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METHODOLOGY OF BACKCASTING OF MANUFACTURING PROCESS ON THE EXAMPLE OF IMPLEMENTATION OF ADVISORY SYSTEMS IN MANUFACTURING PROCESSES

METODYKA WSTECZNEGO PROGNOZOWANIA PROCESU PRODUKCYJNEGO NA PRZYKŁADZIE WDROŻENIA SYSTEMÓW DORADCZYCH W PROCESACH PRODUKCYJNYCH

Summary*: In the present paper, the methodology of the backcasting of manufacturing process and the possibilities of the application of Bizagi Modeler software with the utilization of BPMN notation with the aim to show the analyzed manufacturing processes in the conceptional aspect was submitted. As the example, the problem of the choice of filament in the incremental manufacturing process and the issue of selection of semi-fabricate in the machining process were discussed. The implementation of advisory systems based upon the simulation model in Flexsim software with the application of method of backcasting was analyzed. In the conducted simulation, the times for two analyzed variants in the both mentioned above manufacturing processes were compared. The first variant considered the employment of advisory systems and the second one assumed the standard run of the process, with the verification of senior technologist.*

Keywords*: advisory systems, 3D print, machining, simulation modeling*

Streszczenie: W rozdziale przedstawiono metodykę wstecznego prognozowania procesu produkcyjnego oraz możliwości wykorzystania oprogramowania Bizagi Modeler z wykorzystaniem notacji BPMN w celu przedstawienia analizowanych procesów produkcyjnych w ujęciu koncepcyjnym. Jako przykład w rozdziale wykorzystano problem doboru filamentu w procesie wytwarzania przyrostowego oraz problem doboru półfabrykatu w procesie obróbki skrawaniem. Wdrożenie systemów doradczych przeanalizowano w oparciu o model symulacyjny w oprogramowaniu Flexsim z wykorzystaniem metodyki wstecznego prognozowania.

Słowa kluczowe: Systemy doradcze, druk 3D, obróbka skrawaniem, modelowanie symulacyjne

Introduction

At the present era of Industry 4.0, manufacturing companies introduce, more and more frequently, the advanced computer-based technologies with the aim to organize the production processes in the more effective way. The mentioned technologies are based on the assumptions of Industry 4.0 which emphasizes the integrated digital systems, enabling the automation of processes in the enterprise, *inter alia*, such as management of manufacturing knowledge in a wide range and where the computer simulations are one of the pillars of the discussed idea [5]. Modelling of manufacturing processes is a key issue for introduction of the technology of digital twins within the frames of digital transformation which is also assumed by the conception of Industry 4.0 [1]. Simultaneously, the failures are often encountered in the production environment and the incorrect sequence of manufacturing operations connected with the planned and real material flows is met. To minimize the mentioned faults, and to increase the effectiveness of manufacturing processes, it is necessary to employ the methods of simulation modeling [2].

Striving at implementation of lean manufacturing based on the conception of Industry 4.0 has become not only a strategic priority but actually a condition necessary (sine qua non) for survival and development of enterprises in the contemporary dynamically varying environment. Integration of the advanced digital tools such as simulation modeling and data processing is a key pillar of the fourth industrial revolution. The mentioned modern technologies not only facilitate the improvement of the manufacturing processes by the enterprises but also affect the abbreviation of the time of decision undertaking. Owing to this fact, the enterprises can more effectively react to the varying needs of the market, minimizing the wastage of resources and increasing their competitivity at a global scale [5].

Simulation modeling of processes is a current effective tool, serving the recognition and illustration of economic phenomena [3]. Dynamically varying micro- and macro-environment of manufacturing companies and a very high level of competitivity forces seeking for the solutions, determined by the market requirements [6]. At present, the manufacturing companies must constantly adjust themselves to the requirements of the customers and varying conditions. It affects, in turn, the abbreviation of the life cycle of products and creates the background for initiating the new production. The manufacturing enterprises have to show the flexibility and, at the same time, maintain the costs at the profitable, relatively low level as to be able to react quickly to the varying requirements of the customers [7].

Simulation modeling in manufacturing processes

Simulation of the manufacturing processes is an important approach to understanding the multidimensionality of real and abstractive systems on the plane of manufacturing processes. Development of simulation model allows the presentation of the crucial features of the system [10] which may be – later on – utilized in the implementation of the improvements in manufacturing processes, being analyzed in the present paper. The simulation in work [1] is defined as the imitation of the action of a real world, process or system in a defined time. Modeling of manufacturing processes is a very important instrument in the context of efficient and effective management of manufacturing enterprise [3]. The implementation of simulation modeling and reverse prognosing (backcasting) is a method of analysis of alternative states of the future which may be employed, *inter alia*, in the technology development. The discussed foresight methodology is characterized by a reversed logics of concluding. It is commenced from the definition of the vision of the future which is assumed to be achieved successively, step by step, withdrawing to the contemporary state [9]. Contrary to the traditional prognosing (forecasting) which anticipates the future events on the grounds of the present trends, backcasting is commenced from the future and serves for development of activities and strategy which may change the current state of things towards the specified goal.

In the paper[1] the simulation model of flexible manufacturing system has been developed. Designing of manufacturing systems which meet the production requirements as well as the market needs has become a greater and greater challenge due to variability of demand on a big number of products in many variants and short periods of implementation. The flexibility of production is universally recognized as the proven solution allowing to reach and maintain the strategic as well as operating goals of the enterprises endangered to a global competition. The general simulation model of flexible manufacturing system has been developed by the authors using Flexsim software and then, the authors utilized the exemplified data for demonstration of the developed model [1].

The application of computer software allows creation of models of the manufacturing processes and introduction of changes in them without the necessity of stopping the implementation of the current tasks. We may conduct the successive simulation on a studied model, changing the input data or arrangement of machines and improve it. At present, the simulations are used in modeling of the products and total manufacturing processes; during the nearest coming years, the employment of simulation software will be increased, with the enlargement of the range of its application in the successive domains. The simulations facilitate conducting of the tests before the changes are introduced in a real manufacturing environment. It should be mentioned that construction of correctly functioning model of manufacturing system is labour-consuming and requires a good knowledge of the process to be modelled as well as simulation software [8]. Moreover, the quality of the model is affected by the level of detailedness of mapping. The application of Flexsim software is the appropriate instrument for modeling and simulation of events.

The solution of technical problems, using simulation modeling is effective and its effectiveness was confirmed in scientific developments (*inter alia*, 10, 11]. The researchers state in their work [12] that correctly designed manufacturing process may have an influence on reduction of operating costs in the manufacturing company even up to 50%. The crucial instruments in

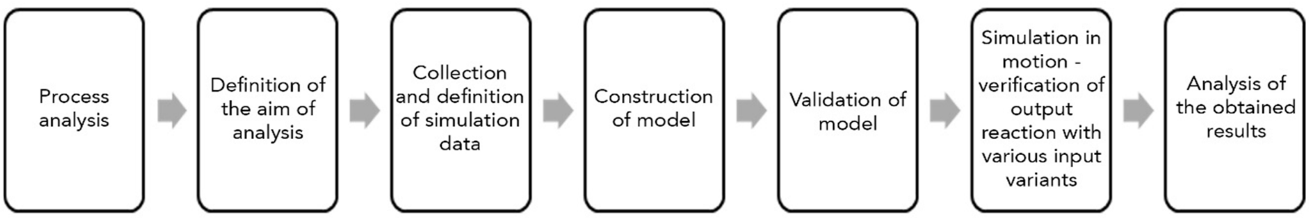

Fig. 1. Run of simulation modeling (own development based on [10])

simulation software serve for modeling of possible scenarios without the necessity of interrupting the on-going production, for visualization of information and analysis of the simulation data [10]. Designing with the employment of the backcasting method is possible owing to utilization of knowledge on the past events. The analysis of the available solutions may derive from the analogical cases, or from the known external potential improvements [14]. Modeling of manufacturing processes, objects and phenomena brings, in effect, obtaining the results in a form of time relationships of statistical data [13]. The run of simulation modeling with the application of backcasting methodology is possible to be presented in a few basic steps [10] as given in Fig. 1.

Application of simulation modeling in manufacturing processes, as analyzed on the example of implementation of advisory systems

Analysis of the lean manufacturing process

To analyze the change i.e. the introduction of advisory system into the machining process, it the scheme of the process run has been given below (Fig. 2). It was shown at the stage of technological designing at technological department in the process aspects, where the junior technologist may take the advantage from the advisory system support. In the authorial assessment of the case, the implementation of the advisory system with the aim to choose a semi-fabricate in the machining process is an innovative solution which contributes to the betterment of manufacturing processes, cost reduction and improvement of the quality of final products. The application of advisory system was highlighted in details at the first stage which includes development of technological processes for the machined parts of the equipment; at this stage, its componential parts were submitted in a simplified way for the needs of visualization of the total process in BPMN notation; it is commended from the choice of semi-fabricates; then, the less experiences worker of technological department has the possibility to consult the assumptions with the more experienced worker; he may also choose, in parallel, the advisory system in which the expert knowledge is recorded. Utilization of the advisory system at the mentioned stage abbreviates considerably the duration time of the whole process and supports meaningfully decision-undertaking by the employee who has a smaller experience. After the choice of the semi-fabricate for production of machine parts, the choice of the machining methods takes place and then, successively, the development of the process structure or machining processes, depending on the complexity of a given product, is carried out.

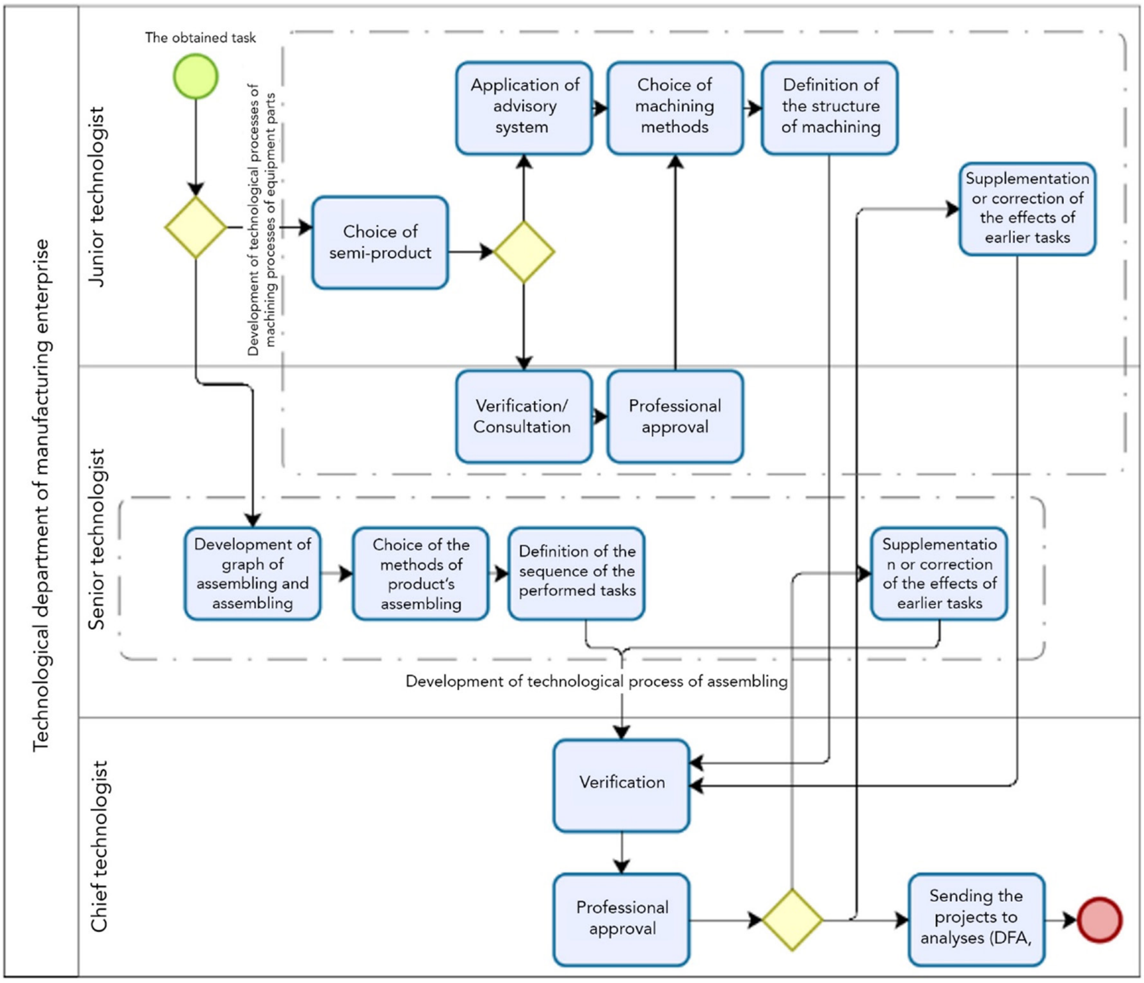

Fig. 2. Diagram of technological designing in conceptional aspect in technological department of the enterprise, with the application of advisory system (own development)

In parallel to the tasks, performed by the junior technologist, the senior technologist develops graph and assembling structure, chooses the assembling methods appropriate for a given product and determines the sequence of performing the set tasks. After termination of the mentioned stages, the verification and professional approval are carried out by the chief technologist; in the case of any irregularities, he sends the effects of the earlier tasks to be complemented or corrected, with the recommendations of sending to the repeated verification. After collection of the developed variants of machining process and implementation of assembling process, the final operation of the discussed stage of manufacturing process (what determines the effect of the total sub-process) includes sending the obtained effects to analyses (for example, the following analyses may be carried out: DFS, DFE, DFR, DFA of DRM). The mentioned above analyses are most frequently implemented as feedbacks and, first of all, they have to serve for the evaluation of constructional solutions of the product, suggested by the workers of technological department as the schemes of ready-to-use technological operations.

Apart from analyzing the run of the process alone, the assessment of the manufacturing process effectiveness may also utilize many indicators. To carry out the analysis of effectiveness in a proper way, the decision and selection of the appropriate indicators should be undertaken on the grounds of consultations with the employees of the enterprise, engineers and managers of the specific departments and also, based on the conducted analyses concerning the manufacture, distribution and sale range, with the consideration of priority tasks, The set of the considered indicators can be modified according to the needs of manufacturing process and the enterprise itself due to the current needs.

When applying the effectiveness indicators, it is possible to differentiate two main groups of the mentioned parameters – financial and non-financial ones which may be referred to the same manufacturing process but also, incomes and costs which are related to a given process [15]. Moreover, the analysis of the effectiveness of manufacturing processes allows distinguishing the weak and strong points of manufacturing processes.

The application of advisory system which supports undertaking of decisions concerning the choice of semi-fabricates for machining, affects the abbreviation of the time of implementation of the contract. A precise estimation of how much the total time of the implementation of the order may by decreased and how much the time of production of one element may be shortened, will be dependent on many factors, *inter alia*, such as number and complexity of the elements, availability of appropriate tools and machines and, also the competence of the workers of the particular departments.

The studies carried out at the enterprise revealed that the introduction of the changes in manufacturing process has brought about the increase of effectiveness. Based on the simulation data, it is estimated that the mean time of the implementation of the orders was decreased by 10% what means that the enterprise is capable to serve higher number of orders at a shorter time. The simulations were conducted basing on the time of the implementation of the order without application of advisory system and they were compared to the variant with the application of the advisory system. The produced simulation

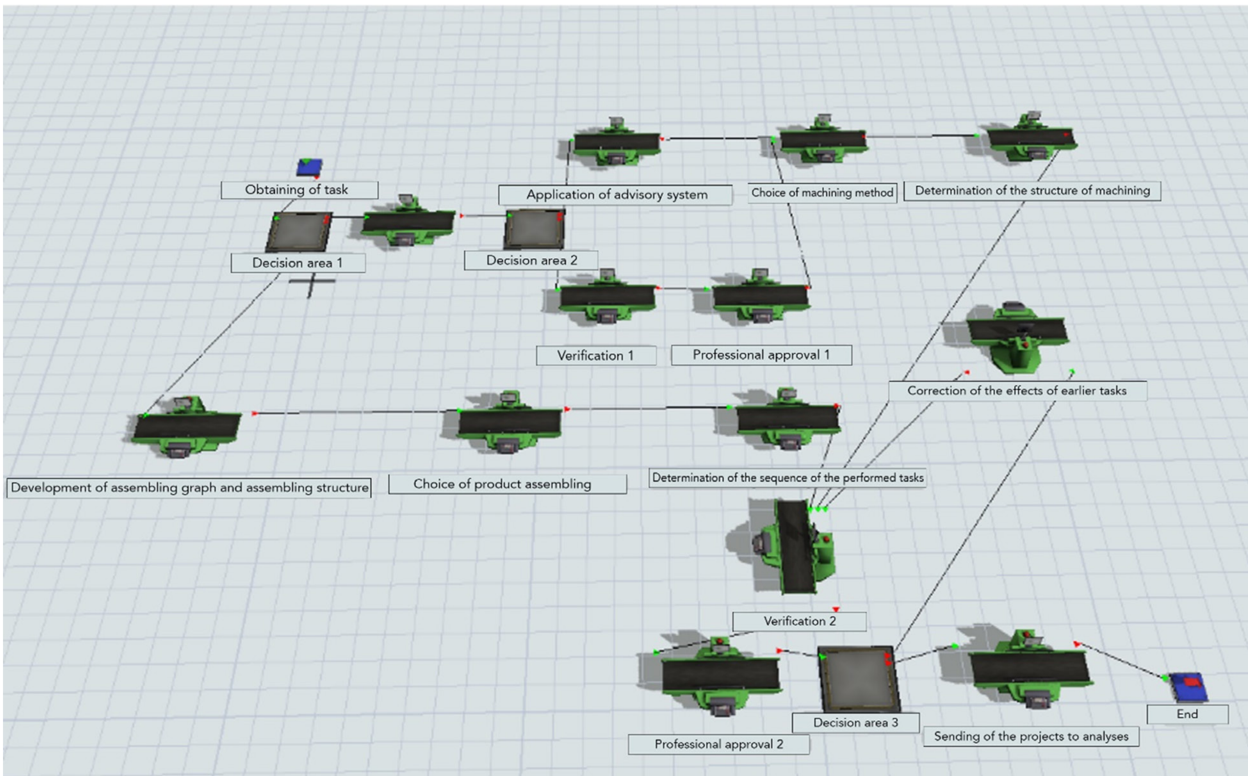

Fig. 3. The example of the simulation model in Flexsim environment for machining process (screenshot developed in cooperation with Mr. Mateusz Gacek)

models of manufacturing process in two variants – without the advisory system and with its application – should consider all stages of the manufacturing process, the time necessary for the performance of each stage and the time of waiting for the resources. The exemplified simulation system, developed in FlexSim environment, in cooperation with Mr. Mateusz Gacek for the machining process is given below (Fig. 3).

The average duration of the simulated process was decreased by more than 10% when using the variant with the advisory system, based on the simulation model times of the processes in the both variants (Table 1 and Table 2).

It is especially significant for manufacturing enterprises which are specialized in production at order where the time of implementation of the orders is crucial for the satisfaction of the customers and reaching the success on the market. It should be mentioned that although the decline of the time of the order implementation for large-series and mass production was lower, it still remained a meaningful increase of production effectiveness. Owing to it, the enterprise may implement a higher number of orders at a shorter time what leads to gain of profits and improvement of the competitivity at the market.

Table 1. Simulation times [h] for machining process in variant with the application of advisory system

Process	Average process time	Minimum process time	Maximum process time
Choice of semi-fabricates	2,02	1,84	2,26
Verification 1	0,00	0,00	0,00
Application of advisory system	0,25	0,25	0,25
Choice of machining methods	2,01	1,66	2,50
Professional approval 1	0,00	0,00	0,00
Determination of the structure of machining processes	4,01	2,99	5,00
Development of assembling graph and of assembling structure	5,03	4,19	6,06
Choice of the methods for product assembling	3,03	2,55	3,44
Determination of the sequence of the performed tasks	2,00	2,00	2,00
Correction of the effects of the earlier tasks	3,16	2,74	3,46
Verification 2	2,91	0,23	5,00
Professional approval 2	2,28	2,00	3,79
Sending the projects to analyses	0,25	0,25	0,25

Table 2. Simulation times [h] for machining process in variant without the application of advisory system

Process	Average process time	Minimum process time	Maximum process time
Choice of semi-fabricates	2,02	1,84	2,28
Verification 1	1,19	0,98	1,45
Application of advisory system	0,00	0,00	0,00
Choice of machining methods	2,07	1,51	2,40
Professional approval 1	2,28	2,01	4,05
Determination of the structure of machining processes	3,98	2,85	5,12
Development of assembling graph and of assembling structure	4,92	4,27	5,61
Choice of the methods for product assembling	2,98	2,55	3,39
Determination of the sequence of the performed tasks	2,00	2,00	2,00
Correction of the effects of the earlier tasks	2,96	2,30	3,52
Verification 2	2,92	0,59	5,01
Professional approval 2	2,28	2,00	3,30
Sending the projects to analyses	0,25	0,25	0,25

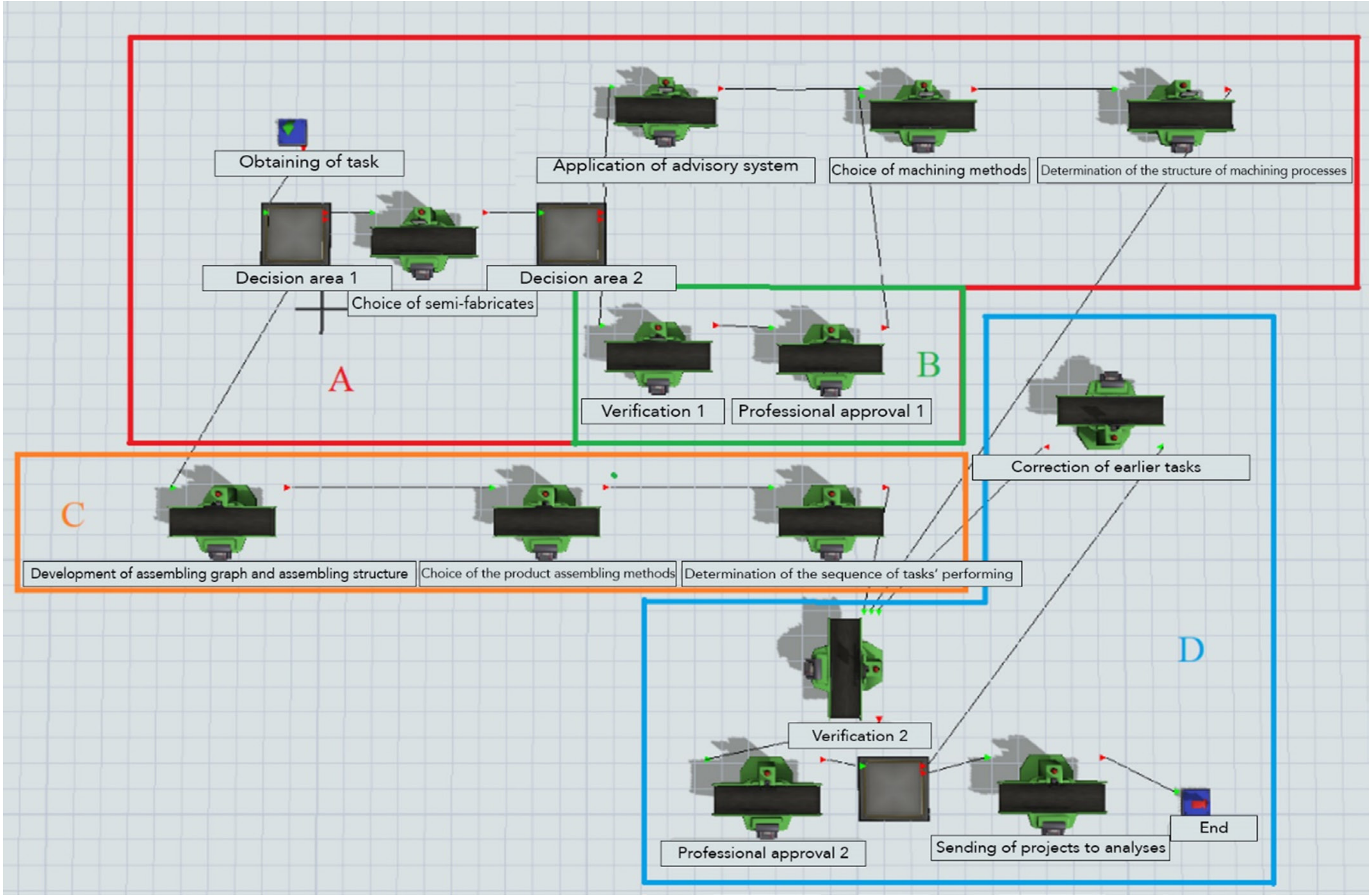

Fig. 4. Division of simulation in Flexsim program into areas (screenshot developed in cooperation with Mr. Mateusz Gacek)

There were presented above the process times for each of the variants which were obtained by 100-times repetition of the process in each configuration. The conducted simulation was divided into 2 variants and 4 area, A, B, C and D, respectively (Fig. 4). The first variant assumed the run of the process with the application of advisory system and concerned the areas A and D, or A, C and D, according to the needs of the implemented order; the division adopted in decision area is 0.5. The second variant concerned areas A, C and D or, analogically to variant 1, A, B and D. The second variant assumed lack of utilization of the advisory system and application of verification by the more experienced technologist. In each of the analyzed cases, a separate run through A, C and D areas was also considered. The mentioned areas are a part of the total analyzed process and its exclusion from the simulation could have a negative influence on the results.

Area A is the area, commencing simulation which begins from the element corresponding to obtaining of the task which is directed, in the further stage, to sector C or remains in area QA. In the case when the order dos not change the area, it is directed to the process of choosing the semi-fabricates and then, to the decision area 2 where the choice is made: verification by the senior technologist, or application of advisory system. If the analyzed task passes the so-called processor (element used in simulation) assuming the utilization of the advisory system, it will go the way via the processors assuming the choice of the machining methods and determination of the structure of machining processes; finally, it comes to area D. Area B will be only activated in variant 2 whereas the order will be directed from area A to area B and then, it will again come to area A and the further procedure will be continued by path A – D. Area C is subordinated to eventual situation when area A and area B are not utilized in simulation. At such case, the order runs via the processors which have been defined as the processes of: developing the assembling graph and assembling structure, choice of the product assembling methods, and determination of the sequence of the tasks' performance. Area D is a connector between areas A and C owing to linking of verification 2 and professional approval 2. In the discussed area, there is also a looping, which may cause delays in a form of correction of the effects of the earlier tasks. If all the operations are approvable and do not require any corrections, or have been approved after the correction, the projects are sent to analyses and the process is terminated. The table given below presents the mean times of both variants and the extrapolated summarized times for 100 processes for the particular variants (Table 3). It allowed to abbreviate the time by 183 hours in 100 events.

In general, however, the application of advisory system is helpful in the abbreviation of the time of the order implementation owing to the decrease of the time necessary for the choice of the appropriate semi-fabricate for machining process, and, also, reduction of the number of errors and elimination of delays,

Table 3. The mean and extrapolated summarized times for 100 iterations (own development)

	Variant I: Application of advisory system	Variant II: Lack of the application of advisory system
Mean time	15,87 [h]	17,7 [h]
Extrapolated summarized time for 100 iterations	1587 [h]	1770 [h]

connected with the improper choice of the semi-fabricate. The precise time by which the order implementation time may be reduced will be dependent on many factors such as complexity of the order, availability of the appropriate semi-fabricates on the market and also, on the effectiveness of the introduced advisory system. Nevertheless, the application of the discussed system contributes to the abbreviation of the time of order implementation by few days or even weeks.

The employment of the advisory system increases the effectiveness of the machining process. Owing to the registered information on the earlier machining operations, such as processing parameters, employed materials and the obtained results, it is possible to avoid the errors and to improve the future operations. It, in turn, leads to the increase of productivity and performance of the machining process.

Analysis of the incremental manufacturing process

Fig. 5 (below) illustrates the run of the process of the choice of filament for incremental production in BPMN notation, in one path with the application of the advisory system; the other one is shown without the application of the advisory system what shows graphically the impact on the abbreviation of the time of the mentioned stage of the manufacturing process. It is also directly manifested in the increase of the analyzed process effectiveness.

The advisory system is the useful tool which affects the abbreviation of the time of the order implementation in the incremental manufacturing process. First of all, the discussed system allows better utilization of the available knowledge, connected with the choice of filament what has a key meaning in the incremental manufacturing process.

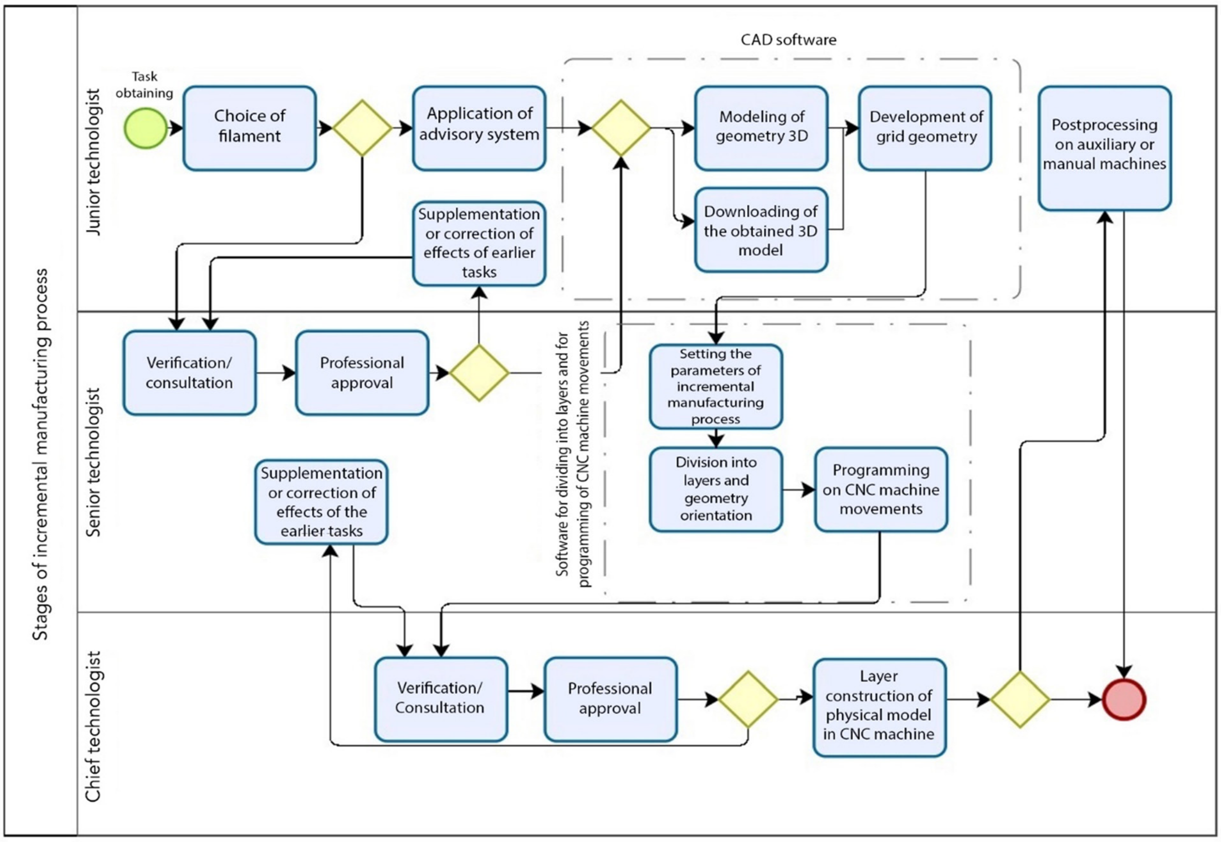

Fig. 5. The stages of the incremental manufacturing process in conceptional aspect at the technological department of the enterprise, with the consideration of advisory system application (own development)

In the mentioned above process, the choice of filament is a significant element, affecting the quality and yield of the printed product. The incorrect choice of filament may lead to defects and errors in print, what increases the time of the order implementation and the manufacturing costs.

Based upon the simulation data, we may state that the duration time of the stages of incremental manufacturing process may be by 10% abbreviated in the case of employment of advisory system. It means that the time of performing the particular stage of the process may be by 10% decreased as compared to the times obtained in the case of lack of advisory system application. The exemplified simulation model, as implemented in Flexsim software, based on the mentioned above stage of incremental manufacturing in conceptional aspect at technological department of the enterprise, with the consideration of advisory system has been illustrated below (Fig. 6). The simulation which was carried out, concerned also two variants as in the case of the previous process. Variant I assumed the run of the process with the application of the advisory system and considered the complete passage via areas A, C, D and E, represented in the scheme given below (Fig. 7).

On the other hand, variant II assumes the run of process without the application of advisory system. The simulation run of the mentioned variant is implemented partially via area A until the moment of reaching the height of decision area 1; then, the order passes through the processes in areas B, C, D and E. In area A, the simulation process is commenced and at the same time, it is a segment where the choice of filament and advisory system are found, there is also here a decision

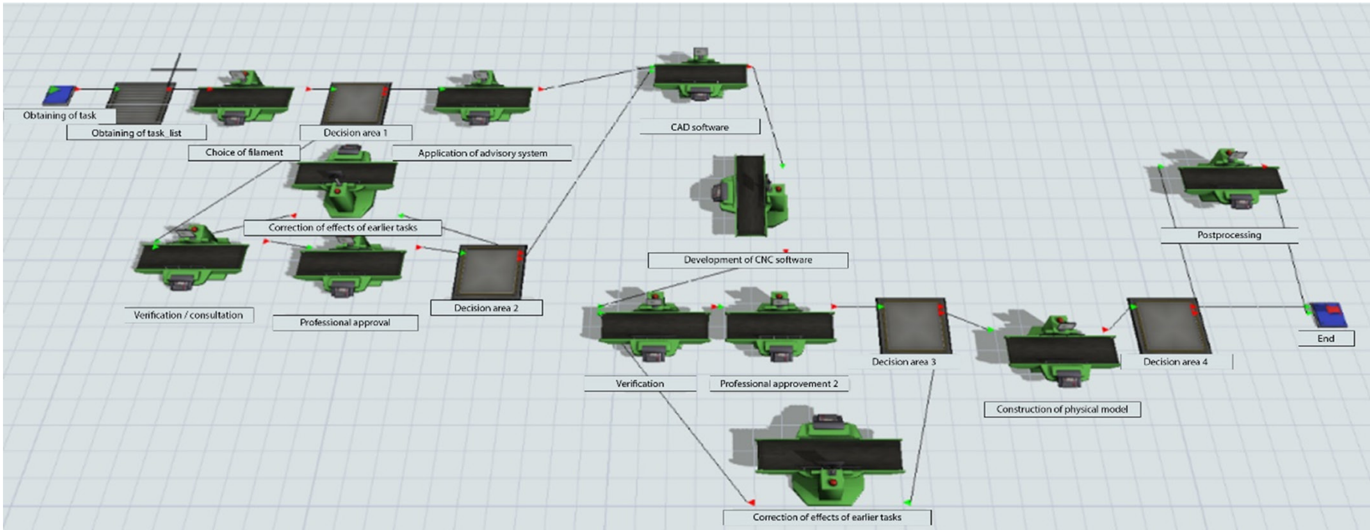

Fig. 6. Example of a simulation model in the FlexSim environment for the additive manufacturing process (screenshot developed in collaboration with Mr. Mateusz Gacek)

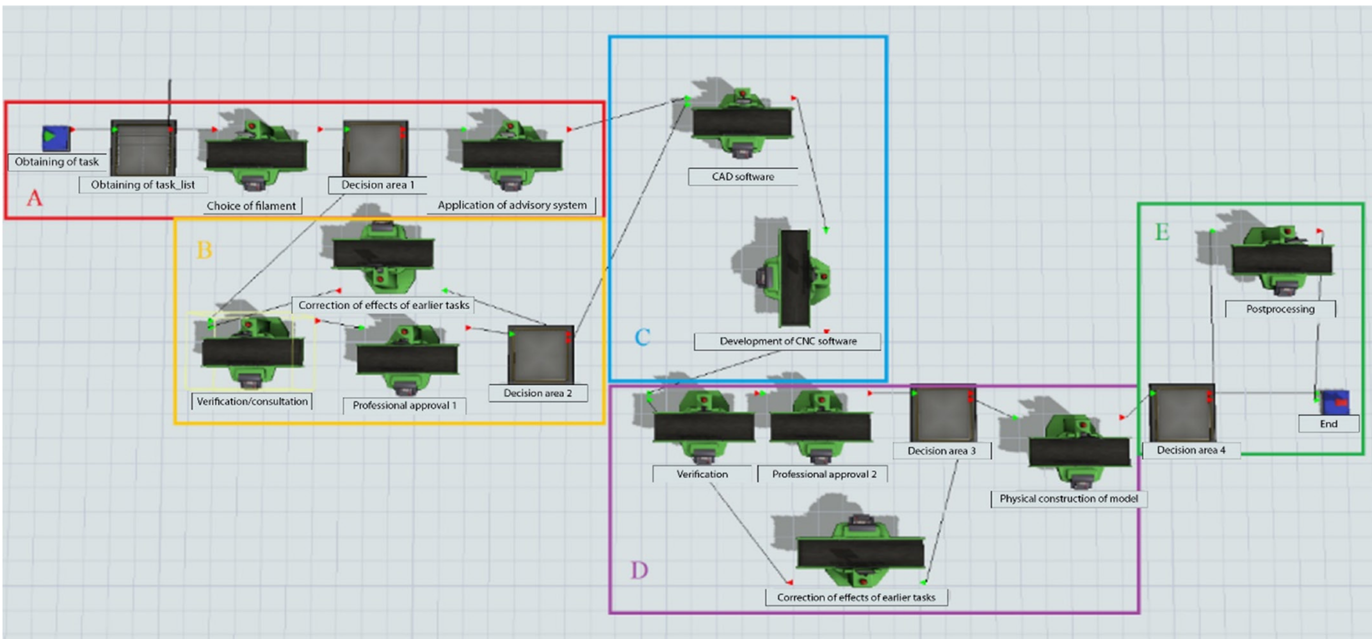

Fig. 7. Simulation areas using Flexsim software (screenshot developed in cooperation with Mr. Mateusz Gacek)

area that re-directs the process to area B. Area B assumes verification of the suggested solution by more experienced technologist. The decision area assumes that the probability of occurrence of the need of correcting the operations or postprocessing is equal to 0.1. Analogically, the probability of non-occurrence of any complications is 0.9. The presence of the decision area in the discussed region creates the possibility of the process looping, that is, the requirement of correcting the operations – the repetitions of the processes which prolong the total time of the implementation of the order. After performing all necessary actions, the order is addressed to area C. For the needs of simulation, the area C has been simplified to two processes. In areas D and E, the prolongation of the time of order implementation may occur due to detection of irregularities and repetition of the loop.

Table 4. Simulation times [h] for incremental manufacturing process in variant without the application of advisory system

Process	Average process time	Minimum process time	Maximum process time
Choice of filament	0,33	0,29	0,37
Application of advisory system	0,00	0,00	0,00
CAD software	6,15	3,46	12,53
Development of CNC software	10,92	10,01	15,35
Correction of effects of earlier tasks	0,00	0,00	0,00
Verification – consultation	3,36	0,97	7,72
Professional approval	0,25	0,23	0,27
Verification	0,27	0,25	0,39
Professional approval 2	0,50	0,50	0,50
Correction of effects of earlier tasks	3,68	3,01	4,37
Construction of physical model	10,43	10,00	12,36
Postprocessing	1,00	1,00	1,00

Table 5. Total simulation time for the incremental manufacturing process in variant without application of advisory system

Total time		
Average process time	**Minimum process time**	**Maximum process time**
32,69	28,24	39,17

Table 6. Simulation times [h] for incremental manufacturing process in variant with the application of advisory system

Process	Average process time	Minimum process time	Maximum process time
Choice of filament	0,33	0,28	0,37
Application of advisory system	0,17	0,17	0,17
CAD software	6,03	3,45	10,24
Development of CNC software	10,92	10,01	13,62
Correction of effects of earlier tasks	0,00	0,00	0,00
Verification – consultation	0,00	0,00	0,00
Professional approval	0,00	0,00	0,00
Verification	0,28	0,25	0,48
Professional approval 2	0,50	0,50	0,50
Correction of effects of earlier tasks	3,75	3,22	4,29
Construction of physical model	10,42	10,00	11,98
Postprocessing	1,00	1,00	1,00

Table 7. Total simulation time for incremental manufacturing process in variant with the application of advisory system

Total time		
Average process time	**Minimum process time**	**Maximum process time**
29,34	25,86	36,01

Table 8. Presentation of the extrapolated summarized times for 100 iterations and the average times for the both variants (own development)

	Variant I: Application of advisory system	Variant II: Lack of the application of advisory system
Mean time	29.34 [h]	32.69 [h]
Extrapolated summarized time for 100 iterations	2934 [h]	3269 [h]

The times for the processes have been differentiated using a normal or Pareto distribution. Values given in Tables 4, 5, 6 and 7 mean the assumed time in hours for the both variants of simulation. The total time of the process run means the time, measured from the task obtaining until the end. The times of the individual processes, i.e. their average, minimum and maximum times were also examined.

In Tab. 8 (below) the times of the processes for the both variants were submitted in a graphical form; they were obtained using the simulation of the process repeated 100 times in each configuration. The diagrams show the average times of the both variants and the extrapolated summarized times for 100 processes. Such procedure allows the evaluation of the process' effectiveness for 100 iterations. In the discussed case, the time was abbreviated by 335 hours for 100 orders.

Summing up

The performed research work provided new knowledge on the actual values of strength parameters of PET thermoplastic formed in the FFF process. In the light of the achievements published in the literature so far, the analysis conducted constitutes a separate approach to a specific problem. The results in question supplement the previous material data in the area of the influence of changes in the printing process parameters on the selected mechanical properties of thermoplastic material commonly used in additive manufacturing techniques. It should be emphasized that the research work carried out constitutes a representative fragment of the study, which fully takes into account additional different model settings in the workspace of the manufacturing equipment. The results determined in the static uniaxial tensile test and static torsion test indicate higher strength values for the research sample models printed using a layer thickness of 0.2 mm. For the maximum tensile stress, the difference is over 23%, and for the tensile strain less than 10%. Similarly, higher torsional strength was determined for the samples with a layer thickness of 0.2 mm. The maximum torsion torque is higher in the variant in question by almost 30% than the maximum torsion torque determined for the 0.3 mm variant. On the other hand, the angle of torsion at sample fracture was determined at a level almost 70% higher for the 0.2 mm variant.

Of course, in the case of the target application of models in a load system requiring lower strength, it is advisable to print in the 0.3 mm layer thickness variant due to the economic factor. The printing time of the series of research models with a defined layer thickness of 0.3 mm was by 20% shorter than for the 0.2 mm variant. The level of material consumption was determined at a similar level for both variants.

The determined strength test results can be used in the process of determining the application area of additively manufactured parts using the FFF technique from thermoplastic PET material. Additionally, in the test process, the values of torsional strength parameters were determined, which are not provided by the manufacturers of model materials, but are necessary for parts such as machine shafts, clutches, gear hubs and many others loaded with torsion torque.

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