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Article

Possibilities to Increase Assembly Line Productivity Using Different Management Approaches

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Abstract: A number of scientific methods are used to support productivity growth in companies, aimed at reducing waste, balancing assembly lines and supporting the introduction of automation into assembly processes. Their use in industrial practice is widespread, especially in large and medium-sized enterprises, and small businesses that use scientific methods to a limited extent. The aim of the research is to show the assembly process of throttle valves implemented in a small company, the effects of balancing the current assembly line and the effects of proposals of variant solutions on the automated assembly line and on the amount of hourly assembly production and costs per product. Within costs, two cost types are monitored: namely the hourly labor costs, and hourly machine costs. The sum of the hourly assembly line costs is determined by their sum. In the results section, the main sources of waste in the assembly process are identified, and eight proposals leading to the elimination of waste are processed. In the discussion, the individual proposals are evaluated in terms of the cost of one product, the hourly production of assembly and the tact times of assembly lines. The proposal that is evaluated as the best process is compared with the current state. The purpose of this article is to point out the advantages of the implementation of scientific methods in industrial practice, the achieved savings in the solved problem, and thus, to support those scientific methods in the management of assembly processes which are beginning to be used in greater extents by small businesses.

Keywords: assembly line; productivity; waste; balancing; automation

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1. Introduction

The current business environment is highly competitive, subject to geopolitical influences and changes that are frequent, rapid and difficult to predict. The company's success is therefore based on skills, the right decisions and the company's actual performance. The main driver of business prosperity is productivity growth; it is the problems of productivity growth in production and assembly processes that are often the subject of research by scientists and practitioners. The solution to these problems is closely related to eliminating waste, balancing lines, and introducing automation and robotics into production and assembly processes.

The solution focus is on the control of assembly processes along these lines. The creation of assembly lines is associated with Industry 2.0 [1]. Since then, the assembly lines have undergone significant changes. While in the early 20th century they were controlled manually by the workforce, today they are mostly controlled by automated robotic arms. In the near future, new technologies related to Industry 4.0 will significantly affect the management of assembly processes [2,3] on the lines.

Today, assembly lines are used in various industries. The main goal is to increase the productivity of assembly lines, which usually allows the assembly of standardized products. Assembly lines are mainly focused on the mass production of large products (production of cars, white goods, etc.) [4,5], but recently they are also used for the small-scale production of custom products (mass-customization) [6]. The productivity of assembly lines is determined by the way they are arranged and the approach to solving their balancing.

Researchers and business experts have been working on assembly line balancing problems for decades. Various models of balancing assembly lines in terms of time, cost and profit were elaborated in the scientific and professional literature.

In terms of timing, assembly line balancing was addressed by the authors [7] by reducing the waste associated with lean line balancing design. They used time studies for all workstations to identify waste. The authors [8] addressed waste by reducing the downtime in production, with an emphasis on meeting all customer requirements and increasing product quality. The balancing of the assembly line, taking into account the time and physical demands of the tasks, was addressed in paper [9]. In her article, the author [10] discussed the problems of balancing several parallel assembly lines and their relevant characteristics.

Cost-based models minimize costs associated with production facilities/investments and costs of economic activity, such as labor costs, inventory costs, repair and maintenance costs, setup costs, downtime costs and delay costs. In published scientific articles, the authors focused on one cost element, on two or more cost types, and on total costs. Most authors considered only one cost element. The authors covered the costs of production equipment/investments in their works [11–16], as well as the wage costs in [17–19], the inventory in [20], and the costs associated with setting up in [21,22]. For example, the work in [23–25] dealt with labor costs, production equipment/investment costs, the cost of production equipment/investment, and the cost of setting up the authors' work [26] and others.

Profit-based models included, in addition to costs, revenues that took into account product prices and production volumes. Their main goal was to maximize profits, but they were less common in the professional literature. Profit tracking in scientific publications was addressed by [27–31] and others. However, some models were based on cost or profit and included indicators that affected assembly productivity, which was also a major issue of the timing approach.

The authors of publication [32] summarized their research findings of scientific works as being focused on balancing assembly lines and stated that when balancing the lines, time is most often taken into account, and in most cases, cost categories are taken into account separately; rarely are the applied approaches based on profit. At the same time, they identified gaps in the solution of balancing lines. They emphasized that the problem requires a solution via a formulated response using mathematical models, multi-criteria decision-making methods and information systems to support decision-making in investment decisions.

Harikrishnan, R. et al. [33] addressed the issue of increasing productivity through the balancing and automation of the line. The authors [34] deal with balancing robotic assembly lines. The solution to the problem was focused on the optimal assignment of robots to stations and balancing the division of labor between stations. Pfeiffer [35] discussed new technological possibilities in robotics in order to ensure high productivity, quality and a smooth flow of material on the assembly line.

The authors [36] also pointed out the gaps between the research and practice in solving the problems associated with the balancing of assembly lines. They emphasized, in particular, the need to discuss line rebalancing, which was usually triggered by a change in demand structure or the introduction of new technologies, as well as the need to discuss modeling of cost synergies—which were closely linked to deciding whether to balance the current line or use additional resources to upgrade it. They emphasized that the cost perspective in addressing these issues was often neglected and costs were often attributed to operations or workplaces. The costs allocated in this way may not reflect the real situation due to the costs arising from the consumption (purchase) or use of a resource that is located at a given workplace. By precisely assigning costs to resources, instead of line sites or operations, more realistic modeling of the decision problem can be achieved.

Theoretical knowledge in the field of assembly line balancing is sufficiently developed, but there is a need to apply it to a greater extent in industrial practice. Based on the authors [37], it can be stated that large and medium-sized companies use scientific methods to a greater or lesser extent in the implementation and management of assembly processes. Scientific methods are aimed at eliminating waste, balancing lines and supporting the implementation of automation of assembly processes. Unfortunately, small businesses use these methods only to a limited extent.

The purpose of this article is to point out the need to use scientific methods in industrial practice through the achieved cost savings in solving the problem and thus to support that scientific methods in the management of assembly processes are used to a greater extent by small businesses. The aim of this research is to demonstrate the assembly processes of throttle valve type FD 160 products, the effects of balancing the current assembly line and the effects of proposals from various solutions regarding the automated assembly line configuration in terms of hourly assembly production and the cost per product. Within costs, two cost types are monitored: namely, hourly labor costs, referred to in the article as the hourly rate of the worker, and the hourly costs for machines, referred to in the article as the hourly rate of robots. The sum of the hourly rate of the worker and the hourly rate of the robots determines the hourly rate of the assembly line.

The methodological part of this work defines the current state of assembly of throttle valve type FD 160 products and analyzes waste on the assembly line. After discovering the sources and causes of waste on the assembly line, solutions are proposed. The solutions are focused on balancing the times of current assembly operations according to workplaces and on proposals aimed at automating the assembly line.

In the discussion, the individual proposals are evaluated in terms of the cost of one product, the hourly production of assembly and the tact time of assembly lines. The proposal that is evaluated as the best is compared with the current situation. The discussion will be extended to decide on the feasibility of balancing the current line or on the feasibility of using additional resources and automating the line by using robots.

2. Materials and Methods

2.1. Current State of Installation of Throttle Valves

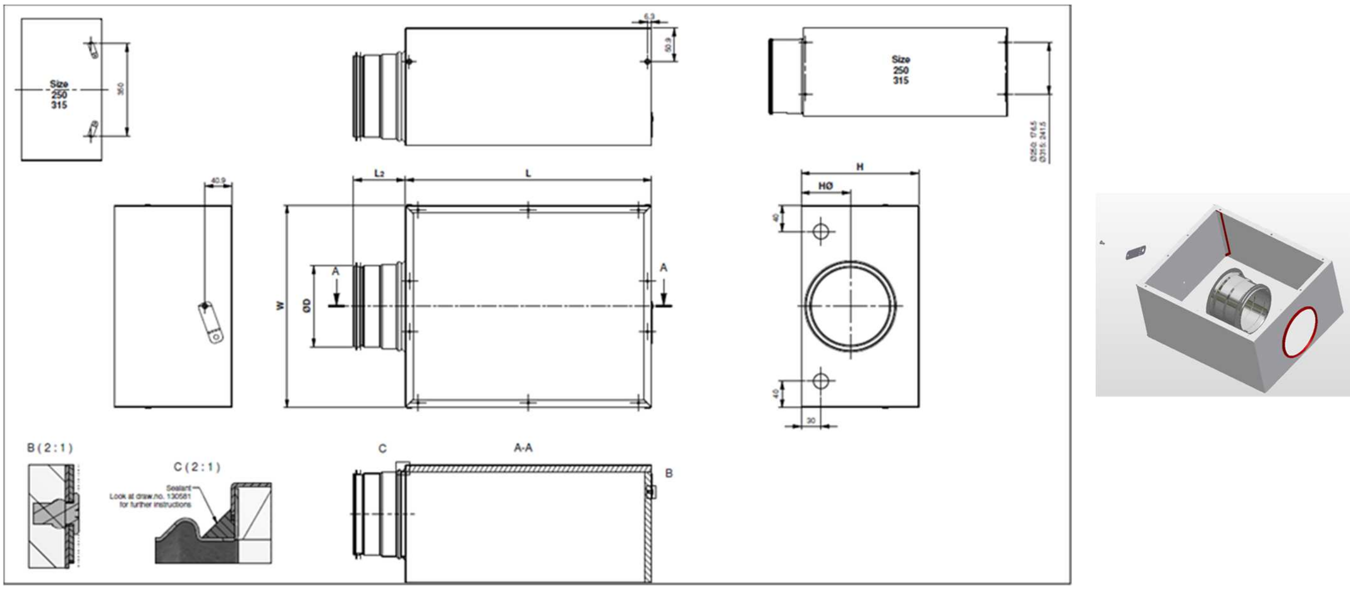
In businesses, especially during the current COVID-19 pandemic, great emphasis is placed on reducing costs and optimizing them. Cost optimization is implemented on the assembly of fire throttle valve products, which form one of the components of building ventilation. This type of assembly, according to the Slovak production classification SK NACE Rev. 2, belongs to section C—industrial production, and division 25—the manufacturing of metal structures, except machinery and equipment.

The assembly of fire throttle valves takes place on the analyzed assembly line in a small company. A 55% share of the total assembly consists of throttle valves type FD, which differ in the size of the chimney diameter in the range of 100 to 315 mm. One type of throttle valve, the FD 160, was chosen for the analysis of the assembly process, which has the largest share in the total volume of production of throttle valves FD. Type FD 160 accounts for 31% of the assembly of FD type products and at the same time, 17% of the total production volume. The shares in the throttle valve assembly volume are documented in Table 1.

Table 1. Production volumes of individual types of throttle valves type FD.

Indicator	Unit	Type of Throttle Valve "FD"						Total
		100	125	160	200	250	315	
Production volume	pcs/year	8647	22,616	28,046	18,777	9522	3237	90,845
Share in "FD"	%	10	25	31	20	10	4	100
Share in total volume	%	5	14	17	11	6	2	55

Throttle valve type FD 160 is shown in 2D and 3D formats in Figure 1. The basic dimensions of the product are chimney diameter (ØD) 160 mm, with the body dimensions of length (L) 456.60 mm, width (W) 377.60 mm, and height (H) 212.30 mm.



(**a**) (**b**)

Figure 1. Drawing (**a**) 2D and (**b**) 3D view of throttle valve FD 160.

Throttle valves are currently being assembled on two assembly lines at the same time. Both lines are identical, have the same workplaces, the same number of employees, equipment and operations performed. The assembly process on the line takes place at three workplaces: Welding, Assembly 1, and Assembly 2. Three workers work on one line. There are a total of six workers on both lines.

Based on the analysis of the working day snapshots (Figure 2), the average hourly production on the assembly line ($\varnothing O_{PV}$) was calculated in the number of 19 pieces according to Formula (1):

$$\varnothing O_{PV} = \frac{\sum_{j=1}^{m} \cdot PV_j}{m} \quad (1)$$

where j = 1 to m is the number of realized measurements, PV_j j-th is the hourly line output.

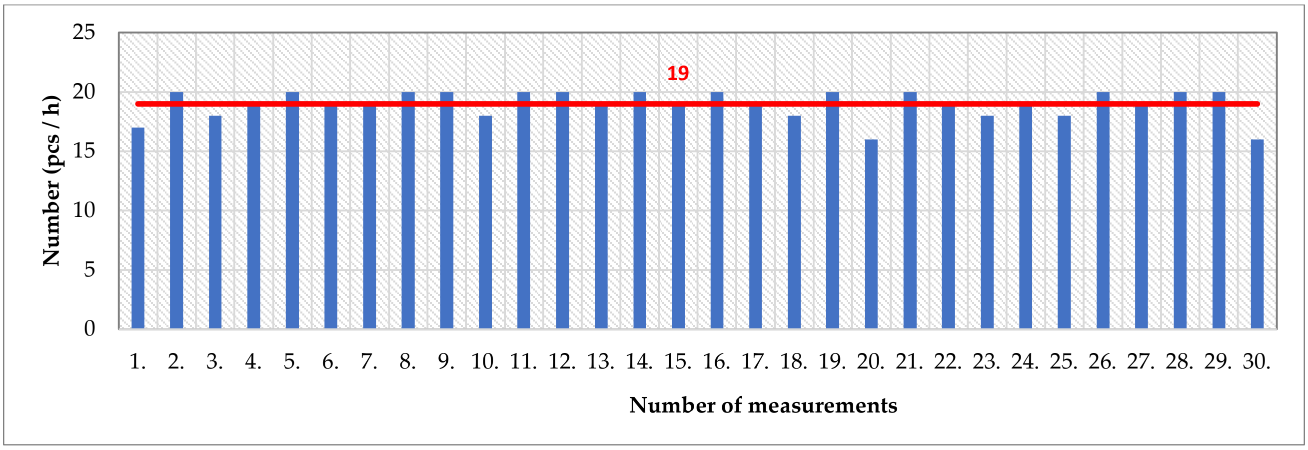
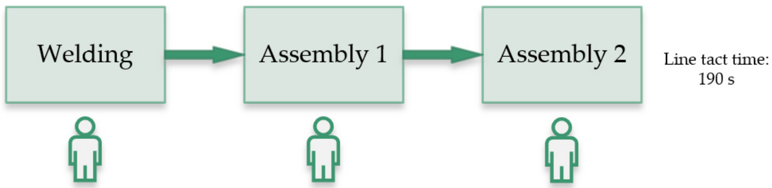


Figure 2. Average hourly line production—current state.

The level of the current FD 160 throttle valve assembly process was characterized by indicators—average hourly line assembly, line tact time, and cost per product (see Table 2).

Table 2. Current state of assembly.

Current State	
Number of lines	2
Number of employees on 1 line	3
Number of employees on 2 lines	6
Hourly employee rate (EUR)	10.50
Hourly rate for 2 lines (EUR)	63.00
Tact time of the line (s)	190
Hourly production the line (pcs)	19
Hourly production of 2 lines (pcs)	38
Cost per piece (EUR)	1.66



The tact time of the line, expressing the production time of one product on the line was based on the knowledge of the hourly production of the assembly line set at 190 s (i.e., 3600 s/19 pieces). Due to the fact that the assembly takes place simultaneously on two identical assembly lines, the hourly production of the two lines is 38 pieces. The hourly rate of one line employee is set at EUR 10.50. There are three employees working on each line, thus a total of six employees. The hourly rate of two lines, determined as the product of the number of employees on two lines and the hourly rate of an employee, is EUR 63.00 (six employees x EUR 10.50). The cost per product, calculated as the ratio of the hourly rate of two lines and the hourly production of two lines is EUR 1.66 (EUR 63.00/38 pieces).

2.2. Methodical Procedure of Solution

The current state of assembly line management uses only limited scientific approaches based on a technical, ergonomic and economical basis. The aim of the research is to point out the effects of balancing the current assembly line on the assembly process of throttle valves and the effects of designing alternative solutions for the arrangement of an automated assembly line in terms of hourly assembly production, tact time of the line and costs per product.

In order to increase the assembly productivity of FD 160 products, it is necessary to analyze the current assembly process in detail. Therefore, the individual workplaces of Welding, Assembly 1, and Assembly 2 are divided into operations based on the analysis of individual activities. The identified assembly operations are analyzed on the basis of snapshots of individual operations, which determines the time required to perform these operations and the actual assembly time of one product. The main sources of waste on the assembly line are identified on the basis of working time snapshots.

After finding out the sources and causes of waste on the assembly line, it is possible to proceed to the proposal of their elimination. Several solution options are proposed. The solutions are focused on balancing the times of current assembly operations according to workplaces and on designs using assembly line automation.

Individual proposals are evaluated according to three criteria, which concisely characterize the assembly process, namely:

- Tact time of line. It expresses the average time required to make one product on an assembly line. As a rule, it is determined by the tact time of the workplace on the line which has the longest duration of all operations performed at the given workplace. The method of calculation is given by relation (2):

$$TT = TT_{Wmax} \tag{2}$$

where TT is the tact time of line, TT_{Wmax} is the tact time of the line workplace with the longest time of all performed operations.

- Hourly production of line. It expresses the number of manufactured products on the assembly line per hour. The method of calculation is given by relation (2):

$$O_h = \frac{T}{TT} \tag{3}$$

where O_h is an hourly production of line, T is the time expressed in seconds per hour.

- Cost per product. Within costs, two cost types are monitored, namely, hourly labor costs, referred to in the article as the hourly rate of the worker, and hourly costs for machines, referred to in the article as the hourly rate of robots. The sum of the hourly rate of the worker and the hourly rate of the robots determines the hourly rate of the assembly line. The method of calculating the costs per product is recorded by relations (4), (5) and (6):

$$r_{oR} = \frac{IC}{T_D \cdot T_{eR}} \cdot c \tag{4}$$

$$r_{oL} = (r_{oE} \cdot N_E) + r_{oR} \tag{5}$$

$$C_o = \frac{r_{oL}}{O_h} \tag{6}$$

where r_{oL} is the hourly rate of the line, r_{oE} is the hourly rate of the employee, N_E is the number of employees on the line, r_{oR} is the hourly rate of robots, IC is investment costs, T_D is the depreciation period of the robot, T_{eR} used effective time fund of the robot, c is the coefficient of overhead costs in the amount of 1.36.

The cost per product is a synthetic indicator that reflects the previous two criteria. Unit costs are an important indicator of the competitiveness of the assembly process—they affect the pricing of these products and the profitability of assembly.

3. Results

The aim of the research is to show the effects of balancing the current assembly line and proposed solutions for the arrangement of an automated assembly line on the amount of hourly assembly production and the cost of one piece of product on the assembly process of throttle valves, type FD 160. To achieve this aim, the research results are divided into two parts. The first part identifies the main sources of waste on the assembly line. The second part presents proposals for solutions to eliminate waste on the assembly line. The individual proposals are technically described and economically evaluated.

3.1. Main Sources of Waste

Methods of direct measurement of time consumption are used to assess labor productivity and possible waste at individual workplaces and assembly line operations, i.e., a snapshot of the individual's working day and a snapshot of the operation.

A snapshot of the working day of individual work positions was taken at the Welding (4 times), Assembly 1 (3 times) and Assembly 2 (3 times). Based on the analysis of the data from the working day snapshot, the waste was quantified according to the types of waste.

The waste by type is expressed as a percentage of the average of all workplaces. The basis for calculating the waste costs (C_W) is an hourly cost per worker in the amount of EUR 10.50, a duration of work shift of 430 min, and the average waste coefficient. Waste costs per worker and one shift are calculated according to Equation (7):

$$C_w = \sum_{i=1}^{n} r_o \cdot w \cdot t_i \quad (7)$$

where r_o is the hourly rate of the worker, w is the average waste of a particular type, expressed by the coefficient per worker, t is the time of work shift in hours, $i = 1 - n$ type of waste.

The calculation of annual waste costs is based on the cost of waste of one worker, the number of workers on one line (3), the number of lines (2), the number of work shifts per day (2) and the annual working time fund (262.5 days). The results are recorded in Table 3.

Table 3. Quantification of waste from working time snapshots.

Type of Waste	Average Waste per 1 Employee (%)	Waste Costs (EUR)	
		1 Worker/1 Shift	2 Lines/1 Year, 2 Shifts/Day
Waiting	11	8.28	26,072.13
Outside the workplace	4	3.01	9481.50
Personal interview	2	1.51	4740.75
Overwork	5	3.76	11,851.88
Other	7	5.27	16,592.63
Total	29	21.82	68,740.88

Based on the analysis, the waste on the assembly line is determined at an average of 29% of the employee's time, which for both lines represents a value of EUR 68,740.88 per year.

The analysis of the working day snapshot showed that each job position on the assembly line is assigned a different workload. For this reason, assembly activities at individual workplaces were divided into smaller units—operations. The average duration of the operation was determined for each operation, which is based on the data obtained from the snapshots of operations. Subsequently, the time cycle of individual workplaces is determined as the sum of the average times of all operations performed at the workplace. The tact time of the assembly line is determined by the tact time of the workplace of the line, whose tact time is the longest.

The activities performed at the Welding workplace were divided into four operations with names and in the order given in Table 4. The average duration of each operation is determined. The sum of the average durations of all operations is 132.78 s, which represents 87% of the working time of the Welding workplace. To this time must be added the average time associated with cleaning the tip of the spot welder, which, based on the analysis of working time images, is set at 19.92 s. Based on the above facts, the tact time of the Welding workplace is 152.70 s. Assembly activities at the Assembly 1 workplace were divided into five operations. Their names and order are given in Table 4. Tact time workplace Assembly 1 is 105.07 s. At the Assembly 2 workplace, the assembly activities were divided into nine operations, the names and order of which are recorded in Table 4. The tact time of the Assembly 2 workplace is 121.00 s.

Table 4. Average assembly time (in seconds) according to workplaces and assembly line operations.

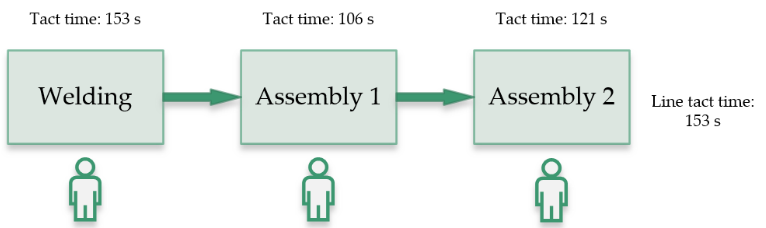
Workplace	**Welding (Tip Cleaning 19.92 s)**				**Assembly 1**				
Operation	Chimney installation	Chimney welding	Sidewall riveting	Sidewall welding	Stickers incl. submissions	Chimney sealing and interior sealing	Insert the seal	Flap installation	Cover sealing
FD 160	15.21	24.43	43.07	50.07	13.43	35.71	17.29	20.50	18.14
Initial state	152.70				105.07				
Workplace	**Assembly 2**								
Operation	Closing by cover	Riveting the lid	Knocking the lid	Labeling	Flap inspection	Inserting accessories	Closing by 2 lids	Labeling QA	Transfer to the box
FD 160	10.93	33.86	12.21	12.93	19.79	3.86	15.00	3.43	9.00
Initial state	121.00								

Based on the values of the tact times of the individual workplaces of the assembly line, it is possible to talk about an imbalance of work at individual workplaces. The difference between the longest and shortest time cycle is 47.63 s.

The summary economic parameters of the initial state of the assembly after snapshot operations are recorded in Table 5. The tact time of the line is at the level of 152.70 s. It is determined by the longest tact time of the line workplace, which is the tact time of the Welding workplace. The hourly production of the assembly line is calculated for 23 products (3600 s/152.70 s), the hourly production of two lines for 46 pieces. There are three employees working on the line, six employees on two lines. The hourly rate for two lines is EUR 63.00 (6 employees x EUR 10.50) and the cost per piece is EUR 1.37 (EUR 63.00/46 pieces).

Table 5. Initial state of assembly after snapshot operations.

Initial State	
Number of lines	2
Number of employees on 1 line	3
Number of employees on 2 lines	6
Hourly employee rate (EUR)	10.50
Hourly rate for 2 lines (EUR)	63.00
Tact time of the line (s)	153
Hourly production the line (pcs)	23
Hourly production of 2 lines (pcs)	46
Cost per piece (EUR)	1.37



3.2. Proposed Solution Variants

An increase in the hourly production of the assembly line can be achieved by reducing the tact time of the line. A total of eight solution variants were proposed, which are referred to as Proposals 1 to 8 in the following text. The individual proposals were analyzed mainly in terms of cost per piece for the FD 160 throttle products.

Proposal 1 optimizes the existing assembly time, balancing the duration of each operation. It does not require any additional investment. Proposals 2 to 8 take into account the investment costs associated with the introduction of automation of selected assembly operations, i.e., with the acquisition of two, respectively three robots. This fact affects the number of workers on the assembly line.

Proposal 1, which takes into account the balance of time consumption at the individual workplaces of the lines, proposes a 15 s assistance from the Assembly 1 workplace at the Welding workplace, which shortens the Welding workplace tact time from 152.7 s (initial state) to 137.7 s. At the same time, there will be an increase in workload by 15 s at the Assembly 1 workplace, which means that the tact time of the Assembly 1 workplace will increase from 105.07 s (initial state) to 120.07 s. The "Labeling" operation is moved from the Assembly 2 workplace to a worker outside the production line—an operator, which will reduce the production workload by 12.93 s at the Assembly 2 workplace, thus the tact time of the Assembly 2 workplace will be reduced from 121.00 s (initial state) to 108.07 s (see Table 6). In Proposal 1, the difference between the longest and shortest workplace tact time is 29.63 s, which is a reduction by 18.00 s, i.e., by 40.3% compared to the initial state.

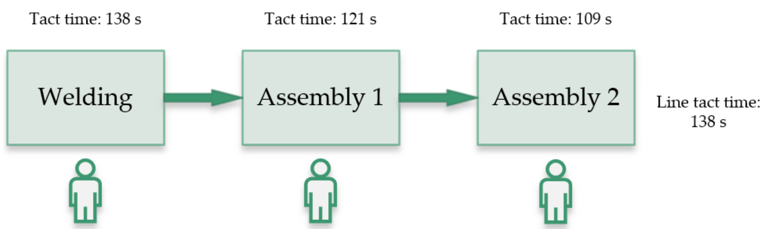
Table 6. Proposal 1—time consumption (in seconds) according to assembly operations and line workplaces.

Workplace	**Welding (Tip Cleaning 19.92 s)**				**Assembly 1**				
Operation	Chimney installation	Chimney welding	Sidewall riveting	Sidewall welding	Stickers incl. submissions	Chimney sealing and interior sealing	Insert the seal	Flap installation	Cover sealing
FD 160	15.21	24.43	43.07	50.07	13.43	35.71	17.29	20.50	18.14
Proposal 1	Assistance from Assembly 1 workplace at "Sidewall riveting" operation 15 s 137.70				Assistance on Welding workplace at "Sidewall riveting" operation 15 s 120.07				
Workplace	**Assembly 2**								
Operation	Closing by cover	Riveting the lid	Knocking the lid	Labeling	Flap inspection	Inserting accessories	Closing by 2 lids	Labeling QA	Transfer to the box
FD 160	10.93	33.86	12.21	12.93	19.79	3.86	15.00	3.43	9.00
Proposal 1	Operation "Labeling" transferred to an off-lime worker (operator) 108.07								

Proposal 1 is recorded in Table 7. After the implementation of the above measures, the tact time of the line decreased by 15 s compared to the initial state, i.e., to 137.70 s, and is determined by the Welding workplace. The hourly production of the line is 26 pieces (3600 s/137.70 s), which means an improvement over the initial state by 13%. The hourly production of the two lines is 52 pieces. There are three employees working on the line, six employees on two lines. The hourly rate for two lines is EUR 63.00 (6 employees x EUR 10.50) and the cost per piece is EUR 1.21 (EUR 63.00/52 pieces), which decreased by EUR 0.16, i.e., by about 12%, compared to the initial state.

Table 7. Proposal 1.

Proposal 1	
Number of lines	2
Number of employees on 1 line	3
Number of employees on 2 lines	6
Hourly employee rate (EUR)	10.50
Hourly rate for 2 lines (EUR)	63.00
Tact time of the line (s)	138
Hourly production the line (pcs)	26
Hourly production of 2 lines (pcs)	52
Cost per piece (EUR)	1.21



A comparison of the economic parameters of the current state of production and Proposal 1 shows that balancing the operation times at the line workplaces increased the hourly production on two lines from 38 to 52 pieces, thus by 36.8% and at the same time reduced unit costs from EUR 1.66 to EUR 1.21, which is 27%.

Proposals 2 to 8 present a possible hourly increase in productivity in the installation of FD 160 throttle valves by introducing automation of selected operations. In this case, it is only possible to automate welding and sealing operations that take place at the Welding workplace. For this reason, it is necessary to modify the assembly process of the FD 160 product. The operations will be redistributed to the Pre-assembly workplace and the Robot workplace. At the Pre-assembly workplace, operations are performed to install the chimney and to install it in the jig. The side riveting operation that took place at the Welding workplace is canceled. The Robot workplace replaces the welding and sealing performed at the Welding workplace.

Seven proposals for the arrangement of robots at the Robot automated workplace were processed. Proposals 2 to 8 take into account the way in which the robots are involved in cooperation with the workers on the assembly line so that the resulting tact timeline is as low as possible, and at the same time, the investment costs do not significantly affect the cost of one product. These are the ways in which the robots are arranged:

- Two robots connected in parallel, one robot performing only welding operations, the other, only sealing operations;
- Two robots connected in series, one robot performing only welding operations, the other, only sealing operations;
- Two robots connected in parallel, both robots performing both welding and sealing operations;
- Two robots connected in parallel with a third robot in the series, with two robots arranged in parallel performing welding operations, and a third robot sealing operations.

Workplaces Assembly 1 and Assembly 2 are left. This means that the automated line consists of four workplaces: Pre-assembly, Robot, Assembly 1 and Assembly 2. For Proposals 2 to 8, only one assembly line is considered.

Table 8 records the times of individual operations according to the workplace's Pre-assembly, Robot, Assembly 1, Assembly 2 and proposals for variant solutions of the automated assembly line layout. Individual Proposals 2 to 8 are described in more detail in Tables 11–17.

Table 8. Operations times in seconds according to automated production line layout proposals.

	Pre-assembly		**Robot**		**Assembly 1**					
	Chimney installation	Installation into the jig	Welding	Chimney sealing	Stickers incl. submissions	~~Chimney sealing~~	Insert the seal	Flap installation	Sealing the cover	Closing the lid
FD 160	15.2	24.4	111.0	19.7	13.4	~~35.7~~	17.3	20.5	18.1	10.9
Proposal 2	30.0		130.7		80.3					
Proposal 3	30.0		130.7		80.3					
Proposal 4	30.0		111.0	19.7	80.3					
Proposal 5	30.0		65.5		80.3					
Proposal 6	30.0		65.5		80.3					
Proposal 7	30.0		56.0	19.7	80.3					
Proposal 8	30.0		56.0	19.7	80.3					

	Assembly 2								**Tact time of the line (s)**	**Line production (pcs/h)**
	Lid riveting	Knocking of rivets	~~Labeling~~	Flap inspection	Inserting accessories	Closing with two covers	Gluing the QA label	Transfer to the box		
FD 160	33.9	12.2	~~12.9~~	19.8	3.9	15.0	3.4	9.0		
Proposal 2	97.1								131	27
Proposal 3	97.1								131	27
Proposal 4	97.1								111	32
Proposal 5	97.1								98	36
Proposal 6	97.1								66	54
Proposal 7	97.1								98	36
Proposal 8	97.1								56	64

The determination of the times for welding and sealing operations carried out at the Robot workplace is based on the input data given in Table 9. The robot welding operation time depends on the number of welds to be performed on the chimney and product body and the welding time of one weld, which in this case is set to 3 s. The distance between the two welds is 77 mm. The operation time for robot sealing depends on the length of the sealant used to seal the chimney, the size of the body and the top cover of the FD 160 product and the time required to apply the sealant. The length of the sealant is expressed in meters and the speed of application of the sealant is 12 m per minute.

Table 9. Input data for calculation of welding and sealing operations by robots.

Indicator	Unit	Value
Number of welds on the chimney	pcs	7
Number of welds on the product body	pcs	30
Welding time for 1 weld	s	3
Length of sealant of chimney	m	0.5
Length of sealant of body	m	1.76
Length of sealant for sealing the top lid	m	3.93
Application time of sealant with a length of 12 m	min.	1

In general, the workplace tact time is calculated as the sum of all operation times performed at a given workplace. In the case of the Robot workplace, the determination of the tact time of the workplace depends on the way the robots are arranged (parallel, in series) and also on whether the robot performs welding only, sealing only, or welding and sealing. For example, when two robots are arranged in parallel in the workplace, with one robot performing only welding and the other robot only sealing, the workplace tact time for the robot is given by the sum of welding and sealing operation times, which is 130.7 s (Proposals 2 and 3).

The determination of the hourly production for Proposals 2 to 8 is realized as a proportion of the hour expressed in seconds and the tact time of the proposed solution. For Proposals 2 and 3, the hourly production of the line is 27 pieces (3600 s/130.7 s).

The company incurs investment costs by purchasing robots. The investment costs include the purchase price of the robots, which depends on the type and number of robots involved in the assembly process in the design, and on the number of activities performed. The value of other costs is determined expertly at 36% of the cost of the investment. The input data for the calculation of costs per product for Proposals 2 to 8 are given in Table 10.

Table 10. Input data for calculating the hourly rate of the robot.

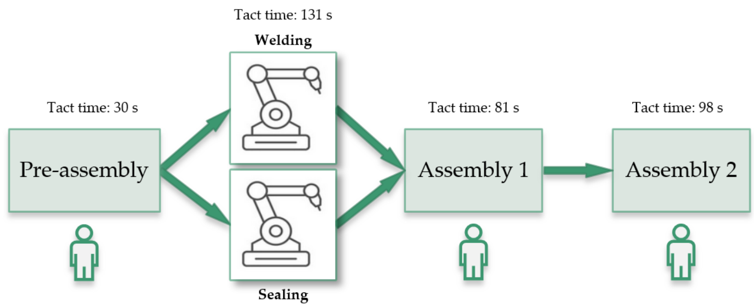
Indicator	Unit	Value		
		2 Robots Parallel	2 Robots Series	3 Robots Series
Purchase price of 2 or 3 robots (investment costs)	EUR	230,000	276,000	370,000
Effective time fund of the robot per year	hours/year		3570.00	
Utilization of effective time fund of the robot	%		85	
Utilization of effective time fund of the robot	hours/year		3034.50	
Depreciation time of the robot	years		6	
Hourly rate of employee	EUR		10.50	
Hourly rate of robot for 2 or 3 robots	EUR	17.18	20.62	27.64

The robot's annual effective time is 3570 h. Its utilization is calculated at 85%, which represents 3034.50 h per year. According to Act no. 595/2003 Coll. on income tax, the robot belongs to the second depreciation group with a depreciation period of six years. The employee's hourly rate is at the level of EUR 10.50. The hourly rate of robots ranges from EUR 17.18 to EUR 27.64, depending on the number and arrangement of robots in the workplace. Their method of calculation captures Equation (4), the hourly rate line Equation (5), and the cost per product Equation (6).

Proposal 2 is shown in Table 11. It is a parallel connection between two robots, whereby one performs a welding operation and the other a sealing operation. The tact time of the line is at the level of 131 s and is determined by the Robot workplace, the hourly production capacity of the line is 27 pieces, and the hourly rate of the line is EUR 48.68. There are three employees working on the line. The investment costs of this proposal are EUR 230,000 and the cost per unit is EUR 1.80.

Table 11. Proposal 2.

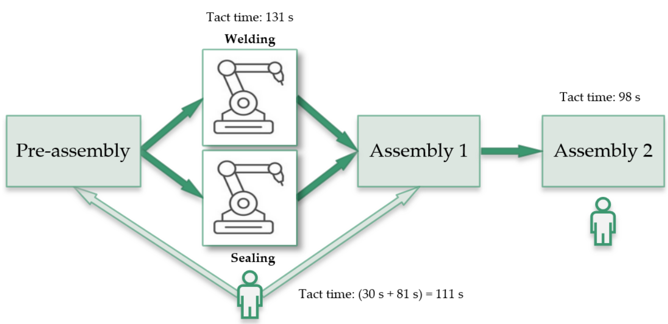
Proposal 2		Investment Costs = EUR 230,000
Number of lines	1	
Number of employees on the line	3	
Hourly employee rate (EUR)	10.50	
Hourly rate of line employees (EUR)	31.50	
Hourly rate of robots (EUR)	17.18	
Hourly line rate (EUR)	48.68	
Tact time of the line (s)	131	
Hourly line production (pcs)	27	
Cost per piece (EUR)	1.80	



Proposal 3 is shown in Table 12. Additionally, in this proposal, two robots are connected in parallel, whereby one performs a welding operation and the other a sealing operation. The difference between Proposal 2 and Proposal 1 is that the work at the Pre-assembly and Assembly 1 workplace is provided by one worker, which saves one worker. The tact time of the line is at the level of 131 s, the hourly production capacity is 27 pieces. The investment costs of this proposal are also EUR 230,000, but the cost per unit is EUR 1.41, which means they are 16% lower than Proposal 1.

Table 12. Proposal 3.

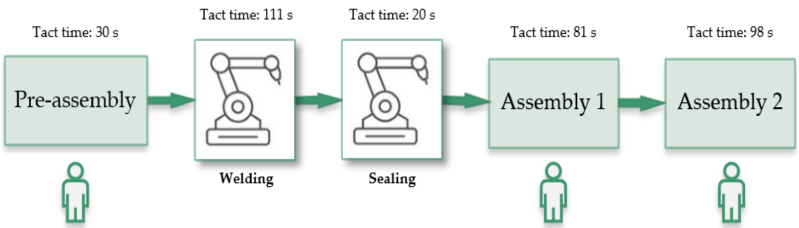
Proposal 3		Investment Costs = EUR 230,000
Number of lines	1	
Number of employees on the line	2	
Hourly employee rate (EUR)	10.50	
Hourly rate of line employees (EUR)	21.00	
Hourly rate of robots (EUR)	17.18	
Hourly line rate (EUR)	38.18	
Tact time of the line (s)	131	
Hourly line production (pcs)	27	
Cost per piece (EUR)	1.41	



Proposal 4 is shown in Table 13. In this case, it is a series connection of two robots, whereby one performs a welding operation and the other a sealing operation. The line tact time is determined by the welding robot and is at the 111 s level. The hourly production capacity of the line is 32 pieces, and the hourly rate of the line is EUR 52.12. Production is provided by three workers. The investment cost of this proposal is EUR 276,000 and the cost per unit is EUR 2.27.

Table 13. Proposal 4.

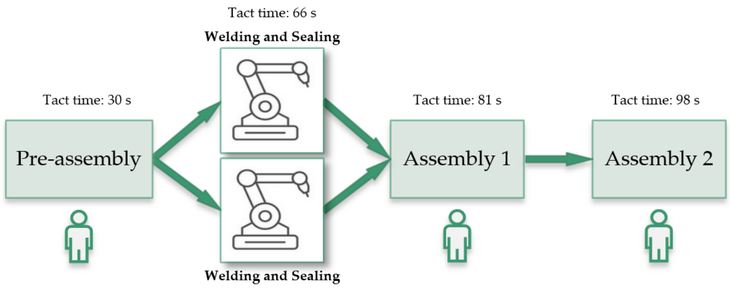
Proposal 4		Investment Costs = EUR 276,000
Number of lines	1	
Number of employees on the line	3	
Hourly employee rate (EUR)	10.50	
Hourly rate of line employees (EUR)	31.50	
Hourly rate of robots (EUR)	20.62	
Hourly line rate (EUR)	52.12	
Tact time of the line (s)	111	
Hourly line production (pcs)	32	
Cost per piece (EUR)	1.63	



Proposal 5 is shown in Table 14. It provides a parallel connection of two robots, whereby both robots are able to perform both welding and sealing operations. The line tact time is determined by the Assembly 2 workplace and is at the level of 98 s, the hourly production capacity of the line is 37 pieces, and the hourly rate of the line is EUR 52.12. Production is provided by three workers. The investment costs of this proposal are EUR 276,000 and the cost per unit is EUR 1.41.

Table 14. Proposal 5.

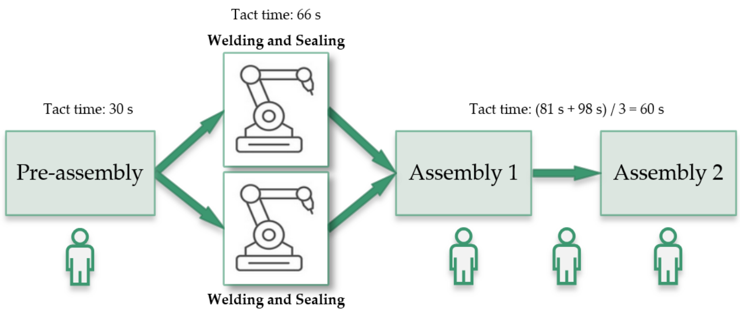
Proposal 5		Investment Costs = EUR 276,000
Number of lines	1	
Number of employees on the line	3	
Hourly employee rate (EUR)	10.50	
Hourly rate of line employees (EUR)	31.50	
Hourly rate of robots (EUR)	20.62	
Hourly line rate (EUR)	52.12	
Tact time of the line (s)	98	
Hourly line production (pcs)	37	
Cost per piece (EUR)	1.41	



Proposal 6 is shown in Table 15. Same as in layout 4, this involves the parallel connection of two robots, one performing welding operations and the other sealing operations. The difference between Proposal 6 and Proposal 5 is in the staff of Assembly 1 and Assembly 2 by three employees, while a total of four employees work on the line. The line tact time is at the level of 66 s, determined by the Robot workplace. The hourly production capacity is 54 pieces, and the hourly rate of the line is EUR 62.62. The investment costs for this proposal are EUR 276,000. The cost per piece is EUR 1.16.

Table 15. Proposal 6.

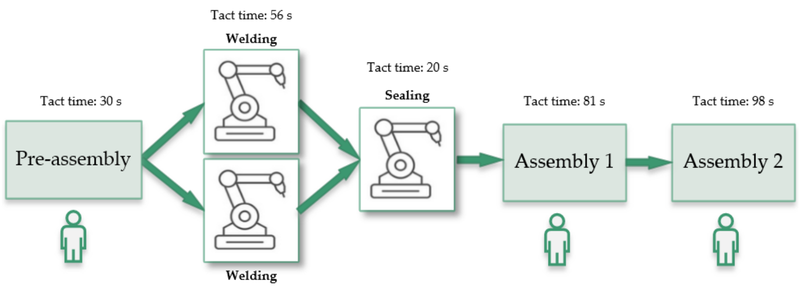
Proposal 6		Investment Costs = EUR 276,000
Number of lines	1	
Number of employees on the line	4	
Hourly employee rate (EUR)	10.50	
Hourly rate of line employees (EUR)	42.00	
Hourly rate of robots (EUR)	20.62	
Hourly line rate (EUR)	62.62	
Tact time of the line (s)	66	
Hourly line production (pcs)	54	
Cost per piece (EUR)	1.16	



Proposal 7 is shown in Table 16. This proposal allows two robots to be connected in parallel with the third in the series, with the robots connected in parallel performing welding operations and the third robot performing sealing operations. The line tact time is at the level of 98 s, determined by the Assembly 2 workplace. Production is provided by three employees. The hourly production capacity of the line is 37 pieces, the hourly rate of the line is EUR 59.14. The investment cost of this proposal is EUR 370,000 and the cost per piece is EUR 1.60.

Table 16. Proposal 7.

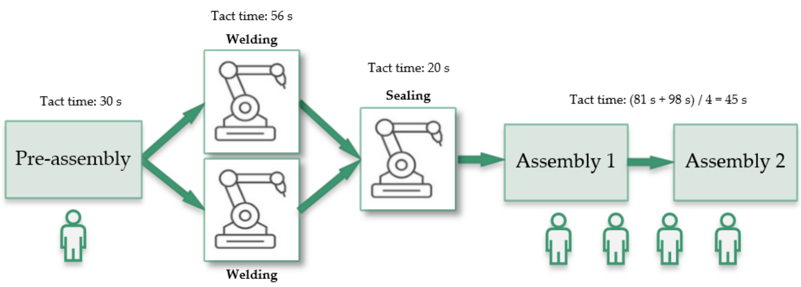
Proposal 7		Investment Costs = EUR 370,000
Number of lines	1	
Number of employees on the line	3	
Hourly employee rate (EUR)	10.50	
Hourly rate of line employees (EUR)	31.50	
Hourly rate of robots (EUR)	27.64	
Hourly line rate (EUR)	59.14	
Tact time of the line (s)	98	
Hourly line production (pcs)	37	
Cost per piece (EUR)	1.60	



Proposal 8 is recorded in Table 17. This proposal also allows two robots to be connected in parallel with the third in the series, with the robots connected in parallel performing the welding operations and the third robot performing the sealing operations. The difference with Proposal 7 is the occupancy of the Assembly 1 and Assembly 2 workplaces by four employees. The line tact time is at the level of 56 s, which is determined by the Robot workplace. Production is provided by a total of five workers. The hourly production capacity is 64 pieces, and the hourly rate of the line is EUR 80.14. The investment cost of this proposal is EUR 370,000 and the cost per piece is EUR 1.68.

Table 17. Proposal 8.

Proposal 8		Investment Costs = EUR 370,000
Number of lines	1	
Number of employees on the line	5	
Hourly employee rate (EUR)	10.50	
Hourly rate of line employees (EUR)	52.50	
Hourly rate of robots (EUR)	27.64	
Hourly line rate (EUR)	80.14	
Tact time of the line (s)	56	
Hourly line production (pcs)	64	
Cost per piece (EUR)	1.25	



Comparing the performance and economic parameters of the seven presented proposals for automated production line layouts, it is clear that the most economically efficient proposal is Proposal 6, which achieves the lowest product cost (EUR 1.16) with an hourly production capacity of 54 products. In terms of the hourly production capacity of the line, the most advantageous is Proposal 8 with an hourly production capacity of 64 products at a unit cost of EUR 1.25.

4. Discussion

The purpose of this work was to point out the importance of implementing scientific methods in industrial practice through the achieved cost savings, and thus, support that scientific methods in the management of assembly processes are used to a greater extent by small businesses. The aim of the research was to show the effects of balancing the current assembly line and proposed variants of the automated assembly line arrangement with the amount of hourly assembly production and the cost of one piece of product assembly, namely the throttle valve type FD 160. The research aimed to achieve the goal and was carried out in two steps.

In the first step, the main sources of waste were identified. For the assembly line "initial state", on the basis of the workers' working day in the positions of welder, assembly 1 and assembly 2, wasted working time per employee, 29%, was identified and quantified, which for both assembly lines for the whole year is a waste amounting to EUR 68,740.88. The main finding was a waste in the form of grinding the welding tip of the spot welder, which accounted for an average of up to 13% of the welder's working time. This waste was eliminated in the company by replacing the tip of the spot welder with a better one, the NITRODE^{TM} brand. The time needed to clean the tip by 2/3 was eliminated, which represents 0.62 h per work shift. The annual savings amounted to EUR 6835.50.

In the second step, proposals were presented to eliminate waste on the assembly line. Based on the classic waste elimination, Proposal 1 was prepared, where the cost of one piece in the amount of EUR 1.21 was achieved by balancing the operations on the assembly line. Proposals 2 to 8 take into account the automation of selected assembly operations of the FD 160 product and will serve as a basis for the considered modernization of assembly in the company. Seven proposals with Pre-assembly, Robot, Assembly 1 and Assembly 2 workplaces were processed. Proposals 2 and 3 present the parallel connection of two robots, one performing the welding operation and the other sealing. The difference in the proposals is in the number of involved workers at the Pre-assembly and Assembly workplaces. Proposal 2 requires two workers, while Proposal 3 requires only one worker. Proposal 4 involves the series connection of robots, with one performing a welding operation and the other a sealing operation. Proposals 5 and 6 show the robots in parallel. In Proposal 5, both robots are able to perform both welding and sealing activities. In Proposal 6, one robot performs a welding operation, the other a sealing activity. The difference between Proposal 6 and Proposal 5 is the occupation of Assembly 1 and Assembly 2 by three workers. Proposals 7 and 8 allow two robots to be connected in parallel with a third in the series, with the robots connected in parallel performing a welding operation and the third robot performing a sealing operation. The difference between Proposal 8 and Proposal 7 is that the Assembly 1 and Assembly 2 workplaces are occupied by four workers, while in Proposal 7 there are only two workers. Of these proposals, the most advantageous is Proposal 6, whose cost per unit of EUR 1.16 has been reduced by 30% compared to the current state of production.

Proposals 1–8 were evaluated using three criteria. The selection of the optimal proposal for the needs of industry is in many cases, carried out by means of multi-criteria evaluation because it can evaluate time and costs, several cost categories at the same time, a large number of solution variants, and so on. [38]. However, the ranking of proposals 1 to 8 is not appropriate for using multi-criteria evaluation methods, given that the cost per product criterion is synthetic. Therefore, the choice of the optimal design, according to the synthetic indicator, is based on the lowest cost per product. The amount of costs per piece is positively affected by the reduction in the hourly rate of the line and the increase in the hourly production of the line. The hourly rate of the line is given by the sum of the hourly rate of the line employees and the hourly rate of the robots. Thus, the cost per hour of work of the line is allocated to resources (see Chapter 1), not to the workplaces of the line or operations, thus obtaining more realistic values for the decision-making process of selecting the optimal proposal. It is true that the higher the number of workers at the assembly line and the higher the investment costs associated with line automation, the greater the negative impact on the cost per product. The hourly line production is affected by the timeline clock, and the shorter the timeline clock is, the higher the hourly assembly line production.

The results of the cost comparison per product according to Proposals 1 to 8 are provided in Table 18.

Table 18. Comparison of proposed solutions to the current state (CS) of the assembly process.

	Inputs Data for Determining the Cost per Piece				Product Cost (EUR/pcs)		Order of Proposals by Product Cost
	Number of Lines (pcs)	Tact Time of Line (s)	Hourly Line Rate (EUR/h)	Hourly Production Line/Lines (pcs/h)	State	Deviation from CS (−) Savings (+) Overrun	
Current state	2	190	63.00	38	1.66	-	-
Proposal 1	2	138	63.00	52	1.21	−0.45	2.
Proposal 2	1	131	48.68	27	1.80	+0.14	7.
Proposal 3	1	131	38.18	27	1.41	−0.25	4.
Proposal 4	1	111	52.12	32	1.63	−0.03	6.
Proposal 5	1	98	52.12	37	1.41	−0.25	4.
Proposal 6	1	66	62.62	54	1.16	−0.50	1.
Proposal 7	1	98	59.14	37	1.60	−0.06	5.
Proposal 8	1	56	80.14	64	1.25	−0.41	3.

Seven out of eight proposals saved the cost per product for the proposed solutions compared to the current state. The lowest cost per product was achieved by Proposal 6. Compared to the current state, this is a reduction of EUR 0.50 per product, i.e., a reduction of 30.12%. The second lowest cost was achieved by Proposal 1. In this case, it is a reduction of costs compared to the current state by EUR 0.45, i.e., a reduction of 27.11%. The third best proposal in terms of cost per product is Proposal 8. In this case, the cost per product was reduced by EUR 0.41, i.e., compared to the current state, i.e., a reduction of 24.47%.

The increase in hourly production of the line for individual proposals compared to the current state (38 pieces/2 assembly lines) was recorded only for Proposals 1, 6 and 8. The highest hourly production was achieved by Proposal 8; namely, 64 pieces were produced on one assembly line, which means an increase in assembly volume by 26 pieces per hour, i.e., by 68%. The hourly production of 54 pieces on one line was achieved by Proposal 6. Compared to the current situation, this is an hourly increase in the volume of assembly by 16 pieces, i.e., an increase of 42%. Proposal 1 achieved an hourly production of 54 pieces on two lines, which means an increase in assembly volume of 14 pieces, i.e., 36.8%, compared to the current situation. Proposals 2–5 and Proposal 7 with one assembly line, although they did not reach the hourly production of the current state (38 pieces/2 assembly lines), all of them increased the hourly volume of assembly compared to the current state of one assembly line (19 pieces/1 assembly line).

The optimal proposal is Proposal 6. It differs from the current state in that the assembly takes place on only one robotic line, namely the workplaces Pre-assembly, Robot, Assembly 1 and Assembly 2. In this proposal, the hourly production of the line is achieved in the number of 54 pieces, which is compared to the current state of assembly by 16 pieces or by 42%. The hourly rate of the line decreased compared to the current situation by EUR 0.62, thus by 0.6%. Proposal 6 assumes four workers at the line's workplaces, which means savings of two workers compared to the current state of assembly.

5. Conclusions

The importance of using scientific methods in the management of these processes was pointed out in the assembly process of throttle valves in a small company. The current state of installation of throttle valves was associated with waste, non-systematic and unbalanced work in individual workplaces. Elimination of waste and a balance of work at individual workplaces was achieved by applying methods of measuring time consumption, balancing workplaces, the introduction of automation of welding and sealing operations using robots. These facts positively influenced the production and economic criteria by which Proposals 1–8 were assessed. Cost savings per product compared to the current situation were achieved for seven proposals, ranging from EUR 0.03 to EUR 0.50 per piece.

It can be stated that both by balancing the assembly line and by the influence of automation of selected operations on the assembly line, an increase in productivity of assembly of FD 160 products was achieved in the submitted proposals. The difference between used approaches lies in the way and time for which the measures can be implemented. By eliminating waste and subsequently balancing production operations, it is possible to achieve growth in production productivity in a short time and at minimal costs, while as a rule, the increase in line productivity is limited. On the contrary, the implementation of automation into production requires longer preparation times, including economic project assessment and higher investment costs, however, on the other hand, it brings benefits in terms of higher productivity and production qualities, as well as material, labor and energy savings, and shorter production lead times.

Before the decision to implement an investment proposal, it must be thoroughly assessed in terms of economic efficiency. When assessing the economic efficiency of an investment proposal, it is appropriate to take into account the revenue side, dynamic evaluation methods that take into account the time value of money and assess risks. Given the current dynamically changing business environment, it is appropriate to use a stochastic approach to risk assessment [39–41] using Monte Carlo simulations.

Why do small businesses only sporadically use scientific methods to manage assembly processes? From a theoretical point of view, methods or entire methodologies are processed sufficiently. However, the extent of the use of these methods in the management of assembly processes depends to a large extent on the educational level of management, the ability and skills of employees to implement these methods for specific conditions, as well as their numbers.

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