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Comparison of the Classic and Hybrid Production Methods with the Use of SLM Taking into Account the Aspects of Sustainable Production Development

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ABSTRACT

Problems on the world market, related to delays in supply chains, have forced enterprises to adopt a more flexible approach in the production processes of the offered products. In order to meet customer needs, companies can often look for alternative supply chains, as well as take over the production of key components necessary to maintain business continuity. Therefore, companies have to make important decisions in the context of management. A simulation model may be a tool helpful in making decisions related to production planning, which, based on the actual data collected from the process, allows for the verification of decisions before entering them into the real system. The motivation to conduct the research was the search for answers: How entrepreneurs, while maintaining profitability, can ensure the continuity of production processes by searching for alternative production methods. The article considers a comparison of two production processes for the production of a shield type product: classic production - on a lathe and hybrid production using the SLM method and machining only technologically significant surfaces on a lathe. The main goal of the research is to compare two production processes: classic and hybrid in terms of efficiency, energy efficiency and production costs. The research takes into account the use of different laser powers and the possibility of incremental production of several products at the same time. In order to achieve the assumed goal, a simulation model was used to carry out the research, which was developed on the basis of preliminary experimental studies. A series of simulations were performed, taking into account the variability criteria, and then the efficiency, energy efficiency and profitability of using alternative production methods were analysed. The purpose of the article is comparison of two production processes, classic and hybrid, in terms of efficiency, production costs and electricity consumption.

Keywords: machining, SLM, sustainable development, production costs.

INTRODUCTION

Raw material scarcity, rising costs and increasingly complex customer requirements are causing massive problems in global business chains. Companies that want to remain competitive on the global market are obliged to focus on innovation. Which means not only intelligent new products, but also the method of their production, because the aspects of sustainable development are becoming more and more important in the purchasing decisions of consumers.

The worldwide geopolitical situation and the related downtime in production processes have disrupted supply chains and the related delays in the delivery of production components and spare parts. Delays in deliveries were additionally aggravated by the situation on the Chinese market. The energy crisis that hit China resulted in limitations in electricity supply and downtime in many production plants in China [1]. The problem of delays in supply chains has forced enterprises to adopt a more flexible approach to production processes. To meet customer needs, companies can often look for alternative supply chains as well as take over the production of key components necessary to maintain business continuity. Of course, the second option is only possible if you have the appropriate hardware and human resources. To do this, businesses need to make important decisions. A tool helpful in making decisions related to production planning can be a simulation model [2, 3, 4] which, based on real data from the process, allows for the verification of decisions before entering them into the real system [5, 6].In the literature, you can find examples of modelling e-business processes [7, 8] and the extension of models to supply chains [9], as well as descriptions of the benefits of using a new methodological approach to develop static and dynamic simulation models [10, 11]. In [12] the simulation was used to test the real system model and see the results of the optimization of the production system in concrete conditions, which bring specific improvements in concrete case – increased pieces of final product, better utilization of production time and reduction of storage times to minimum. Also in research [13] the benefits of using simulation methods to optimize the production process were presented. The studies have shown the possibility of increasing efficiency by more than 25%.

Comparing the production of products with the classical method (machining) and the method of additive manufacturing, including the SLM method, in the literature on the subject have already been discussed, among others, by [14, 15, 16, 17]. M. L. da Costa Valente et al. In [14] presented research and evaluation of wettability, topography, chemistry and structure of titanium-aluminum-vanadium (Ti-6Al-4V) discs produced by selective laser melting (SLM) and conventional machining. The obtained results confirmed the possibility of replacing the conventional treatment with the SLM technique. For SLM, higher roughness and lower wettability were obtained without changing the chemical properties and structure of the titanium alloy. In contrast, Ingarao et al. in [15] he dealt with the comparison of product production methods using the following methods: SLM, machining and forming, taking into account the life cycle analysis. Obtained by Ingarao et al. The results show that in the analysed case studies, SLM manufacturing for aluminium components is sustainable only for shapes with high complexity, significant weight reduction and application in transport systems. Sustainable development of the production of metal products with the use of additive manufacturing was also dealt with by Fredriksson in [16], where he presented the results of energy consumption research for the production process of the product using the EBM (Electron Beam Melting) method. The presented result was compared with the installed energy as well as with the production of the product by machining. As a result of the comparative studies carried out, it was found that in the context of the life cycle, both the production of metal powder and the additive manufacturing process itself contribute significantly to the total energy consumption. J. K. Watson et al. in [18]. In the article [18] he presented a model that allows to compare the energy use for the production of a given metal part using two production methods based on actual data from process measurements. On the other hand, Liu in [17] presented an analysis of the manufacturing costs with the SLM method and machining. The research presented in Liu [17] shows that in the production of small production batches SLM has an economic advantage over the production by machining. The technological complexity of the product and the type of material also affect the economic advantage of the SLM method over traditional machining. A comparative analysis of the classic SLM method of processing and production was also carried out by the team of Grzesiak et al. in [19], where the authors presented the results of experimental work on the production of two products by machining and SLM, paying attention to the maintenance of the quality parameters of both products, process costs and energy consumption. The comparison of SLM technology and machining is also presented in [20], where the authors compared the production of disc-type parts for machining 1, 10 and 100 pieces of products in terms of energy, time and production costs. The presented article is a continuation of the team's research work on finding an answer to the question: How can entrepreneurs, while maintaining profitability, ensure the continuity of production processes by looking for alternative production methods?

An additional aspect that will be discussed in the analyzed article is the concept of Sustainability on Production in the aspect of Industry 4.0, in which new procedures and technologies are constantly appearing, introducing methods and practices aimed at preventing environmental damage. A wide range of cleaner production initiatives contributes to sustainable development not only through the effective management of resources and energy, but also through the development of new and intelligent technologies, new ways to support policy development and the organization of supply chains, sectors in individual industries [21, 22, 23, 24]. In the literature, there is an article by Giannetti et al. [21], which presents an overview of the latest trends that follow the goals of sustainable development in the practice of clean production. The article summarizes and shows the relationship between the concept of clean production and production practices, along with the selection of sustainable development goals. In the literature, Bag et al. [25] explores the impact of implementing Industry 4.0 advanced technologies in line with the 10 R principle (Rebusem, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover) on sustainable development. The advanced manufacturing capabilities of the 10R have been found to have a positive impact on sustainability performance. Similarly, Diaz et al. [26] described the impact of adopting the R strategy on decision making in the sustainable product development SPD process. Industry 4.0. is also characterized by an increase in the energy efficiency of production processes, which affects, inter alia, maintaining energy security, reducing energy costs and protecting the natural environment. These benefits are appreciated by more and more countries that are developing special energy strategies. Poland is also one of them. In 2016, the Act of May 20, 2016 on energy efficiency (Journal of Laws 2020, item 264) entered into force, specifying formal rules and obligations of entrepreneurs, aimed at improving energy efficiency, including by implementing innovative solutions, preparing the company's energy audit and improving overall performance in various sectors of the economy. According to the report "Accelerating Clean Energy through Industry 4.0" [27] published by UNIDO in 2017, industrial digital technologies offer many environmental benefits, including increasing the use of renewable energy in production, reducing carbon dioxide emissions, increasing energy efficiency in industry or increasing the productivity of enterprises. In summary, the concept of Industries 4.0 is a complex process of technological and organizational transformation of enterprises, which includes the integration of the value chain, the introduction of new business models and the digitization of products and services, which supports the achievement of the sustainable development goals, which were included in the document "Transforming Our World: The 2030 Agenda for Global Action " [28].

The article considers a comparison of two production processes for the production of a disc type product: classic production – on a lathe and hybrid production– carried out with the use ofadditive manufacturing and lathe machining of only technologically significant surfaces. The aim of the research is to compare two production processes, classic and hybrid, in terms of efficiency, energy efficiency, sustainabilityandproduction costs. The research presented in the article is a continuation of the research contained in [20], where the authors presented the results of hybrid production using a 100 W laser. The results presented in [20] indicated the validity of using hybrid production for single products. Therefore, the research team formulated the research problem of increasing the profitability of hybrid production by increasing the laser power and the simultaneous production of several products using the SLM method.To conduct the research, a simulation model was used, developed on the basis of the conducted experimental tests involving the manufacture of two products. During the research, actual measurements of the electricity consumed were carried out.To determine the sustainability impact of both production methods, three main indicators were selected: carbon footprint, eutrophication index and acidification index, as well as energy consumption. These indicators were chosen because of their widespread use in the context of sustainable development.

MATERIAL AND METHODS

A general purpose 17-4PH stainless steel disk element was used to conduct the experimental tests.The dimensional and shape accuracy is presented in Figure 1. The main objective of the research is to compare two production processes: classic and hybrid in terms of efficiency, energy efficiency and production costs, while maintaining the aspects of sustainable development. During the experimental tests, two copies of the parts were made, which in the next stages were called "classic production process" and "hybrid production process". The research takes into account the use of different laser powers and the possibility of incremental production of several products at the same time. To achieve the assumed goal of the research, a simulation model was used, which was

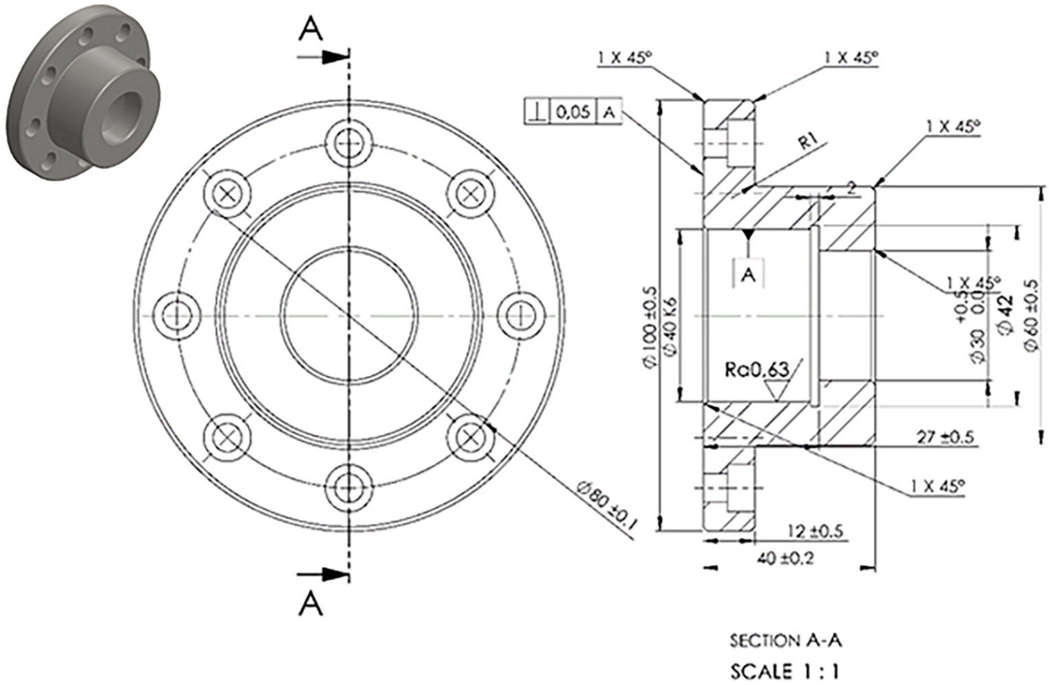

Fig. 1. Disc element isometric view and cross section view– 17-4PH stainless steel

developed on the basis of preliminary experimental studies. The initial assumptions for the analyzes carried out were the omission of the purchase and maintenance costs of machine tools and AM devices and the omission of the purchase costs of technological equipment that was not worn during the experiment (tool holders, part holders, base plates for the SLM process).

The classic process is characterized by the technology of producing an element that is created by subtracting material, cutting, e.g. using a lathe, milling machine or machining center. A CTX Ecoline turning center with Y-axis positioning and driven tools was used to perform the tests for the classical process. The technological process and NC programs were prepared by a qualified technologist, there was no need for 3D modelling of the parts. A rod with a diameter of 110 mm and a length of 3000 mm was purchased to make the disc element.

All 3D printers, regardless of the method, make parts based on the principle: a three-dimensional model is created by hardening the material applied layer by layer. Therefore, this technology is called additive or additive manufacturing. Finally, the elements are subject to finishing treatment, the purpose of which is to improve the mechanical properties and appearance. In order to carry out research on the hybrid process, it was divided into two stages. The first stage was the design by a qualified technologist of the target element model with appropriate allowances on the surfaces intended for post-processing, which were exported in the STL format for data exchange in additive manufacturing. Such a file contains the geometry of parts and load-bearing elements divided into successive layers and information about the operating parameters: laser power 100W and 400W, working surface, layer thickness and the beam's movement strategy on the molten surface. The entire batch file preparation process was carried out in the ReaLizer Control Software. In the next step, the additive manufacturing process was carried out using the SLM Realizer II device, which consisted of the actual operation of the device as well as preparatory and post-processing activities, which in the case of selective laser melting are: placing the base plate in the process chamber, loading the powder, heating the build platform , filling the process chamber with inert gas, removing the manufactured part from the process chamber, and removing the residual powder. The second stage is the finishing of the disc element on the above-mentioned. machine tool. The manufactured part was cut from the base plate (a band saw was used) and transported to the machining department, where a qualified operator selected cutting tools and technological parameters, and then processed selected surfaces, removing the remaining allowance. CCMT 120404EN-SM CTC2135 boards were selected for roughing, and for finishing DCMT

11T304EN-SM CTC2135 boards. The axial hole was drilled with the XOMT 060304SN CTPP430 folding drill. The holes were drilled with carbide drills WPC-VA. 6.60.R.3D.IK.DIN6535.HA TIALN, and countersinking with a SE.N countersink. 6.40X11.00.180 ° DF.DIN373. For the hybrid process, the raw material was metal powder.

Electricity consumption was measured for the SLM Realizer II device and the CTX Ecoline turning center using the Lumel ND 20 recorder. The current was measured using transformers, while the voltage was measured directly. The measurement was carried out on the main power supply of each device. Transformers with a current intensity of 200A were used for the measurement, with the current accuracy class of 5A. The results were recorded using the PowerVIS recording software.

Digital models for both production processes were made in Tecnomatix Plant Simulation 16. The classical and hybrid methods were simulated for each model in order to identify manufacturing time and throughput, with a variable batch size, to obtain information on the profitability of using spare parts manufacturing methods. Additionally, in order to optimize the time and energy consumption of the additive manufacturing process, the laser power parameter and the possibility of incremental production of 2, 3 and 4 products simultaneously on one base plate were changed.

The analysis of the impact of product production on the environment in the context of sustainable development was developed using the Solidworks 2022 software – the Sustainability tool. This tool was used to determine the environmental impact of the material and production process used in terms of clean production and sustainable development. Mainly three indicators were used for the assessment: carbon footprint, air acidification and water eutrophication. In addition, the energy efficiency was determined. All indicators include the material used in the form of 17-4HP stainless steel, the production process for which the energy used in the process has been defined based on the simulation model made in Tecnomatix Plant Simulation 16 and the end of life stage of the product. The analysis omitted the aspect of transport due to the use of the product in the company where it is produced. It was assumed that both production and use take place in Europe.

In order to analyse the production costs, the main assumptions presented in Table 1 were adopted, which take into account the labor costs of the operator, technologist and quality controller, as well as the costs of energy, materials and tools used.

RESULTS AND DISCUSSION

The geopolitical situation has disrupted supply chains, resulting in delays in production components (spare parts). Due to delays, entrepreneurs are forced to look for alternative supply chains, as well as a flexible approach in the production of key components necessary to maintain business continuity. Therefore, the article presents the

Table 1. Unit production costs of an item

Cost	Classic manufacturing	Hybrid manufacturing	Unit
Operator’s work *	8.56	10.05	EUR/h
Technologist’s work **	12.38	58.33	EUR/h
Work of the quality controller ***	8.40	8.40	EUR/h
Materials ****	48.53	77.19	EUR
Tools *****	116.28	27.27	EUR
Energy******	0.4218	0.4218	EUR/kWh
* Average earnings for the positions of CNC machine tool operator (for classic production) and CNC machine operator (for hybrid production): source: [29]			
** Average earnings for the position of process technologist: source: [29]			
*** Average earnings for the position of a quality controller: source: [29]			
**** Cost of a roller with a diameter of 110 mm (for classical machining) and 1.07 kg of metal powder (for the hybrid process)			
***** Tool costs include the cost of purchasing the following tools: For roughing, CCMT 120404EN-SM CTC2135 plates were selected, for finishing the DCMT 11T304EN-SM CTC2135 plate. The axial borehole was drilled with a folding drill bit XOMT 060304SN CTPP430. Drill holes were drilled with carbide drill bits WPC VA.6,60.R.3D.IK.DIN6535.HA TIALN, and deepening in holes with countersink SE.N. 6.40X11.00.180 ° .DF.DIN373.			
****** The cost of energy consumption includes the cost of active energy consumption. 1 kWh of electricity currently costs PLN 1.3810 - PLN 2.5921. source: [30]			

possibilities of using the simulation model in Tecnomatix Plant Simulation 16, which gives the opportunity to verify the implementation of the development of new and intelligent technologies, to check the effective management of resources and energy, as well as new ways to support the development of business policies, taking into account a wide range of initiatives related to cleaner production. contributing to sustainable development.

In order to search for alternative solutions, digital models for two manufacturing methods were presented. To better illustrate the difference in the course of the manufacturing processes, the figures below show the use of the classical process (machining) (Fig. 2) and the hybrid process (SLM + machining) (Fig. 3).

In both processes: classic and hybrid, there are Analytical Activites and Technical preparation, which are carried out only once for the entire production batch. For a hybrid process, these steps occur for both lathe and SLM. For both processes, activities related to quality control were also defined, carried out at two stations, including measurements of dimensional accuracy and shape as well as roughness of the manufactured parts.

The first stage of the research was to compare two production processes: classic and hybrid in terms of time and efficiency of the manufactured disc elements. In order to optimize the implementation time of the hybrid method, the tests take into account the use of different laser powers of 100W and 400W and the possibility of incremental production of several products at the same time. The order completion times for the target element obtained from simulation tests are presented in Table 2.

The data presented in Table 2 shows that the order processing time for classic and hybrid production methods increases with the size of the production batch. For 1 piece of the disc element, the production time for the hybrid method for the 100W laser power is 6 times greater, and for the 400W laser power – about 2 times greater than for the classic method. As production batches increase, the lead time increases in direct proportion to the sum of the unit time of the disc element of a given production batch for both production methods. With an increase in the production batch, the added value for the hybrid process decreases much faster compared to the classical process. This means higher costs related to the expectation due to the bottleneck of the additive manufacturing process, which was confirmed in accordance with the article by Grzesiak et al. in [19].

Comparing the production with the laser power of 100W and 400W, it can be seen that

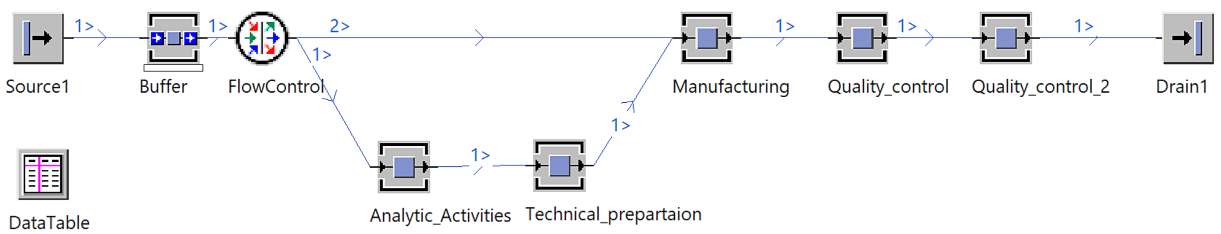

Fig. 2. Model of the product manufacturing process by the classical machining method

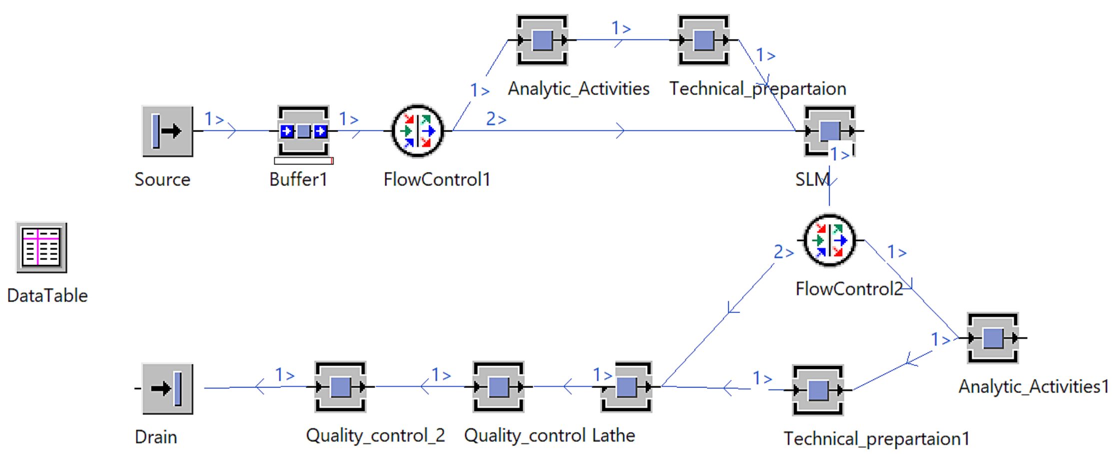

Fig. 3. Model of the product production process using the hybrid method (SLM + machining)

Table 2. Summary of production process parameters for selected production batch sizes

Production type	Production value	Mean life time	Productive performance	Throughput	Production	Storage	Value added
Classic manufacturing	1 psc	5:51:15	4.102	1	100.00%	0.00%	100.00%
	5 psc	10:03:25	11.932	1	100.00%	0.00%	100.00%
				4	18.29%	81.71%	81.71%
	10 psc	15:18:50	15.672	1	100.00%	0.00%	100.00%
				9	13.97%	86.03%	13.97%
	15 psc	20:34:15	17.501	1	100.00%	0.00%	100.00%
				14	17.46%	82.54%	12.55%
	20 psc	25:49:40	18.584	1	100.00%	0.00%	100.00%
				19	18.12%	81.88%	12.35%
Hybrid manufacturing 100W	1 psc	31:38:27	0.759	1	100.00%	0.00%	100.00%
	5 psc	147:01:55	0.816	1	100.00%	0.00%	100.00%
				4	28.75%	71.25%	28.75%
	10 psc	109:42:55	0.818	1	100.00%	0.00%	100.00%
				9	18.40%	81.60%	18.40%
	15 psc	438:00:35	0.822	1	100.00%	0.00%	100.00%
				14	16.13%	83.87%	12.58%
	20 psc	583:29:55	0.823	1	100.00%	0.00%	100.00%
				19	16.37%	83.63%	11.17%
Hybrid manufacturing 400W	1 psc	13:21:37	1.796	1	100.00%	0.00%	100.00%
	5 psc	55:37:45	2.157	1	100.00%	0.00%	100.00%
				4	29.04%	70.96%	29.04%
	10 psc	109:42:55	2.179	1	100.00%	0.00%	100.00%
				9	17.22%	82.78%	17.22%
	15 psc	163:48:05	2.198	1	100.00%	0.00%	100.00%
				14	16.47%	83.53%	12.91%
	20 psc	217:53:15	2.203	1	100.00%	0.00%	100.00%
				19	16.67%	83.33%	11.48%

for higher laser power the added value is higher, which is related to the shorter production time. Also, the productivity rate for a 400W laser power is as much as 2.6 times higher than the production with a 100W laser.

The literature often describes the result parameters which characterize the performed SLM process. An important parameter is the total production time which determines the efficiency of the process. Another parameter of the analysed research is the efficiency of processes for the classical and hybrid methods. When analysing the data, a logarithmic trend line was noticed for the efficiency of the processes, which is presented in Fig. 4–6. The trend line in the analysed range shows an increasing dependence of the efficiency of production processes to the size of the production batch.

In the case of the classical processes, Fig. 4, the function adjusted to the experimental data tends asymptotically to constant values of approximately 18.55 pieces per day for the process efficiency with the production batch size equal to 20. The degree of matching the function is very good, and the lowest coefficient of determination obtained was $R^2 = 0.99$. The study of the efficiency of the classical process shows a clear increase in efficiency at the beginning of the production process, which is caused by taking into account the time of technical and organizational service, as well as the experience gained about the processes performed.

In the 100W hybrid process (Figure 5), the function adjusted to the experimental data asymptotically tends to constant values of approximately 0.822 pieces per day, respectively, for the process efficiency with a production batch size of 20. The degree of matching the function is weak, and the lowest coefficient of determination

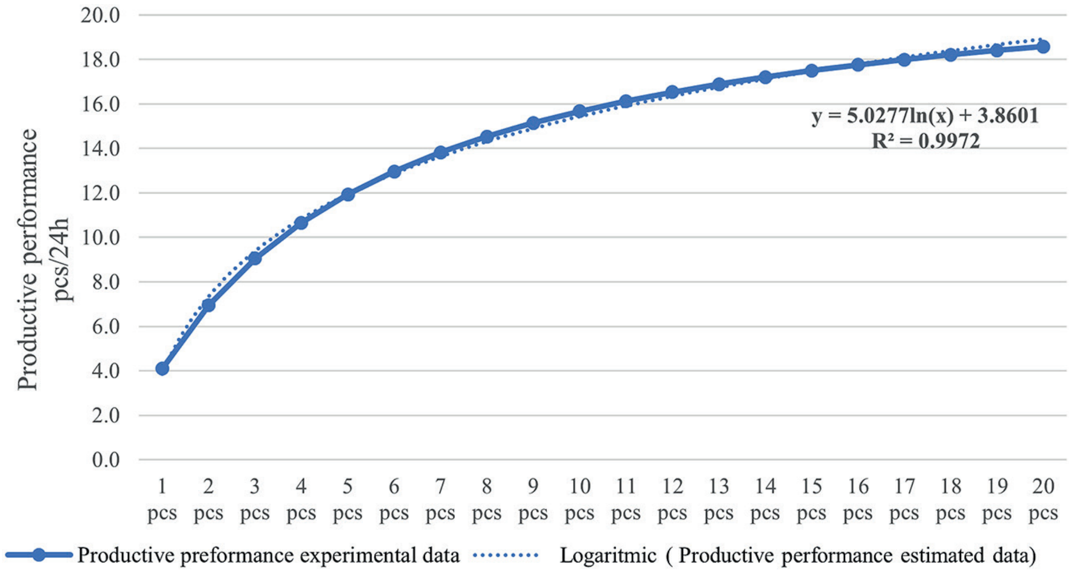

Fig. 4. Efficiency chart for classic manufacturing

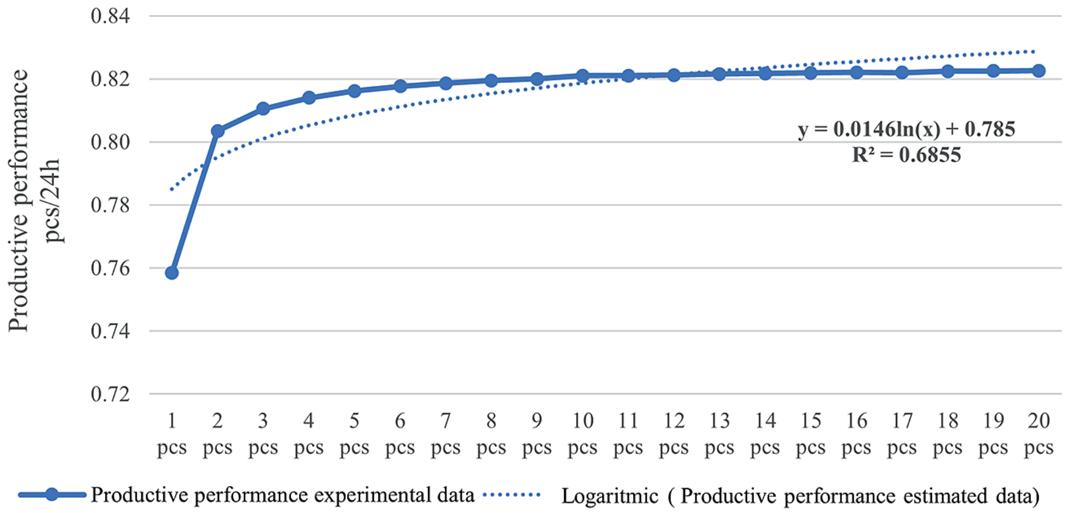

Fig. 5. Performance chart for 100W hybrid manufacturing

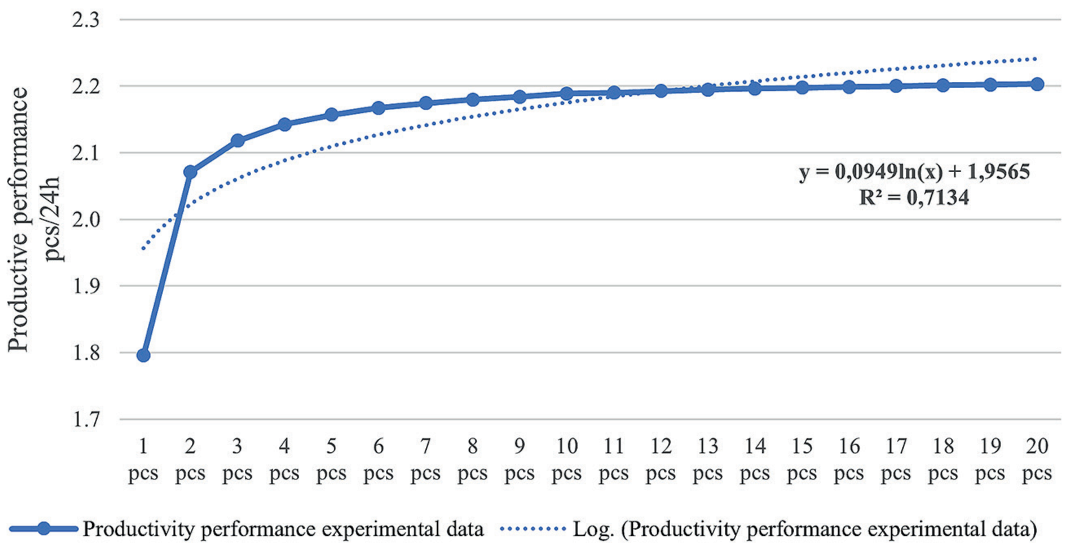

Fig. 6. Performance chart for 100W hybrid manufacturing400W

obtained is R^2 = 0.68. For the 400W hybrid process (Figure 6), the function adjusted to the experimental data asymptotically tends to constant values of approximately 2.203 pieces per day for the process efficiency with the production batch size equal to 20. The degree of matching the function is satisfactory, and the lowest coefficient of determination obtained is R^2 = 0.71. Summing up, the efficiency of the classic production process is 22.5 times higher than the efficiency of the 100W hybrid process and 9 times higher than the efficiency of the 400W hybrid process.

In the case of the analysis of additive manufacturing, an important factor influencing the effects of production and the efficiency of the process is the strategy of selecting technological parameters (P_SLM). The P_SLM selection strategy is a strictly defined sequence of scanning successive areas of the model within one layer, but also the distance between the beam passes, the time of the beam's interaction at a point, power, velocity, and thickness of the powder layer. Therefore, it is worth continuing research on the impact of the SLM technological parameter strategy on the efficiency of production processes.

The next step in the optimization of alternative production processes was the verification of the possibility of incremental manufacturing of several products at the same time. Table 3 summarizes the implementation time and process efficiency for the production batch size of 12 pieces, taking into account the division into the simultaneous production of 2, 3 or 4 disc elements.

From the presented data, it can be concluded that with the increase in the number of products manufactured simultaneously, the task completion time is reduced and the process efficiency increases. When comparing alternative production methods, the optimal parameters are demonstrated by the use of hybrid production for 400W laser power for the 4×20 strategy, where the implementation time and efficiency are approx. 3.5 times shorter than the 100W (4×20) hybrid production. Increasing the laser power shows a significant relationship for shortening the lead time and increasing the efficiency. Therefore, it is worth continuing research on the impact of the SLM technological parameters strategy on the efficiency of production processes, taking into account the strength and quality aspects of the surface produced. To sum up, the analysis of the simulation model of the disc element shows that the classic production process still shows the best results in terms of the shortest time and the highest efficiency for larger production batches (12 pcs.).

One of the assumptions of the Industry 4.0 concept is the modeling of production processes aimed at maintaining clean production in accordance with the principle of sustainable development. For this reason, the energy efficiency of the modeled processes was verified while maintaining the aspects of sustainable development. First, the energy efficiency of the production process was analyzed. The results of the analysis are summarized in Table 4. The data presented in Table 5 show that classic production, regardless of the size of the production batch, is characterized by a demand for electricity from several to several times lower. Comparing the hybrid production for 100W and 400W laser power, it can be seen that the process in which the 400W laser power was used has a lower demand for electricity. This is directly due to the shorter processing time. When analyzing the data for 12 items, it can be noticed that the electricity demand for the hybrid process compared to the classic production is 9.6 times higher for the 100W laser power and 4.5 times higher for the 400W laser power. The possibility of reducing the demand for electricity in the hybrid process is the implementation of several products at the same time. In the case of the production of 4 products at the same time, the demand for electricity for the hybrid process, compared to classic production, is 8 times higher for a 100W laser power and 3 times higher for a 400W laser power.

Then, an environmental impact analysis was performed in Solidworks Sustainability to check the environmental impact of both production

Table 3. Summary of performance and lead time for 12 pieces of elements, taking into account the production of several products at the same time

Parameters	Classic manufacturing for 12 psc	Hybrid manufacturing 100 W for 12 psc			Hybrid manufacturing 400 W for 12 psc		
	1-20	2×20	3×21	4×20	2×20	3×21	4×20
Productive performance	16.536	0.889	0.914	0.927	2.761	3.017	3.159
Mean life time	17:25:00	323:39:59	314:48:59	310:30:59	104:17:59	95:26:59	91:08:59

Table 4. Summary of electricity consumption in the classic and hybrid production process

Number of items	Electrycity consumption [kWh]								
	Classic manufacturing	Hybrid manufacturing 100 W				Hybrid manufacturing 400 W			
		1×20	2×20	3×21	4×20	1×20	2×20	3×21	4×20
1	4.74	43.23	-	-	-	20.22	-	-	-
2	9.21	86.35	79.70	-	-	40.32	31.45	-	-
3	14.34	129.45	-	116.16	-	60.41	-	43.10	-
4	18.76	172.56	159.28	-	152.63	80.51	62.77	-	54.76
5	23.17	215.66	-	-	-	100.61	-	-	-
6	27.58	258.78	237.84	232.20	-	120.71	93.08	86.08	-
7	32.00	301.88	-	-	-	140.80	-	-	-
8	36.41	344.99	316.40	-	305.13	160.90	123.39	-	109.39
9	40.82	388.08	-	346.70	-	180.98	-	127.51	-
10	45.24	431.21	394.96	-	-	201.09	153.70	-	-
11	49.65	474.30	-	-	-	221.17	-	-	-
12	54.06	517.41	473.52	461.20	457.63	241.27	184.01	168.96	164.02
13	58.47	560.53	-	-	-	261.37	-	-	-
14	62.89	603.63	552.08	-	-	281.46	214.32	-	-
15	67.30	646.74	-	575.70	-	301.56	-	214.99	-
16	71.71	689.84	630.64	-	610.13	321.66	244.63	-	218.65
17	76.13	732.96	-	-	-	341.76	-	-	-
18	80.54	776.06	709.20	690.20	-	361.85	274.94	256.43	-
19	84.95	819.17	-	-	-	381.95	-	-	-
20	89.37	862.28	787.76	-	762.63	402.04	305.25	-	273.28
21	-	-	-	804.70	-	0.00	-	297.87	-

methods. The results of the conducted analysis are shown in Figures 7–9. The conducted analyzes show that the classical process has the lowest environmental impact, both in the form of carbon footprint index, as well as air acidification and water eutrophication (Fig. 7). The hybrid process for both 100W and 400W laser power is characterized by a much greater environmental impact. The results obtained for a 100W laser (Fig. 8) are over 9 times higher than the classic production. For the carbon footprint, an 825% greater impact can be noticed, for the air acidification index 827% greater, and for water eutrophication 824% greater than for classic production.Comparing the hybrid production with a 100W and 400W laser, it can be seen that the environmental

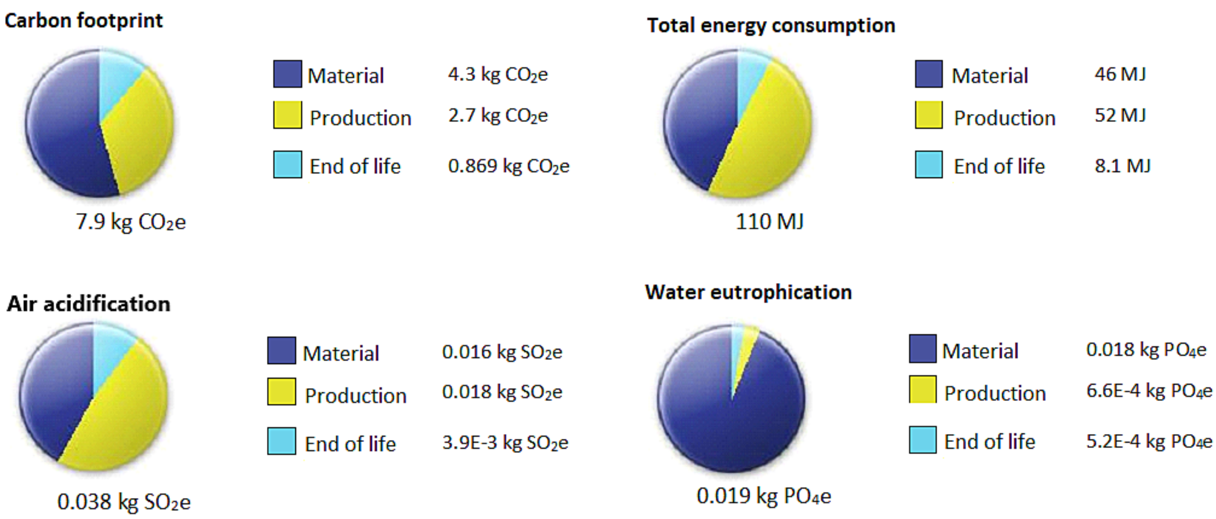

Fig. 7. Environmental impact indicators for the production of 1 product using the classical method

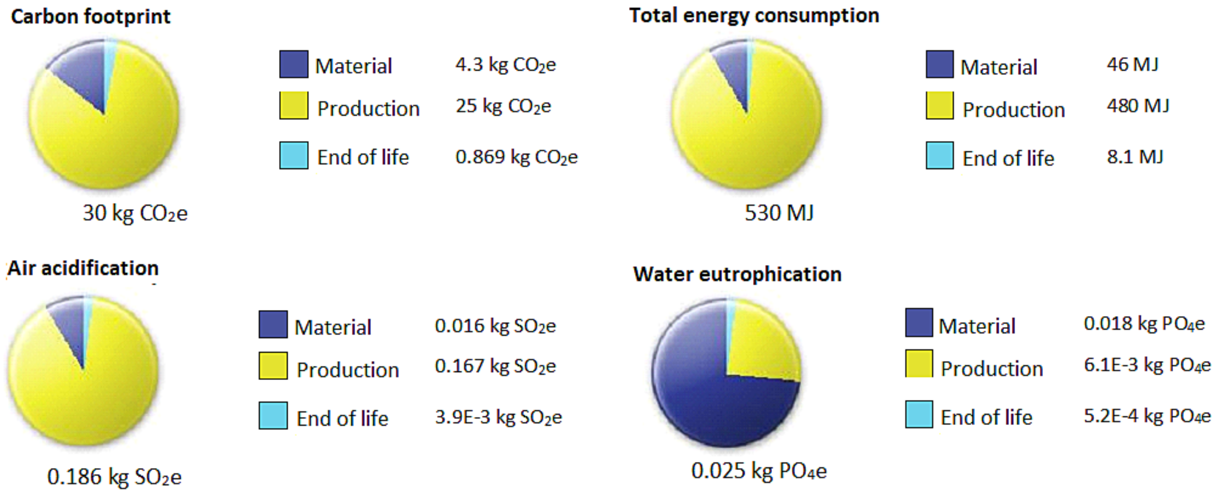

Fig. 8. Environmental impact indicators for the production of 1 product using a hybrid method with a 100W laser

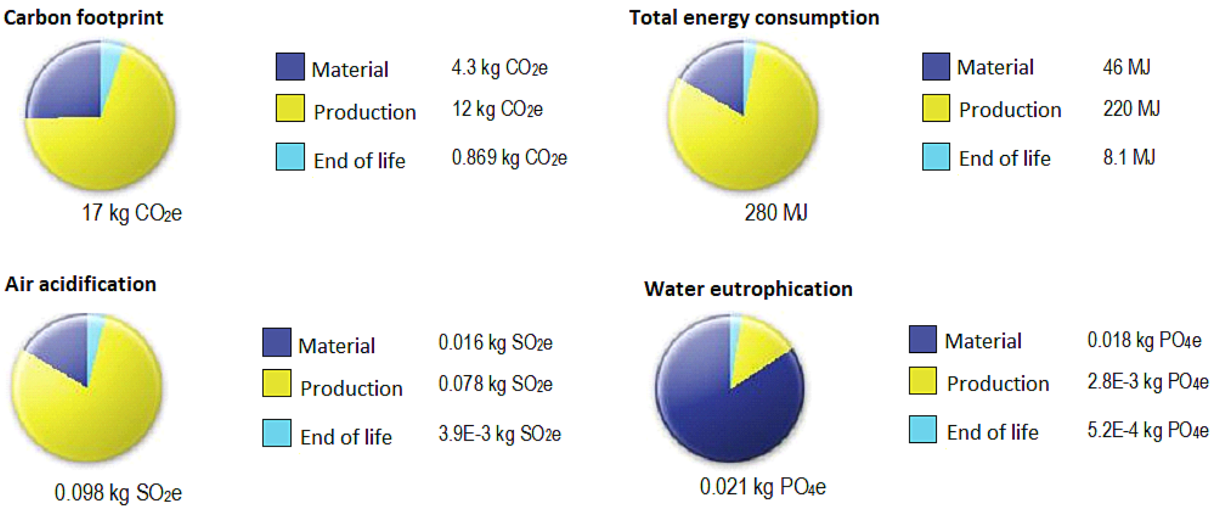

Fig. 9. Environmental impact indicators for the production of 1 product using a hybrid method with a 400W laser

impact indicators for a 400W laser (Fig. 9) are more than 2 times lower. For the carbon footprint, the impact is 43% lower, for the air acidification index 47% lower, and for water eutrophication 54% lower compared to hybrid production with a 100W laser.

The last step was to compare the production costs for the classic and hybrid methods, taking into account the variability criterion, including laser power and incremental manufacturing of several products at the same time. Table 5 shows a comparison of production costs for different production methods.

Table 5. Production cost statements for various manufacturing methods

Cost item	Costs for classic manufacturing			Costs for hybrid manufacturing 100W			Costs for hybrid manufacturing 400W		
	1 psc	10 psc	20 psc	1 psc	10 psc	20 psc	1 psc	10 psc	20 psc
Operator's work [EUR]	21.12	102.16	192.03	9.56	19.27	29.97	9.59	19.27	29.97
Technologist's work [EUR]	35.71	35.71	35.71	10.32	10.32	10.32	10.32	10.32	10.32
Work of the quality controller [EUR]	4.20	42.02	84.03	4.20	41.68	94.45	4.20	41.68	94.45
Materials [EUR]	48.53	485.31	970.62	77.19	771.91	1543.82	77.19	771.91	1543.82
Tools [EUR]	116.28	116.28	116.28	27.27	27.27	27.27	27.27	27.27	27.27
Energy [EUR]	2.00	19.08	37.69	17.81	181.87	363.68	8.53	84.81	169.57
Total cost [EUR]	227.84	800.55	1436.36	146.36	1052.32	2069.51	137.10	955.26	1875.40

The simulations show that the use of hybrid production is recommended for unit production, which was also proven in the article by Grzesiak et. al. [19], in order to control the continuity of supply chains and the related delays in the delivery of components. In the production of spare parts, the use of 400W hybrid production will be ideal as an alternative production method while maintaining the same order execution costs as for the classic process. Authors M.L. da Costa Valente et al. in [14], also confirmed the possibility of replacing conventional treatment with the SLM technique. With the increase in the size of the production batch of disc elements, the costs of order fulfillment increase. In serial production, the cheapest and the shortest method of production is the classic process, the costs for a batch of 20 pieces are PLN 6,765.26, while the hybrid process for 100W is more expensive by about 44%, and 400W is more expensive by about 30%. In order to optimize the hybrid production method, in a further step, the costs of producing the disc element were verified, taking into account the possibility of producing several products simultaneously with the incremental method: 2, 3 and 4. Data on the production costs for a batch of 12 items are presented in Table 6. The data presented in Table 7 clearly shows that for a batch of 12 products, the most cost-effective method is production using the classical method. The cost of production of 12 products using the classical method is over 2 times lower than for the hybrid method with a 100W laser and over 1.2 times lower than for the hybrid production with a 400W laser. The largest share in the cost of manufacturing with the hybrid method has the cost of material and energy costs, resulting directly from the long processing time.

The simulations of the digital model of the disc element production have shown that despite the parallel production of SLM, it is not profitable to implement hybrid machining for serial or mass production. In the article by Liu [5], it also confirmed the thesis that in the production of small production batches, SLM has an economic advantage over the production by machining. The technological complexity of the product and the type of material also affect the economic advantage of the SLM method over traditional machining. It should be noted that the cost difference between the classical method and the hybrid method for 400w and producing 4 items simultaneously is small. Therefore, it is necessary to continue working with the optimal selection of parameters of the SLM production strategy in order to maintain the profitability of using alternative production methods in accordance with the idea of sustainable development and the concept of Industry 4.0.

CONCLUSIONS

The article analyses the production of a disc-type element using the classical method - machining and the hybrid method with the use of additive manufacturing and machining of only technologically significant surfaces. In addition, to optimize the time and energy consumption of the process, hybrid production was verified for two laser powers of 100W and 400W and the possibility of incremental production of 2, 3 and 4 elements at the same time. The research presented in the article clearly shows that hybrid production is profitable only for unit production. The total production costs for 1 piece of disc element using the classical method are approx. 36% higher for hybrid

Table 6. Summary of production costs for 12 psc disc element made with different production methods

Cost item	Costs for classic manufacturing	Costs for hybrid manufacturing 100W			Costs for hybrid manufacturing 400W		
	12 pcs						
	-	2×20	3×21	4×20	2×20	3×21	4×20
Operator’s work [EUR]	192.03	19.44	21.41	21.55	21.41	21.41	21.55
Technologist’s work [EUR]	35.67	10.32	10.32	10.32	10.32	10.32	10.32
Work of the quality controller [EUR]	9.67	42.02	50.08	72.44	50.42	50.08	72.44
Materials [EUR]	48.53	582.37	582.37	582.37	582.37	582.37	582.37
Tools [EUR]	116.28	27.27	27.27	27.27	27.27	27.27	27.27
Energy [EUR]	22.80	199.71	194.52	193.01	77.61	71.27	69.18
Total cost [EUR]	424.98	881.13	885.97	906.96	769.39	762.72	783.12

production with a 100W laser and approx. 40% higher for hybrid production with a 400W laser power. However, the production time for the hybrid method for the 100W laser power is 6 times longer, and in the case of the 400W laser power about 2 times longer than the classical method. The obtained results clearly indicate that taking into account the process efficiency, energy consumption and environmental impact indicators in the form of: water and air acidification, production using the classical method shows much better results. The conducted research showed that with the increase in production batches, the lead time increases in direct proportion to the sum of the time per unit of the disc element of a given production batch for both manufacturing methods.

Summarizing, by comparing alternative production methods, the optimal parameters are demonstrated by the use of hybrid production for 400W laser power for the 4×20 strategy, where the implementation time and efficiency are approx. 3.5 times shorter than the 100W (4×20) hybrid production. Increasing the laser power shows a significant relationship for shortening the lead time and increasing the efficiency. Therefore, it is worth continuing research on the impact of the SLM technological parameters strategy on the efficiency of production processes, taking into account the strength and quality aspects of the surface produced.

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