130		

4.2 Collaborative assembly

When introducing a collaborative machine (Cobot) into the CW, in this case the Cobot performs the operations of Inserting parts 1 and Screwing, we find that these two operations are no longer the bottleneck of product assembly. We find that the average utilization of the worker and the Cobot is 78.83 %, with a standard deviation of 11.53. Based on the numerical results, we conclude that in the case of CW, the operations are more evenly occupied, but it is necessary to further study the most heavily utilized operation in this case, Inserting parts 2. After the additional study, it would be useful to transfer part of this operation to a Cobot if technologically possible.

Using the CW simulation model, we find that the optimization parameter Time processing correlates with the utilization parameter of the operations. The cost analysis shows the total operating costs of operations and the idle time for the operations to be executed. The total operating cost of operations is 1586.48 EUR or 1.10 EUR per piece, which leads to the conclusion that the collaborative workplace can produce 1440 pieces in one shift by implementing CW with Cobot. The total waiting cost is 226.44 EUR or 0.16 EUR per piece. The introduction of the additional energy consumer (Cobot) changes the considered parameter of electricity consumption, which in the case of CW totals 40.6 kWh or 28.2 Wh per piece. By increasing the production capacity, we reduce the necessary consumption of electrical energy per piece produced, which has a positive impact on both the economic and environmental aspects of such a workplace. By introducing the Cobot, while taking advantage of its reproducibility and robustness, the assembly operation has been able to reduce the scrap rate from 12 % before to 4 % based on the analysis, which has a significant impact on the number of parts in scrap, which is now 58 parts per shift. By reducing process emissions, we positively impact the justification parameter of environmental sustainability of the proposed CW by reducing the consumption of natural resources and materials. When selecting a collaborative machine, we emphasize the importance of work safety parameter between the worker and the Cobot, which increases the level of safety and consistency of the work.

Table V: Collaborative assembly workplace results.

Operation	Preparing parts	Inserting parts 1 (Robot)	Screwing (Robot)	Inserting parts 2	Inserting covers	Finishing & packaging
Utilization (%)	66.26	82.94	76.46	99.81	65.82	81.71
Time processing (h)	4.96	6.22	5.73	7.48	4.94	6.13
Operating costs (EUR)	173.94	255.04	705.34	269.49	182.67	202.25
Idle costs (EUR)	35.42	26.23	108.57	0.19	37.93	18.10
Energy consumption (Wh)	5704	7650.6	7047.9	7106	4693	8398.1
∑ **Number of finished products** (pcs)				1440		
∑ **Scrap** (pcs)				58		

4.3 Results comparison

Graphical results in Fig. 7 show a comparative analysis between a MW and a CW. In terms of worker and Cobot utilization parameter, we see that the average occupancy increases by 11.1 % with the introduction of a CW compared to MW.

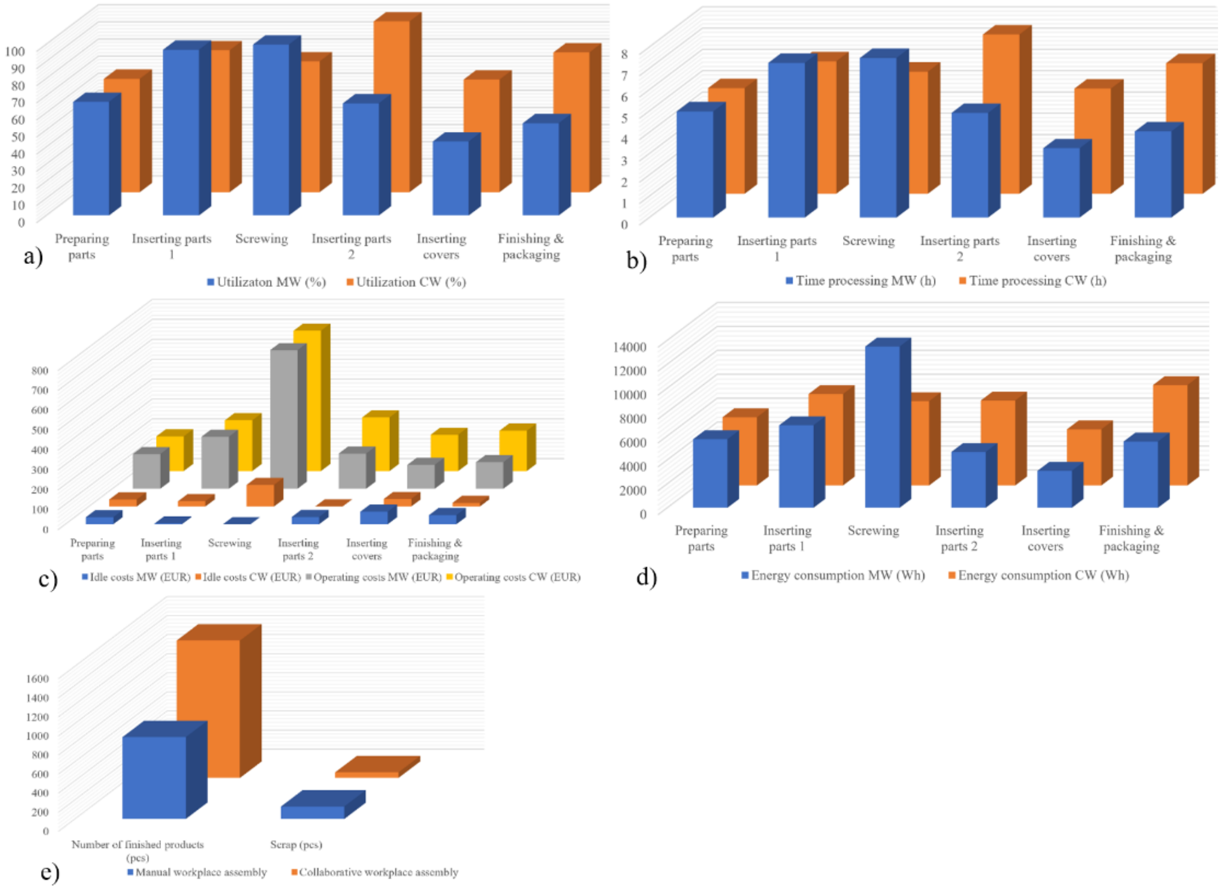

Figure 7: Results comparisons of MW vs CW: a) Utilization, b) Time processing, c) Idle and Operating costs, d) Energy consumption and e) Number of finished products and Scrap quantity.

Fig. 7 a shows a more consistent occupancy during operation, allowing for a more consistent product flow and a more predictable and efficient assembly. As mentioned in the previous two subsections, the time processing parameter, shown in Fig. 7 b, also confirms the efficiency associated with utilization.

Analysing the economic justification of a MW or a CW, we see that a CW significantly reduces the operating cost in relation to the piece produced, from 1.82 EUR per piece to 1.10 EUR per piece, which means 39.6 % lower production costs when Cobot is implemented. Considering that the efficiency of production is higher when CW is implemented, in addition to the lower production cost, the cost of idle time during assembly is also reduced, in the studied case considered by 23.8 %, as seen in Fig. 7 c.

Studying the electric energy consumption, Fig. 7 d, despite the introduction of a new electric consumer in CW, given the larger number of production pieces, it can be noted that electricity consumption per production piece decreases by 38.5 % in CW. Such a decrease in electricity consumption per piece has a positive impact on both the environmental and financial aspects of sustainable production not only for the company but also on wider society. Production capacity increases by 68 % in terms of pieces produced due to the introduction of CW and, in this case, exceeds the company's desired value of pieces produced, which is 1000 pieces per shift. The introduction of CW allows a more constant and reliable operation, with the Cobot enabling the use of assembly 'takt time', reducing (partially eliminating) unforeseen downtime in manual assembly operations. Thanks to the robustness and repeatability of the Cobot, process scrap is reduced by 55.4 %, results presented in Fig. 7 e. The comparative analysis carried out shows the benefits of introducing the collaborative machine, which have a positive impact on most aspects of sustainable production.

5. DISCUSION AND CONCLUSIONS

The presented work analyses the comparison between an existing workplace and a workplace with a collaborative machine. Such studies have been conducted recently and show the importance of a more detailed investigation. In our case, we focus on the study of sustainable manufacturing aspects, which are very important in today's fast market dynamics. The results of the applied simulation modelling method in evaluating the efficiency of jobs from the point of view of sustainable manufacturing show that the presented approach provides a detailed analysis of the current situation, based on which a production or service company can respond to its own needs and the needs of the market. The research problem posed in the introduction, which deals with the implementation of a simulation study to justify the production system of product composition from the point of view of sustainable production, shows the state in which the production system is, where its limits are and, most importantly, what are the possibilities for improving the main building blocks. Using the presented method, we found that the current situation does not allow to assemble the desired number of products in one shift, namely the average number of products produced is 857, and the company's goal is to produce 1000 pieces. It was found that two operations are bottlenecks in product assembly. Based on these results, we proposed the introduction of a Cobot to replace a worker and perform the operations that are currently bottlenecks. In a comparative study, it was demonstrated that the introduction of a collaborative robot in the considered case has a positive impact on all six optimization criteria describing a sustainable production orientation. A significant advantage is shown especially for a higher final piece count, with the analysis of costs, energy, time and production capacity per produced piece clearly supporting the introduction of a CW. The positive results for almost all optimization criteria are slightly above the expected positive effects of introducing a CW in the production system. From the sustainable production aspects, the CW is surprisingly efficient in the consumption of electrical energy, which is lower per piece produced than in MW. Of course, the introduction of a CW also has negative consequences. In the case of the discussed problem, the number of employees in the workplace with manual composition is reduced by half, here it is necessary to emphasize the appropriate restructuring of personnel in production, which is recently a major challenge in the EU and in the countries of the developed world. Another limitation is the amount of investment that the company must take into account when introducing such a workplace; the recovery of investment costs must be accurately calculated at the time of execution of orders or implementation of a particular project. However, one of the advantages of a Cobot is its adaptability and ease of reconfiguration. The right choice of a Cobot must be made from the point of view of the optimal use of its technical characteristics, its potential adaptability and its production capacity.

Based on the obtained results, we would like to extend the simulation modelling methodology presented in the paper to study the justification of CW of sustainable production to several considered cases. We want to transfer the obtained numerical results of the simulation model to a real environment, with the help of which we can study the deviations from the predicted values and, of course, study in more detail the limitations that such a workplace entail. We would also like to study more closely the social aspect of introducing the collaborative machine to CW. According to the current studies, we can assume that the collaborative machine has positive and negative social impacts on the worker. These influences need to be studied in more detail, only then we can provide the simulation model with more detailed data appropriately.

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