Heuristic Control of the Logistic Manufacturing System with Regeneration of Tools: The Simulation Case Study

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Abstract**—**The paper highlights the problem of mathematical modelling and the subsequent simulation of the complex logistic manufacturing system with regeneration of tools. The system itself consists of identical parallel manufacturing subsystems in which there is a certain number of production stands arranged in a series. Each stand can carry out an operation on the specific order with the use of a dedicated tool. Tools can be regenerated a limited number of times only. Heuristic algorithms are implemented in order to control the choice of the order or the choice of the required stands in the discussed manufacturing system. Manufacturing criteria are used to evaluate implemented control algorithms. The simulator which was created for the purpose of this work is used for obtaining certain result data which is subsequently analysed thoroughly in order to evaluate the simulation case study.

Keywords**—** Heuristic algorithm, control algorithms, manufacturing system, mathematical modelling, optimisation criteria, manufacturing strategies

I. INTRODUCTION

THE word “simulate” implies imitation while the word “modelling” refers to an object built to scale to represent an existing model. The task of imitating or simulating the object requires a simulator which should possess specific capabilities and intelligence. The degree of fidelity of the model is proportional to the capability of the simulator. Modelling and simulation are intimately connected to each other, however, modelling refers to notion of representing the desired behaviour of the target object or idea in the host computer and simulation refers to the execution of the model on the host computer. Real world systems import an unprecedented degree of complexity in the interaction between the large number of units, especially asynchronous ones, which the analytic models find very difficult to represent accurately. The particular advantage of the use of simulated data consists of obtaining a set of data which will deliver the expected solution. The experimental approach, with its emphasis on simulation-based solution seeking, seems to be the only way of finding an acceptable procedure. The properly constructed model will provide a powerful cost-minimising tool.

The right decision-making approach is unavoidable in each complex manufacturing system. Manufacturing companies are currently facing very strong pressures in terms of cost, quality, flexibility, customisation and a product delivery time to the defined market. The production systems of these companies have to be flexible and able to react to changing production capacity requirements [1]. Methodologies of industrial production control, manufacturing strategies and production management can support today’s companies in addressing the aforementioned challenges. A critical review of popular production management methodologies is presented for example in [2]. The work [3] compares the competitive priorities of manufacturing strategies in four different types of companies with some international comparisons and one longitudinal case study for benchmarking. Different methodologies and control algorithms meet different needs and so can be classified by their main purposes. Some algorithms operate as read only, some modify elements, and some change the order of elements.

It is possible to solve the problem of production control, strategies and management with the use of modelling and simulation methods of such manufacturing systems [4]. Over the past three decades a large amount of research has been devoted to the analysis and modelling of production line systems or logistics systems. Papadopoulos and Heavey [5] present a comprehensive literature review of related papers. Another work [6] compares the performances of push, pull, and hybrid production control systems for a single line of the multi-stage and continuous process using simulation as a tool. The study is inspired by a production scheduling problem in a large aluminium rolling and processing factory in Istanbul. One of the most useful tools is computer simulation. Some common application areas of computer simulation or simulation optimisation are service stations such as airports

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Manuscript received August 30, 2013. This work was supported in part by European Regional Development Fund within the project CEBIA-Tech No. CZ.1.05/2.1.00/03.0089.

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[7], call centres and supermarkets; road and rail traffic; industrial production lines [8] and logistical operations like warehousing and distribution [9, 10]. The possibilities and limits of simulation employed to create optimal order sequences for flow-shop production systems are outlined as well as discussed and some examples are emphasised in the work [11]. However, this kind of approach requires using sophisticated methods supported by validated tools created on the basis of thoroughly analysed background. Even if the final output of the company can be achieved with the use of the traditional methods, complex data analysis may result in finding proper solution to the cost cutting issue [12].

Heuristic algorithms are responsible for meeting the set criterion. Developing solutions with heuristic tools offers two major advantages: shortened development time and more robust systems [13]. Moreover, many problems can be solved by means of adequate multi-criteria decision-making using modern heuristics [14]. The work [15] uses the criteria which are implemented to either maximise the production output or minimise the lost flow capacity of the production system or minimise the tool replacement time. The criterion of minimising the total production time is possible to use for determination of the best order realisation sequence. The idea of time scaling by means of the simulation method with the use of heuristics algorithms is presented in [16] and [17]. This method is implemented in order to determine the best possible order realisation time. Methods of mathematical modelling supported by heuristic approaches can be implemented in a lot of fields of contemporary experiments [18, 19, 20].

Simulation enables training exercises without the need to use real equipment. Among the main advantages of simulation one can find reduction of expenses related to training as well as reduction of risks associated with training exercises. It allows actions that are not possible with real equipment and which are recommendable for the training exercises. Another important thing is the possibility of increasing the skills of experienced operators without any risk resulting from changing the way a product is manufactured. The simulator is designed to allow both a "screening" or worst-case analysis, as well as more detailed assessments. The modular design allows an independent evaluation of the performance of each of the individual components. Finally, the simulator also provides tools for an objective evaluation of the progress and the acquired skills of each operator. A training simulator allows repetition of manoeuvres and exercises under a very wide range of conditions and allows the trainee to track many extraordinary events that are not possible when using real machinery [21]. Information methods of modelling the synthetic manufacturing environment is, without doubt, another vital aspect to support meeting manufacturing goals [22].

The problem highlighted in the paper is based on a specific model of the complex manufacturing system stated in [23]. Moreover, this model is enriched by the case study whose goal is to deliver the satisfactory solution to the problem stated hereby. Results are subject to thorough analysis supported by time scales of order manufacturing in separate work stands.

II. MATHEMATICAL DESCRIPTION OF IMPLEMENTED MANUFACTURING SYSTEM

A sample manufacturing structure which is controlled by means of decisions made in a deterministic way is introduced. The scheme of assumed manufacturing system is presented in Fig. 1. The problem itself consists of determining the sequence of the order which is to be manufactured subsequently. The proposed heuristic algorithms choose the required order on which certain operations are carried out.

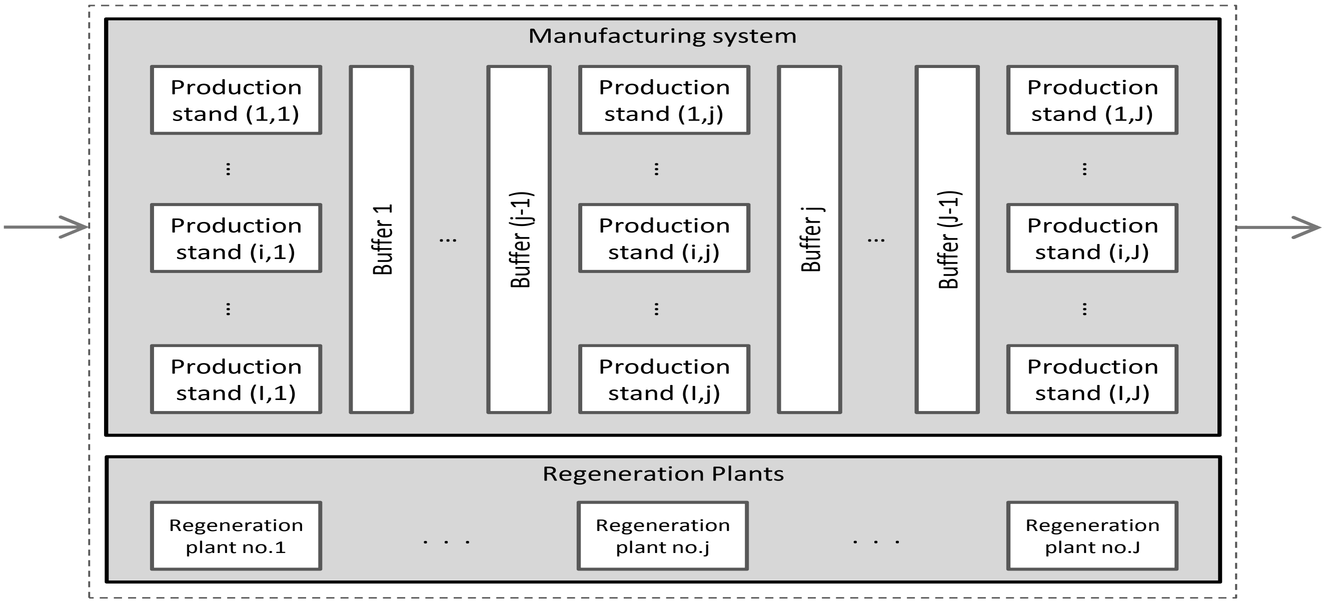

Fig. 1 The scheme of the assumed manufacturing system with regeneration plants

It is assumed that every decision about production, replacement or regeneration is made at the stage *k-1* after passing the identical time intervals. The state of orders decreases after each production decision which influences the state of the whole manufacturing system at each stage k, $k=1,...,K$.

The assumed production system consists of I parallel manufacturing subsystems. Each ith subsystem consists of J production stands arranged in a series. Manufactured orders are passed subsequently through each stand in the ith subsystem. This system requires K stages to manufacture one unit of the order. It is possible to set a certain number of stages to manufacture particular elements of the order vector in the form (1), where z_n is the number of units of the nth production order at the k-th stage. The stage k, $k=1,\ldots,K$ is the moment of making the production decision.

$$Z^k = \left[z_n^k\right] \tag{1}$$

Each jth production stand located in the ith row of the production system can carry out an operation on the nth order. It is assumed that each production stand placed in the jth column of any manufacturing subsystem manufactures the same operation with the use of identical tools. Moreover, it must also be assumed that $I<N$.

There are buffer stores between subsequent production stands. Let us introduce the matrix of buffer stores in the form (2), where $b_{n,j}^k$ is the capacity of the jth buffer store in case of storing the semi-product of the nth order at the kth stage.

$$B^k = \left[b_{n,j}^k\right] \tag{2}$$

It is assumed that the capacity of each jth buffer store is limited. In this case it is possible to introduce the maximal buffer store matrix in the form (3), where $b_{n,j}^{\max}$ is the limit of the jth buffer store in case of storing the semi-product of the nth order.

$$B^{\max} = \left[b_{n,j}^{\max}\right] \tag{3}$$

Moreover, we assume that all stands in the jth column share only one jth interoperation buffer store. If $b_{n,j}^k = b_{n,j}^{\max}$, then no unit of nth order can leave any production stand in the jth column unless the equation (4) is valid.

$$b_{n,j}^k < b_{n,j}^{\max} \tag{4}$$

The state of the jth interoperation buffer store is verified according to the form (5) after every decision which is made in the system.

$$b_{n,j}^k = \begin{cases} b_{n,j}^{k-1} + x_{n,j}^k - x_{n,j+1}^k & \text{in case of an activity in the given buffer store,} \\ b_{n,j}^{k-1} & \text{otherwise.} \end{cases} \tag{5}$$

The variable $x_{n,j}^k$ represents the number of units of the semi-product of the nth order leaving production stands in the jth column and $x_{n,j+1}^k$ is the number of units of the nth order entering the production stand located in the column $(j+1)$.

The production system consists of J regeneration plants. The jth regeneration plant can regenerate tools which are used in each manufacturing stand placed in the jth column of the discussed production system. The number of regeneration processes of the given tool is limited. Let us introduce the matrix in the form (6) whose elements represent the number of still allowable regeneration processes of the tool for the stand located in the jth column.

$$R = \left[r_{i,j}\right] \tag{6}$$

$$R^{\max} = \left[r_j^{\max}\right] \tag{7}$$

The vector in the form (7) then represents the maximal allowable number of regeneration processes of tools from the stands in the jth column. If $r_{i,j}=0$ comes into being, then a tool from the ith stand in the jth column cannot be regenerated and must be replaced by a new one. Each regeneration plant uses the FIFO procedure consisting in regenerating the worn out tools which are placed in the queue as the first ones. Then, in due course, the tool after completing the regeneration procedure is returned to the adequate production stand which has been in standstill mode for the longest period of time. Machines in production stands use tools which either can be regenerated or must be replaced by new ones.

To define the production system structure it is necessary to define the assignment matrix in the form (8) where the element $e_{n,j}$ takes the value in accordance with the form (9).

$$E = \left[e_{n,j}\right] \tag{8}$$

$$e_{n,j} = \begin{cases} 1 & \text{if the stand from the } j\text{th column is used for realizing the order } z_n, \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

We assume that all orders are manufactured in each work stand arranged in a series.

The life matrix of the production system for a brand new set of tools is defined in the form (10) where $g_{n,j}$ is the number of units of the *n*th order which can be manufactured in any production stand in the *j*th column before its tool is completely worn out and requires an immediate replacement with either a regenerated or new tool.

$$G = \left[g_{n,j} \right] \tag{10}$$

Let $\tau_{n,j}^{pr}$ be the time of manufacturing one conventional unit of the *n*th order in the production stand in the *j*th column. Similarly, the variable τ_{j}^{repl} is the replacement time of the tool in the production stand in the *j*th column.

In order to calculate the total manufacturing time of all orders, it is necessary to take into account the production time, the replacement time and, finally, the regeneration time of used tools. The formula stated in [16] enables us to calculate the total realisation time. The order realisation time can be optimised by employing more production lines at the same time to manufacture the *n*th order or replacing tools only then when they are fully worn or optimising the regeneration process so that the tool is available on demand after its regeneration process is completed.

Minimising the total production time by means of minimising the regeneration time of tools as well as finding the optimal sequence of production decisions which are meant to send totally worn out tools to the *j*th regeneration plant remain the most important goal of the problem stated hereby.

A. The state of the system

The state of the discussed manufacturing system changes in case of beginning or ending manufacturing a certain unit of the *n*th order. The state of each production stand and the state of each buffer store can be tracked.

The state of this system changes in case of manufacturing the *n*th order according to the scheme shown in (11), where S_n^k is the state matrix of production stands in case of the *n*th order manufacturing at the *k*th stage.

$$S_n^0 \rightarrow S_n^1 \rightarrow \ldots \rightarrow S_n^k \rightarrow \ldots \rightarrow S_n^K \tag{11}$$

$$S_n^k = \left[s_{n,i,j}^k \right] \tag{12}$$

This matrix is defined in the form (12), where $s_{n,i,j}^k$ is the number of units of the *n*th order already manufactured in the work stand in the *i*th row of the *j*th column with the use of the installed tool. This variable takes the value according to the form (13) where $x_{n,i,j}^k$ is the number of units of the *n*th order manufactured in the work stand in the *i*th row of the *j*th column at the *k*th stage.

$$s_{n,i,j}^k = \begin{cases} s_{n,i,j}^{k-1} & \begin{array}{l} \text{if no unit of the } n\text{th order} \\ \text{is realized in the } i\text{th stand} \\ \text{of the } j\text{th column} \\ \text{at the } k\text{-1 stage,} \end{array} \\ s_{n,i,j}^{k-1} + x_n^k & \text{otherwise.} \end{cases} \tag{13}$$

The state of the production stand in case of replacement of the tool changes according to the form (14).

$$s_{n,i,j}^k = \begin{cases} s_{n,i,j}^{k-1} & \begin{array}{l} \text{if the tool is not replaced} \\ \text{in the } i\text{th stand of the} \\ j\text{th column at the stage } k\text{-}1, \end{array} \\ 0 & \text{otherwise.} \end{cases} \tag{14}$$

It is also possible to watch the state of the production system by means of the available capacity matrix of the production system in the form (15) where $p_{n,i,j}^k$ is the number of units of the *n*th order which still can be manufactured in the stand in the *i*th row of the *j*th column.

$$P_n^k = \left[p_{n,i,j}^k \right] \tag{15}$$

If the condition in the form (16) is valid, then the *n*th order waits for completing the regeneration process and installing a new tool to enter the production system.

$$\underset{1 \le i \le I}{\forall} \; p_{n,i,1}^k = 0 \tag{16}$$

On the basis of the above assumptions we can determine the available capacity of the production stand in the *i*th row of the *j*th column for the *n*th order at the *k*th stage in the form (17).

$$p_{n,i,j}^k = g_{n,j} - s_{n,i,j}^k \tag{17}$$

The manufacturing procedure consists of manufacturing orders in parallel production routes in sequence. It is assumed that manufacturing another order element in a route can begin when the previously manufactured one leaves the route. Its disadvantage consists of the need to wait for the completion of the manufacturing process of a certain product in this route before resuming it again for the next one. This results in not using the available capacity of the whole production system. Moreover, during the production course tools must be replaced. The state of the system has to be recalculated when any decision is to be made in the system.

III. HEURISTIC ALGORITHMS TO CONTROL AND MANUFACTURING CRITERIA

In order to control the choice of the order we need to implement heuristics which determine elements from the vector Z for the production process. In this case the control algorithms of the maximal or minimal order are put forward. These algorithms choose the order characterised by either the maximal or minimal number of units to be manufactured.

In order to control the choice of the production stand we need to implement heuristics which determine the route for producing the order on the basis of the available capacity of the routes (subsystems). The algorithms of the maximal and minimal available capacity of the subsystem are put forward.

The algorithm of the maximal available capacity of the sub-system chooses the route characterised by the maximal available capacity of the subsystem i.e. the work stand which can manufacture the highest number of order units is chosen for manufacturing in each work station. To choose the route the condition in the form (18) must be met. It is assumed that the nth order is manufactured in the minimal number of subsystems which should not lead to splitting the order.

On the other hand the algorithm of the minimal flow capacity of the sub-system chooses the route characterised by the minimal available capacity of the subsystem i.e. the work stand with maximal wear of tool is chosen for manufacturing in each work station (still it is able to manufacture a single order unit). To choose the route the condition in the form (19) must be met. It is assumed that the nth order is manufactured in a bigger number of subsystems which should lead to manufacturing the order faster.

$$\underset{1\le j\le J}{\forall}\ \max_{1\le i\le I} p_{n,i,j}^{k} \tag{18}$$

$$\underset{1\le j\le J}{\forall}\ \min_{1\le i\le I} p_{n,i,j}^{k} \tag{19}$$

Some manufacturing criteria can be used to evaluate implemented control algorithms. In our case, the total order realisation time, the value of the unused capacity of tools, the total tool replacement time and the number of tool regenerations are considered.

It is assumed that the total order realisation time can be minimised by reducing the unused capacity of tools (the so-called residual pass) as other processes (e.g. the time of tool replacement is defined) cannot be shortened. Therefore, the maximal possible use of tools is one of the most important goals and leads to implementing the unused capacity criterion in the form (20) which is reduced to the tool replacement bound specified in the form (21) and the order bound (22), where $y_{i,j}^{k}$ takes the values specified in the form (23).

$$Q_1 = \sum_{k=1}^{K} q^k = \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J} y_{i,j}^{k} \sum_{n=1}^{N}\sum_{i=1}^{I}\sum_{j=1}^{J} p_{n,i,j}^{k} \to \min \tag{20}$$

$$\sum_{j=1}^{J} y_{i,j}^{k}\tau_{j}^{repl} \le c \tag{21}$$

$$\sum_{n=1}^{N} x_{n}^{k} \le z_n \tag{22}$$

$$y_{i,j} = \begin{cases} 1 & \begin{array}{l}\text{if the replacement of the tool}\\ \text{in the } i\text{-th stand of the } j\text{-th column}\\ \text{is carried out,}\end{array} \\ 0 & \text{otherwise.} \end{cases} \tag{23}$$

The minimal tool replacement time criterion in the form (24) is reduced to the flow capacity bound specified in the form (25) and the order bound (26).

$$Q_2 = \sum_{k=1}^{K}\sum_{i=1}^{I} y_{i,j}^{k}\tau_{j}^{repl} \to \min \tag{24}$$

$$y_{i,j}^{k}\sum_{i=1}^{I} p_{n,i,j}^{k} \le g_{n,j} \tag{25}$$

$$\sum_{n=1}^{N} x_{n}^{k} \le z_n \tag{26}$$

IV. THE SIMULATOR OF THE COMPLEX LOGISTIC SYSTEM

The computer simulator dedicated to solve this particular programming problem was created in the C# programming language with the use of the programming environment Microsoft Visual C# 2010 Express. Additionally, Extensible Markup Language (XML) is used to store simulation input data and preserve the simulation output data. Also, Language Integrated Query (LINQ) was implemented for querying, sorting, and aggregating data.

The program simulates the complex manufacturing system described in this chapter by means of the extended assumptions which formed the basis for the subsequent model of the system. The simulator is the virtual representation of a real system and the input data for simulation has to match the real one. The process operation performed in the real system is simulated in accordance with the real data. This is achieved by mapping the production machines and regenerative stations as well as tools by the objects in the simulator. The objects included in the system have properties of real ones and are served by methods for operations handling. Operations on semi-products, tools replacement, regeneration, and buffer storage transactions are computed during the simulation process. The choice of the sequence of orders is governed by the determined heuristic algorithm and was carried out using the LINQ language.

The simulation process is carried out in several loops. The main loop for order manufacturing is executed as long as all order matrix elements are completely manufactured and moved to the store of ready products. Nested loops are used for running production stands in three separate lines connected by buffer stores. The work of regeneration stations takes place throughout the entire time of the simulation process. Tools that require regeneration wait in a separate FIFO queue for each line. A regeneration stand may only renew one tool at a time. Tool regeneration may be performed a finite number of times only. If the tool regeneration counter reaches the maximum number of regeneration procedures, the production tool cannot be regenerated any more. Results are available in a numerical form, production charts, production schedule charts, and as a tool state after of the simulation process is completed. The program allows data to be exported to an XML file for further analysis and presentation. The simulator also allows us to generate a histogram of the simulation with filtering options that define which information should be displayed. The histogram of the simulation may be saved as a text file for further analysis.

The simulator allows to experiment and answer questions concerning the number of production stands used throughout the manufacturing process, probability of tool wear out, information when a new tool for production is required, the order manufacturing time, etc. The simulation can be carried out for two ordering heuristics (maximal and minimal orders) and two heuristics for tool selection. Final results are presented in the table form. The table includes: the total manufacturing time, the lost capacity, the tool replacement time, and the number of regenerations. It is possible to see production times for each production stand and order and set the sum of production times for all orders and each production stand.

The accuracy of the simulator was verified by comparing analytically calculated results with those generated by the program for the same input data. As the complexity of calculations is very high, input data was simplified to let us check all occurrences emerging from it within the course of production. This also gives the possibility of confirming the accuracy of the simulation results manually. The correctness of implemented heuristic algorithms for orders and tool selection was verified by analysing the results returned by the program in the form of production timescales and comparing them with the input data and simulation parameters. This is particularly evident during the simulation where there is a need for multiple tool regeneration [24].

V. THE CASE STUDY OF THE SPECIFIC MANUFACTURING SYSTEM

The case study assumes that the complex production system consists of 4 identical parallel manufacturing subsystems. Each subsystem consists of 3 work stands arranged in a series. All orders are manufactured in each work stand arranged in a series. The number of conventional units of the orders is specified in the vector (27).

$$Z^0 = \begin{bmatrix} 23 & 65 & 78 & 131 & 43 & 9 \end{bmatrix} \tag{27}$$

We assume that the charge is universal and tools can be regenerated. The given tool can be regenerated only a predefined number of times. The numbers of maximal allowable regeneration procedures of tools is given in the vector (28) and regeneration times for specific tools are given by the vector (29).

$$R^{\max} = \begin{bmatrix} 10 & 12 & 6 \end{bmatrix} \tag{28}$$

$$T^{reg} = \begin{bmatrix} 15 & 20 & 10 \end{bmatrix} \tag{29}$$

The life matrix G for a new brand set of tools is given in the form (30).

$$G = \begin{bmatrix} 50 & 20 & 40 \\ 20 & 10 & 30 \\ 30 & 30 & 20 \\ 40 & 20 & 40 \\ 50 & 10 & 20 \\ 60 & 20 & 30 \end{bmatrix} \tag{30}$$

The times of manufacturing one conventional unit of the specific order in the specific work stand are defined in the matrix (31).

$$T^{pr} = \begin{bmatrix} 7 & 9 & 5 \\ 8 & 4 & 6 \\ 9 & 4 & 8 \\ 8 & 7 & 9 \\ 7 & 8 & 9 \\ 3 & 5 & 8 \end{bmatrix} \tag{31}$$

The vector of replacement times of tools is defined in the form (32).

$$T^{repl} = \begin{bmatrix} 3 & 4 & 2 \end{bmatrix} \tag{32}$$

We assume that there are buffer stores between subsequent production stands. It is assumed that the capacity of each buffer store is limited. The matrix (33) indicates the limits of buffer stores for a specific order.

$$B^{\max} = \begin{bmatrix} 10 & 10 \\ 20 & 10 \\ 10 & 20 \\ 30 & 10 \\ 10 & 10 \\ 20 & 20 \end{bmatrix} \qquad (33)$$

Manufacturing can be carried out in various configurations. Table 1 shows combinations of control algorithms and manufacturing conditions used for simulation. Each configuration of system (simulation set) is to be run for different initial wear values of tools. Manufacturing criteria are used for evaluation of the implemented control algorithms and assumed conditions.

Table I: The specification of simulation sets

Manufacturing conditions		**Simulations**					
No.	**Description**	**Set1**	**Set 2**	**Set 3**	**Set4**	**Set5**	**Set 6**
1	The algorithm of the maximal order.	X		X		X	
2	The algorithm of the minimal order.		X		X		X
3	The algorithm for choosing a tool: maximal wear of tools (the most worn out tools are chosen for manufacturing, however, they can still make a single product).	X	X	X	X		
4	The algorithm for choosing a tool: maximal availability capacity (tools which can make the highest number of products are chosen for manufacturing).					X	X
5	The work stand waits for a regenerated tool (there is no tool for replacement).	X	X				
6	Each tool has its replacement tool (when the tool becomes worn out, it is replaced with its replacement tool).			X	X	X	X

A. Results of simulation

The results of six sets of simulations are shown in the tables below. Each table includes one of tracked manufacturing criteria. The value of the total order manufacturing time (see Table II), the value of the total unused capacity of tools (see Table III), the value of the total replacement time (see Table IV) and the number of tool regenerations (see Table V) are presented.

Table II. The values of the total realization time

Initial tool wear	**Condition of simulation**					
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Set 6**
0%	938	939	866	866	866	866
10%	968	969	866	866	866	866
20%	983	984	871	871	871	871
30%	1004	1005	871	871	871	871
40%	1026	1027	874	874	874	874
50%	1036	1037	876	876	876	876
60%	1046	1047	876	876	876	876
70%	1046	1070	877	877	877	877
80%	1094	1095	882	882	882	882
90%	1105	1126	883	884	883	884
100%	1111	1121	882	882	882	882

All manufacturing criteria are evaluated for six sets of simulations and for different initial wear values of tools beginning with tools which are new and finishing with completely worn out tools. The minimal values are highlighted.

Table III. The values of the total unused capacity of tools

Initial tool wear	**Condition of simulation**					
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Set 6**
0%	1133	1233	1263	1263	1263	1263
10%	1097	1097	1137	1137	1137	1137
20%	1091	1091	1181	1181	1181	1181
30%	1105	1105	1105	1105	1105	1105
40%	1069	1069	1179	1179	1179	1179
50%	1043	1043	1213	1213	1213	1213
60%	947	947	1017	1017	1017	1017
70%	751	751	801	801	801	801
80%	645	645	882	882	882	882
90%	799	799	979	979	979	979
100%	975	975	1305	1305	1305	1305

Table IV. The values of the total tool replacement time

Initial tool wear	**Condition of simulation**					
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Set 6**
0%	180	180	228	228	228	228
10%	180	180	236	236	236	236
20%	180	180	268	268	268	268
30%	180	180	276	276	276	276
40%	180	180	328	328	328	328
50%	180	180	344	344	344	344
60%	180	180	344	344	344	344
70%	180	180	356	356	356	356
80%	180	180	372	372	372	372
90%	180	180	420	420	420	420
100%	180	180	440	440	440	440

Table V. The values of the number of tool regenerations

Initial tool wear	**Condition of simulation**					
	Set 1	**Set 2**	**Set 3**	**Set 4**	**Set 5**	**Set 6**
0%	16	16	14	14	14	14
10%	18	18	16	16	16	16
20%	31	29	28	24	28	24
30%	33	33	30	29	30	29
40%	46	46	44	41	44	41
50%	51	51	52	50	52	50
60%	52	52	52	51	52	51
70%	55	55	53	55	53	55
80%	64	64	58	60	58	60
90%	75	78	69	76	69	76
100%	84	87	71	83	71	83

Results of simulations must be analysed from different points of view. First of all, it should be noticed that Set 1 and Set 2 do not have tools for replacement whereas all other Sets 3 - 6 take for granted that each tool has its replacement tool which can be implemented on demand. The results of simulations show that, for all kinds of approaches, the shortest manufacturing time is generally obtained for the lowest initial tool wear of tools whereas the longest manufacturing time is obtained for the 90 % wear of tools but for Set 1 where it takes place in case of the total initial wear of tools. It can be concluded that the higher the initial wear of tools is, the longer the manufacturing time of the order vector elements becomes. The total unused flow capacity of tools is the lowest in case of the simulation process for the 70% initial wear of tools for all simulation approaches (Sets 1 - 6). The total unused flow capacity of tools is the biggest in case of the total initial wear of all tools for all simulation approaches (Sets 1 - 6). The total tool replacement time does not change in case of simulation approaches with the use of Set 1 and Set 2. In all simulation approaches for Sets 1 – 6 the total unused capacity steadily grows from the same value of 180 to the value of 440. The lowest number of tool regenerations is achieved in case of Set 3 and Set 5 whereas the biggest number of tool regenerations in case of Set 2.

Secondly, results show that by using replacement tools it is possible to decrease the total order manufacturing time. Decreasing this time is achieved despite the fact that the total tool replacement time increases. This phenomenon is caused because there is no need to wait for a regenerated tool. The regeneration process takes place in the background while the manufacturing process is carried out in separate machines. These conclusions are justified by the measure of increasing the value of the total manufacturing time for different initial values of tool wear. The total manufacturing time increases very slowly in the case of simulation experiments where each tool has its replacement tool (it equals only 1%). However, this time increases rapidly in case a work stand has to wait for the adequate regenerated tool (the increase equals 14%). On the other hand, from the point of view of minimising the value of unused capacity of tools it is much better to implement the strategy without tool replacement (the work stand waits for a regenerated tool). In this case, it is more convenient to use the algorithm of the maximal order. This algorithm is able to manufacture all orders faster in comparison with the algorithm of the minimal order. Additionally, the results show that the use of different algorithms for choosing a tool (either the maximal wear of tools or the maximal available capacity of tools) does not have any impact on the final results.

B. The detailed results for Set1 and 70% initial usage of tools

Let us analyse the case of 70% initial usage of tools in more detail. All previously defined initial values remain valid. The simulation process was carried out for Set 1. It is similarly assumed that the work stand waits for the regenerated tool and that the order was manufactured with one specified tool only which means that there are separate tools for each order. Manufacturing consists of choosing the machine with the lowest number. If this is not possible, the order goes to the next machine placed vertically. Heads are the same type but they must be equipped with new tools. The replacement time is the same as the tool replacement time. It is assumed there is one agent replacing and exchanging tools. It is assumed that manufactured products have the same dimensions. Operations require different tools in the same heads. Tools are partly worn out. Regeneration takes place in the background.

The results for this case study are presented in the graphic form below. Work time of all work stands in all subsystems is presented in Fig. 2. The following abbreviations are meant to describe the course of the manufacturing process: τ_w – time of work; τ_repl – time of tool replacement; τ_reg – time of waiting for a regenerated tool; τ_sp – time of awaiting for a semi-product or a buffer store is filled up.

The simulator allows us to generate time schedule charts illustrating the behaviour of the system throughout the course of the manufacturing process. Time schedules presented in Fig. 3 and Fig. 4 show the sequence of actions at the first and third work stands for all subsystems.

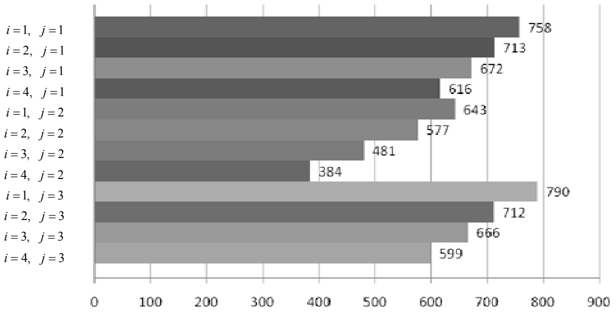

Fig. 2 The values of work time of each work stand

VI. CONCLUSIONS

Implementing regeneration plants is a very important issue as, thanks to it, we can examine their influence on the whole manufacturing process from the point of view of minimising the total manufacturing time. Moreover, there is no need to get rid of tools which can be reused for the same manufacturing purpose. However, the use of replacement tools, which are available at once, enables the operator of the manufacturing system to resume the manufacturing process just after the replacement procedure has been carried out.

As we can see, another important aspect which emerges from the case study is the influence of the initial state of tools on the final results. Additionally, carrying out a big number of simulations of the manufacturing process gets us to the conclusion that each order vector requires an identical approach as it is almost impossible to calculate in an analytical way the course of the manufacturing process, especially for the extended initial data. Using an approach which finds the satisfactory solution for one set of initial data becomes a trap in case of a slightly different set of initial data. Time scales show the sequence of actions at every work stand and enable an operator of such a system to plan the whole course of manufacturing process.

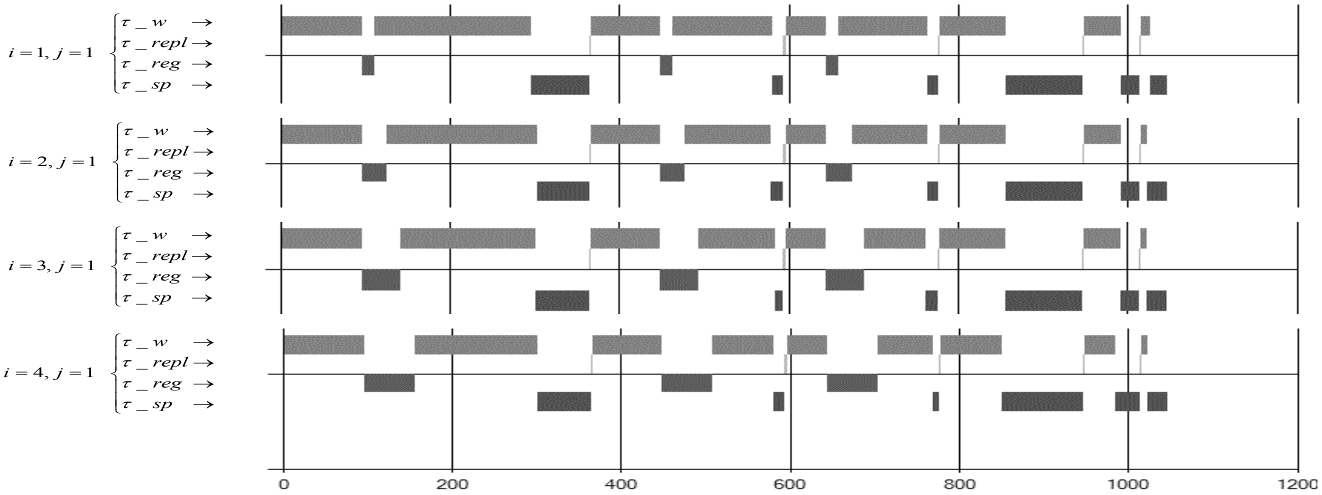

Fig. 3 The time scheduling of the first work stand for all subsystems

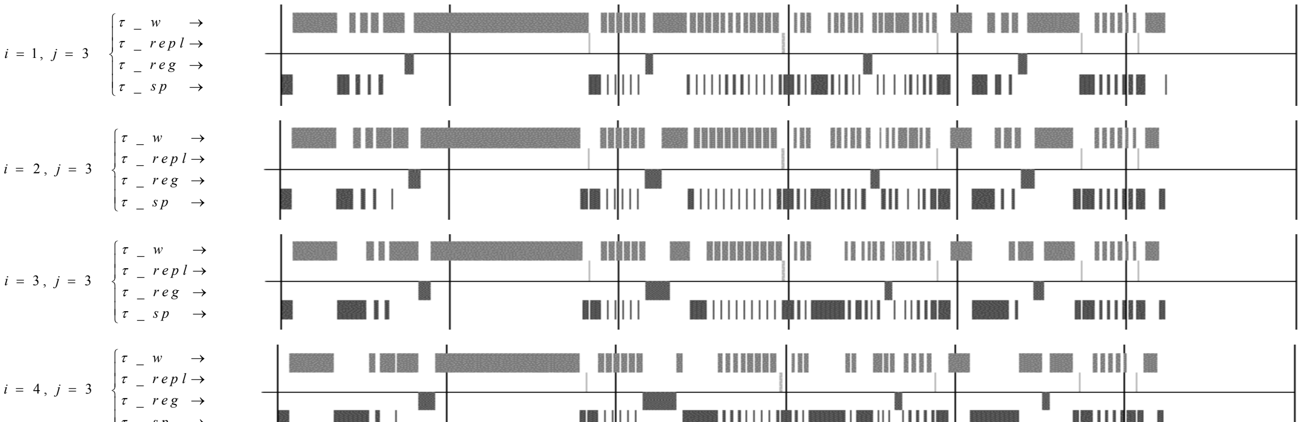

Fig. 4 The time scheduling of the third work stand for all subsystems

To sum up, it must be admitted that the more complex a system is, the more sophisticated approach it requires. The simulator which was used to solve this study case lets the operator have a full insight into the precise graphic representation of the whole manufacturing process, time scales and numerical results. There is also a need to experiment with different conditions during the manufacturing process.

REFERENCES

[1] V. Modrák and R. S. Pandian. *Operations Management Research and Cellular Manufacturing Systems: Innovative Methods and Approaches*. IGI Global, 2012, p. 439, ISBN 978-1-61350-047-7.

[2] E. Katsanos and A. Bitos. "Methods of Industrial Production Management: A Critical Review." *In Proceedings of the 1st International Conference on Manufacturing Engineering, Quality and Production Systems (Volume I)*, WSEAS Press, Brasov, 2009, pp. 94-99.

[3] J. Takala, J. Hirvelä, Y. Liu and D. Malindžák. "Global manufacturing strategies require "dynamic engineers"?: Case study in Finnish industries", *Industrial Management and Data Systems*, Vol. 107, Issue 3, 2007, pp. 326-344.

[4] M. Dlouhý. "A Problem-Oriented Taxonomy of Simulation and Management Methods", *Ekonomika a informatika. 2010*. Vol. 2, Issue VIII, pp. 117--127. ISSN 1336-3514.

[5] H. T. Papadopoulos and C. Heavey. "Queueing theory in manufacturing systems analysis and design: A classification of models for production and transfer lines," *European Journal of Operational Research*, Volume 92, Issue 1, July 1996, pp. 1-27, ISSN 0377-2217.

[6] K. Onan and B. Sennaroglu. "A comparative study of production control systems through simulation" *In Proceedings of the 12th WSEAS International Conference on Applied Mathematics (MATH'07),* Cairo, Egypt, WSEAS Press, 2007, pp. 377-382, ISBN: 777-222-4444-66-1.

[7] G. Guizzi, T. Murino and E. Romano. "A discrete event simulation to model passenger flow in the airport terminal", *In Proceedings of the 11th WSEAS international conference on Mathematical methods and computational techniques in electrical engineering (MMACTEE'09)*. Athens, Greece, WSEAS Press, 2009, pp. 427-434.

[8] B. Chramcov, P. Beran, L. Daníček and R. Jašek. "A simulation approach to achieving more efficient production systems," *International Journal of Mathematics and Computers in Simulation [online]* , Volume 5, Issue 4, 2011, [cit. 2011-06-30]. Available from: <http://www.naun.org/journals/mcs/>. ISSN 1998-0159.

[9] R. Bucki, Z. Frąckiewicz and F. Marecki. "Modelling and Simulation of Complexes of Operations in Logistic Systems", *In Proceedings of the 29th International Conference on Mathematical Methods in Economics*. Janská Dolina, Slovakia, 2011, pp. 88-93.

[10] V. Modrák. "On the conceptual development of virtual corporations and logistics", *In Proceedings of the International Symposium on Logistics and Industrial Informatics - LINDI 2007*, University of Applied Sciences Wildau, 2007, pp. 121-125.

[11] R. Schmidt. "Application of simulation for order sequencing in flow-shop production systems," *In Proceedings of the 21st annual symposium on Simulation (ANSS '88)*, Los Alamitos, CA, USA, IEEE Computer Society Press, 1988, pp. 71-89.

[12] P. Fiala et al. *Operační výzkum - Nové trendy*. Praha: Professional Publishing, 2010, ISBN: 978-80-7431-036-2 (in Czech)

[13] K. Z. Lee and M. A. El-Sharkawi. *Modern Heuristic Optimization Techniques: Theory and Applications to Power Systems*, J. Wiley & Sons, 2007. ISBN 9780471457114.

[14] Z. Michalewicz and D. B. Fogel. *How to Solve It: Modern Heuristics*, Springer, 2nd ed. Revised and Extended, 2004, 554 p. ISBN 978-3-540-22494-5.

[15] R. Bucki and P. Suchanek. "The Method of Logistic Optimization in E-commerce." *Journal of Universal Computer Science*, Volume 18, Issue 10, 2012, pp. 1238 - 1258.

[16] R. Bucki and B. Chramcov. "Modelling and simulation of the order realization in the serial production system," *International Journal of Mathematical Models and Methods in Applied Sciences [online],* Volume 5, Issue 7, 2011, [cit. 2012-04-30]. ISSN 1998-0140.

[17] R. Bucki and B. Chramcov. "Information support for logistics of manufacturing tasks," *International Journal of Mathematical Models and Methods in Applied Sciences*, vol. 7, no. 3, pp. 193–203, 2013.

[18] A. Antonyová A. et al. "Hygrothermal Properties of Building Envelopes: Reliability of the Effectiveness of Energy Saving." *Energy and Buildings*, Volume 57, Elsevier, 2013, pp. 187-192.

[19] V. Modrák and V. Moskvich. "Impacts of RFID Implementation on Cost Structure in Networked Manufacturing." *International Journal of Production Research*, Volume 50, Issue 14, 2012, pp. 3847-3859.

[20] D. Malindzak, A. Gazda, M. Malindzakova and D. Vitko. "The basic principles and rules for heuristic model creation in metallurgy. *Metalurgija*. Vol. 52, Issue 4, 2013, pp. 549-552.

[21] R. Bucki and F. Marecki. *Digital Simulation of Discrete Processes*. Network Integrators Associates. Parkland, Florida, 2006, p. 162, ISBN 978-09-7886-068-4.

[22] R. Bucki. "Information Methods of Modelling the Synthetic Manufacturing Environment", *In: Antonyová, A. et al. Mathematical Modelling in Logistics*. Faculty of Management, University of Prešov in Prešov, Grafotlač Prešov, 2011, pp. 64-82, ISBN 978-80-555-0406-3.

[23] R. Bucki, B. Chramcov and. R. Jašek. "Algoritmization of the Information Concept of the Complex Logistic System", *International Journal of Mathematics and Computers in Simulation*. Issue 1, Vol. 6, 2012, pp. 127-135, ISSN 1998-0159.

[24] M. Flisek. *The Computer Simulator of the Manufacturing System with the Shared Regeneration Stands*. Diploma thesis, Institute of Management and Information Technology, Bielsko-Biała, 2013, p. 85.

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