# Information Support for Logistics of Manufacturing Tasks

Robert Bucki, Bronislav Chramcov

***Abstract*—**The paper focuses on modeling the hypothetical complex manufacturing system consisting of identical workstations arranged in a series. Each workstation is formed with tool centers and can be used for fixing various kinds of the same tool type. The workstations are used to manufacture elements of the specific orders from determined charge materials. The general model of the manufacturing system is presented. Equations of state illustrate the change of state of the system and orders after each decision about either production or replacement of worn out tools. Control of the complex manufacturing system consists in implementing heuristic algorithms. The algorithms of the maximal and minimal orders are proposed in order to meet the minimal tool replacement time criterion which is accompanied by the defined constraints of the flow capacity as well as the order bounds. These assumptions form the basis for creating the adequate simulator which can be used for searching the satisfactory solution.

***Keywords*—** Discrete event simulation, heuristic algorithm, manufacturing strategies, mathematical modeling, optimization criteria, production system.

## I. Introduction

THE manufacturing system is defined as being the ensemble of machining systems which are used for realization of a certain product. Each of these machining systems is made up of machine-tool/tools, apparatus, parts, an operator and it executes one of the manufacturing operations [1]. Manufacturing is performed on the basis of customers' orders and each order can be unique. Naturally, the through put times of the components may differ from one another. Producing customized products in a short time at low costs is one of the goals of the manufacturing systems. Nowadays the unpredictability of market changes, the growing product complexity and continuous pressure on costs force enterprises to develop the ability to respond and adapt to change quickly and effectively. In order to sustain competitiveness in such dynamic markets, manufacturing organizations should provide the sufficient flexibility to produce a variety of products with the use of the same system.

The flexible manufacturing system (FMS) is regarded as one of the most efficient methods in reducing or eliminating today's problems in manufacturing industries [4]. FMS is a series of automatic machine tools or items of fabrication equipment linked together with an automatic material handling system, a common hierarchical computer control, and provision of random fabrication of parts or assemblies that fall within predefined families. The objective of a FMS is to make possible manufacturing of several families of parts, with shortened changeover time in the same system. To achieve a goal of FMS, it is quintessential to generate system design alternatives rapidly during the design stage. Typical manufacturing system design involves a number of interrelated subjects e.g. the tooling strategy, allocation of buffer storage structures with certain capacities between stations, system size, process flow configuration, flexibility needed for future engineering changes or capacity adjustment, space strategy, the design of control procedures for the material handling system, etc. [3], [5].

Effective organization and management of the materials, processes and human resources of a company is a prerequisite in today's highly competitive industrial landscape. Methodologies of industrial production management can support today's companies in addressing the aforementioned challenges. Key goals of these methodologies are to improve planning and scheduling of processes, increase productivity, minimize inventory level, improve responsiveness to changes in demand, improve quality, and lower operation cost.

Choosing the wrong methodology can result in well-planned processes that are not really required for a specific type of company or for a company in a certain context. Choosing the wrong one is a very expensive mistake. The paper [6] presents a critical review of popular production management methodologies. The planning of manufacturing systems frequently involves the resolution of a huge amount and variety of combinatorial optimization problems with an important impact on the performance of manufacturing organizations. Examples of those problems are represented by sequencing and scheduling problems in manufacturing management, routing and transportation, layout design and timetabling. It is possible to solve such problems by means of different optimization methods. Many optimization problems in the field of production control may be approached using heuristic and meta-heuristic technique. These alternative methods are able to determine not perfectly accurate, but good quality approximations to exact solutions. These methods, called heuristics, were initially based essentially on experts'

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knowledge and experience and aimed to explore the search space in a particularly convenient way. Heuristics were first introduced by G. Polya in 1945 [7] and were developed later in the 70's, when various heuristics were also introduced for specific purpose problems in different fields of science and techniques [8],[9],[10],[11]. Heuristic algorithms are used to control the production process in the work [12] where the criteria are given to either maximize the production output or minimize the lost flow capacity of the production stands or minimize the tool replacement time. The new paradigms were called meta-heuristics and were first introduced in mid-80's as a family of searching algorithms able to approach and solve complex optimization problems, using a set of several general heuristics. The term meta-heuristic was proposed in [13] to define a high level heuristic used to guide other heuristics for a better evolution in the search space. The family of Meta-Heuristics includes, but it is not limited to Tabu Search, Simulated Annealing, Soft Computing, Evolutionary Methods, Adaptive Memory procedures, Ant Systems, Scatter Search and their hybrids. Meta-Heuristics approaches have proved to be a very effective tool for finding good approximate solutions for difficult scheduling [14] and optimization problems arising in industrial [15], economic, and scientific domains [16].

Scheduling is one of the most important issues in the planning and operation of manufacturing systems. Development of scheduling algorithm is a fundamental and important problem for realizing flexible manufacturing systems. The goal of the scheduling may be formulated as follows: to find the optimal strategies of producing devices for job (resource) scheduling. The scheduling problem can be seen as a decision making process for operations starting and resources to be used. A variety of characteristics and constraints related with jobs and production system, such as operation processing time, release and due dates, precedence constraints and resource availability, can affect scheduling decisions. In many manufacturing processes the schedule of production is determined in a heuristic way by an expert operator. He solves the scheduling problem in such a way that the solution is feasible but not necessarily optimal. In recent complicated processes, however, even a feasible solution is difficult to obtain. Several approaches have been investigated to overcome the difficulties. The work [17] provides a review of the recent achievement and discusses the agent internal structure, multi-agent scheduling model and agent negotiation mechanism which are key issues in implementing manufacturing processes. Besides, the methods and strategies of rescheduling with multi-agent technique in manufacturing process are also analyzed and described. The production schedule produced by GA is a numerical solution that the end-users find hard to understand, especially as they are usually not interested in the methodology itself. The papers

[18] and [19] direct the attention to a genetic algorithm (GA) which aims at obtaining a suboptimal solution by a skilful combination of random search with heuristic method. In these papers, various methods of individual description are presented to improve the performance of GA for scheduling problems in manufacturing processes. Genetic algorithms were used as an optimization method also for a real case customized flexible furniture production optimization, represented as a job shop scheduling problem with recirculation where furniture is produced in very small or no series at all [20]. Computer aided scheduling with use of genetic algorithms and a visual discrete event simulation model is also solved in [21]. This article describes the method of upgrading conventional scheduling with the use of problem decomposition and genetic algorithms combined with a visual discrete simulation model.

Any jobs in manufacturing systems require a set of tools to be processed. Since the machine's tool magazine is limited, tool switches are necessary to process the jobs. In the minimization of tool switches problem we seek a sequence to process a set of jobs so that the number of tool switches required is minimized. In the work [22] different variations of a heuristic based on partial ordered job sequences are implemented and evaluated. Minimization of the tool switches problem has been also solved in [23], [24]. In discrete manufacturing processes such as stamping, assembly, or machining processes, product quality, often defined in terms of the dimensional integrity of work pieces, is jointly affected by multiple process variables. During the production phase, the states of tooling components, which are measured by adjustable process variables, are subject to possible random continuous drifts in their means and variances. These drifts of component states may significantly deteriorate product quality during the production process. Therefore, maintenance of the tooling components with consideration of both their continuous state drifts as well as catastrophic failures is crucial in assuring desired product quality and productivity. In contrast to traditional maintenance models where product quality has not been well addressed, especially for discrete manufacturing processes, a general quality oriented maintenance methodology is proposed to minimize the overall production costs [25]. In this research, the total production cost includes product quality loss due to process drifts, productivity loss due to catastrophic failures, and maintenance costs.

One of the most useful tools in the arsenal of an operations research (industrial engineering) management science analyst consists in computer simulation. Computer simulation can be an effective alternative in studying the characteristics in behavior of a system, as it is capable of combining the relevant elements of the system according to the actual logic of the operations, which can help reflect the real behavior of the system [26]. Perhaps the biggest benefit of the simulation is the possibility to evaluate the impact of the local changes on the whole system performance [27]. Simulation analysis has been proved a necessity by several studies, as due to the highly uncertain environments of the discrete manufacturing systems, it is hard to build mathematical models for the analysis and optimization of the systems. Computer simulation approach is perhaps the only choice. One feature of simulation is that one can change the parameters of a simulation model easily and try to observe the system performance under different sets of parameters. Therefore, it is natural to try to find the set of parameters which optimizes the system performance and is understood as optimization via simulation or simulation optimization [28].

During the last few years a new and interesting application field of computer simulation and simulation optimization is becoming the one connected to operational decisions, as tool supporting short-term planning and control activities of a logistic or manufacturing system. This kind of application implies the development and the use of simulation models much more detailed and updatable, in a very little expensive and fast way, according to the real system evolution. Moreover the integration of these models with enterprise information systems allows to carry out the so-called real-time simulation. Examples of operational decisions to which computer simulation can be applied with clear advantages, are operations scheduling, capacity planning and production control [29]. The use of simulation, as support tool to the operational decision making process, allows to analyze, from a statistical point of view, the behavior of a production or logistic system, that is subjected generally to controllable and not controllable factors. Through computer simulation it is possible to select those operational decisions that maximize an objective function or a system performance parameter, and to evaluate the effects of these decisions with the not controllable factors variability. An approach to implement efficiently and effectively simulation models in manufacturing systems, as decision support system, is deployed for example in [30]. Some other common application areas of computer simulation or simulation optimization are service stations such as airports [31], call centers and supermarkets; road and rail traffic; industrial production lines [32] or technological process [33] and logistical operations like warehousing and distribution [34], [35]. 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 emphasized in the work [36].

The paper shows basic characteristics of current manufacturing systems emphasizing models for further optimization and simulation processing. First of all, the general background related to this topic is given. The next parts focus on the specific manufacturing system and suggest the ways of optimizing it to meet the given criteria with the use of heuristic algorithms.

## II. Problem Formulation

The production system modeled hereby consists of $I$ identical workstations arranged in a series. There are $J$ tool centres in each workstation. Each tool centre can be used for fixing $U$ various kinds of the same tool type e.g. a drill, a friction disc, etc. The principal scheme of suggested serial rearrangeable manufacturing system is shown in Fig.1. There are no buffer stores between the workstations so no operation on a semi-product can be carried out in the $i$-th workstation, $i = 1,...,I-1$ if it is still in use. Then the semi-product must be kept in the workstation $i-1$ as long as either the operation in the $i$-th workstation or a tool replacement process is carried out in it. The workstations are used to manufacture the elements of the specific orders.

This system requires $K$ stages to realize the order elements. The matrix of orders at the $k$th stage is considered in the form (1), where $z^k_{m,n}$ is the number of conventional units of the $n$th order of the $m$th customer at the $k$th stage. The stage $k$, $k$=1,…,$K$ is the moment of the production decision.

$$Z^k = \left[z^k_{m,n}\right] ,m=1,...,M;\ n=1,...,N;\ k=1,...,K, \tag{1}$$

The order vector is modified after every decision about production in accordance with the specification (2).

$$z^k_{m,n} = \begin{cases} z^{k-1}_{m,n} - x^k_{m,n} & \text{if the number of units } x^k_{m,n} \text{ is realized at the } k \text{ stage,} \\ z^{k-1}_{m,n} & \text{otherwise.} \end{cases} \tag{2}$$

Some of the charge materials are used for making products of specific order. Let us assume that charge materials are represented by the vector of charges in the form (3) where $w_l$ is the number of units of $l$-th charge material.

$$W = \left[w_l\right] ,\ l = 1,...,L \tag{3}$$

The assignment matrix of ordered products to charges takes the form (4) where $\omega_{m,n}$ is number of charge material assigned to the order $z^k_{m,n}$

$$\Omega = \left[\omega_{m,n}\right] ,\ m=1,...,M;\ n=1,...,N; \tag{4}$$

Elements of the assignment matrix take the values according to the specification (5).

$$\omega_{m,n} = \begin{cases} l & \text{if the order } z_{m,n} \text{ is realized from the } l\text{th charge,} \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

We also assume that used charge vector elements are immediately supplemented which means that we treat them as the constant source of charge material. However, for simplicity reasons, we assume that each order $z_{m,n}$ is made from the universal charge which enables realization of the given element of the order matrix from any $l$-th charge vector element.

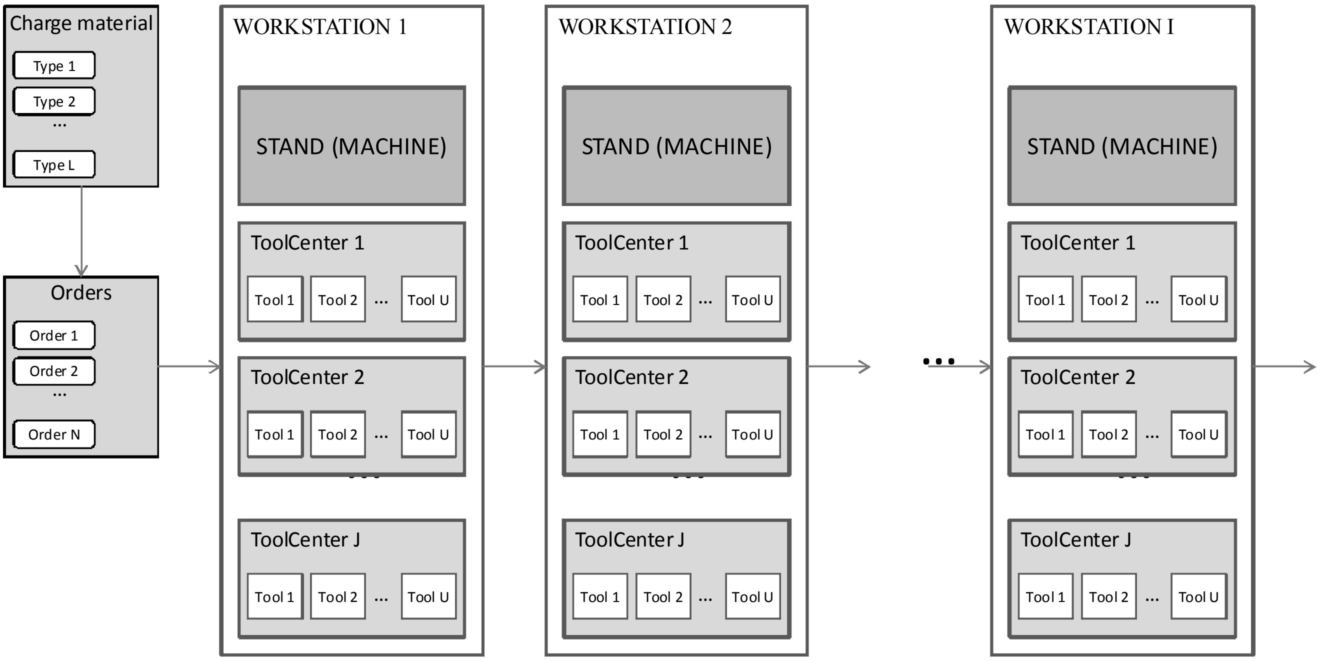


Fig. 1: The scheme of suggested serial rearrangeable manufacturing system

## III. General Model of the Manufacturing System

Let us present the structure matrix of the manufacturing system in the form (6), where $e(i,j) \in \langle 1, U \rangle$ is the number of the tool kind in the *j*-th tool centre in the *i*-th workstation.

$$E = [e(i,j)] \ , i = 1,\dots,I \ , \ j = 1,\dots,J \tag{6}$$

Elements of the structure matrix take the values according to the specification (7).

$$e(i,j) = \begin{cases} u & \text{for production by the } u-\text{th type of tool in the } j\text{th tool centre in the } i-\text{th workstation} \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

Now we can introduce the assignment matrix in the form (8) for realizing the order $z_{m,n}$, where $e_{m,n}(i,j)$ is the number of the type of tool in the *j*-th tool centre in the *i*-th workstation able to realize the *n*-th order of the *m*-th customer.

$$E_{m,n} = [e_{m,n}(i,j)] \tag{8}$$

At the same time the elements of this structure take the values according to (9).

$$e_{m,n}(i,j) = \begin{cases} u & \text{if the order } z_{m,n} \text{ is realized by the } u-\text{th tool type in the } j-\text{th tool centre in the } i\text{th workstation} \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

The life matrix of a new brand set of the *u*-th type of tools used to manufacture elements of the order $z_{m,n}$ takes the form (10) where $g_{m,n}(i,j_u)$ is the number of units which can be manufactured by the *u*-th tool type in the *j*-th tool centre in the *i*-th workstation before the discussed tool is completely worn out and requires immediate replacement. If the *u*-th tool type in the *j*-th tool centre in the *i*-th workstation is not used for manufacturing the order $z_{m,n}$, then $g_{m,n}(i,j_u) = -1$.

$$G_{m,n} = [g_{m,n}(i,j_u)] \ ; u=1,\dots,U \tag{10}$$

## IV. Equations of the System State

Let $S^k_{m,n} = [s^k_{m,n}(i,j_u)]$, $i=1,\dots,I;$ $j=1,\dots,J;$ $m=1,\dots,M;$ $n=1,\dots,M;$ $u=1,\dots,U;$ $k=1,\dots,K;$ be the matrix of state of the system in case of realizing the order $z_{m,n}$, where $s^k_{m,n}(i,j_u)$ is the number of units which have already been manufactured by the *u*-th tool type in the *j*-th tool centre in the *i*-th workstation till the *k*-th stage.

If the $u$-th tool type in the $j$-th tool centre in the $i$-th workstation is not used for manufacturing the order $z_{m,n}$, then $s^k_{m,n}(i,j_u) = -1$.

The state of the the $u$-th type of tool in the $j$-th tool centre in the $i$-th workstation in case of the product $z_{m,n}$ manufacturing changes consequently according to (11).

$$s^0_{m,n}(i,j_u) \to \ldots \to s^k_{m,n}(i,j_u) \to \ldots \to s^K_{m,n}(i,j_u) \quad (11)$$

The elements of state matrix $S^k_{m,n}$ take the values in accordance with the specification (12), where $x^k_{m,n}(i,j_u)$ is the amount of the product $z_{m,n}$ units realized by the $u$-th type of tool in the $j$-th tool centre in the $i$-th workstation at the $k$-th stage.

$$s^k_{m,n}(i,j_u) = \begin{cases} s^{k-1}_{m,n}(i,j_u) - \text{if the order } z_{m,n} \\ \text{is not realized by } u-\text{th type of tool} \\ \text{in the } j-\text{th tool centre in the } i\text{th} \\ \text{workstation at the } k-\text{th stage} \\ \\ s^{k-1}_{m,n}(i,j_u) + x^k_{m,n}(i,j_u) \text{ otherwise} \end{cases} \quad (12)$$

Let $\rho_{\upsilon,\zeta_\pi}$ be the $u$-th type of tool in the $j$-th tool centre in the $i$-th workstation to be replaced at the $k$-th stage, $1 \le \nu \le I$, $1 \le \zeta \le J$, $1 \le \pi \le U$. The state of this tool in case of replacement of tools changes as shown in (13).

$$s^k_{m,n}(i,j_u) = \begin{cases} s^{k-1}_{m,n}(i,j_u) & \text{if } i \ne \upsilon,\ j \ne \varsigma \text{ and } u \ne \pi \\ & \text{at the stage } k\text{-1} \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

Let $P^k_{m,n} = \left[p^k_{m,n}(i,j_u)\right]$, $i=1,\ldots,I;$ $j=1,\ldots,J;$ $m=1,\ldots,M;$ $n=1,\ldots,M;$ $u=1,\ldots,U;$ $k=1,\ldots,K;$ be the capacity matrix of the system in case of realizing the order $z_{m,n}$, where $p^k_{m,n}(i,j_u)$ is the number of units which still can be manufactured by the $u$-th tool type in the $j$-th tool centre in the $i$-th workstation at the $k$-th stage. If the $u$-th tool type in the $j$-th tool centre in the $i$-th workstation is not used for manufacturing the order $z_{m,n}$, then $p^k_{m,n}(i,j_u) = -1$.

On the basis of the above assumptions the flow capacity of the $u$-th tool type in the $j$-th tool centre in the $i$-th workstation at the $k$-th stage for the element $z_{m,n}$ can be determined in the form (14).

$$p^k_{m,n}(i,j_u) = g_{m,n}(i,j_u) - s^k_{m,n}(i,j_u) \quad (14)$$

## V. Total Manufacturing Time

It is possible to define the matrix of production times in the form (15) where $\tau^{pr}_{m,n}(i,j_u)$ is the time of realization one conventional unit of the product $z_{m,n}$ with the $u$-th tool type in the $j$-th tool centre in the $i$-th workstation.

$$T^{pr}_{m,n} = \left[\tau^{pr}_{m,n}(i,j_u)\right] \quad (15)$$

If the product $z_{m,n}$ is not realized by the $u$-th tool type in the $j$-th tool centre in the $i$-th workstation, then $\tau^{pr}_{m,n}(i,j_u) = 0$. Throughout the manufacturing process tools get worn out and require replacement for new ones. The manufacturing process is brought to a standstill in the workstation in which the tool cannot realize any order and, as a consequence, leads to stopping a production activity in the preceding workstation. For this reason, the replacement process is to be carried out. Let us define the vector of replacement times for tools in the form (16) where $\tau^{repl}_j$ is the replacement time of the tool in the $j$-th tool centre. If the tool in the $j$-th tool centre is not implemented in the production process, then $\tau^{repl}_j = 0$.

$$T^{repl} = \left[\tau^{repl}_j\right] \ ; j=1,\ldots,J; \quad (16)$$

The total manufacturing time of the element $z_{m,n}$ is calculated according to (17) where $y^k_{pr}(i,j)$ is the value indicating that one conventional unit of the product $z_{m,n}$ is manufactured with the use of the $j$-th tool centre in the $i$-th work station at the $k$-th stage and $y^k_{repl}(i,j)$ is the value indicating replacement of the tool in the $j$-th tool centre at $k$-th stage. The variable $y^k_{pr}(i,j)$ takes the values in accordance with specification (18) and the variable $y^k_{repl}(i,j)$ takes the values in accordance with specification (19).

$$T = \sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{u=1}^{U} y^k_{pr}(i,j)\cdot\tau^{pr}_{m,n}(i,j_u) + \sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J} y^k_{repl}(i,j)\cdot \quad (17)$$

$$y^k_{pr}(i,j) = \begin{cases} 1 & \text{if realizing the order } z_{m,n} \\ & \text{with the use of the } j-\text{th tool} \\ & \text{centre in the } i\text{th workstation} \\ & \text{at the } k-\text{th stage is carried out} \\ \\ 0 & \text{otherwise} \end{cases} \quad (18)$$

$$y^{k}_{repl}(i,j) = \begin{cases} 1 & \text{if the replacement procedure of the } j\text{th tool centre in the } i\text{th workstation at the } k\text{th stage is carried out} \\ 0 & \text{otherwise} \end{cases} \qquad (19)$$

## VI. Control of Manufacturing System

### A. Mathematical algorithms

An algorithm is a list of operations which are to be carried out to solve the problem. Classic algorithms are realized by one processor (the so-called serial algorithms). However, in a general case, algorithms can be realized by many processors. To solve discrete problems the following serial algorithms are distinguished:

i) *Optimal algorithms* in which the decision tree is generated in stages. The idea of these algorithms is based on dynamic programming (recurrent functions).
ii) *Sub-optimal algorithms* in which the decision tree is generated by trajectories. These algorithms determine allowable solutions subsequently and only the best current solution is stored. As not all allowable solutions are generated, the current best solution is not usually the optimal one, however there exits the measure of quality of such a solution.
iii) *Conversational algorithms* in which an operator of the computer makes decisions in the process of generating a solution with information support. The characteristic feature of these algorithms is the possibility of returning after a generated trajectory if it is not perspective.
iv) *Agent algorithms* in which decisions are made on the basis of artificial intelligence. The decision about transition from one stage to the subsequent stage consists in choosing a heuristic which may deliver the best expected solution to the stated problem. These algorithms require the knowledge about the effectiveness of heuristics.
v) *Heuristic algorithms* in which the allowable solution is generated by means of determined rules without optimization guaranty. The entire trajectory, from the initial stage to a goal stage, is generated by means of the same heuristic.
vi) *Random heuristics* in which allowable solutions are generated at random. Every subsequent decision about generating a subsequent state is a random choice in the set of allowable options. The best of generated solutions is treated as the best one currently. Moreover, the histogram of solutions is created.

Serial algorithms can be generalized to the form of parallel algorithms. Parallel algorithms enable calculations with the use of many processors. However, acceleration of calculations is not multiplied by the number of processors because of constraints of algorithms, software and hardware.

Deterministic problems are characterized by deterministic data of time and other resources. There are no random variables in deterministic models. Non-deterministic models consist of non-determined data. Stochastic non-deterministic models contain random variables whereas probabilistic models contain probabilities of random variables. Non-deterministic models describe real processes in a better way; however making use of such models is difficult in practice. Non-deterministic processes are used in modelling and computer-based simulation while implementing generators of pseudo-random numbers [37]. Another issue that plays an important role in supporting solving deterministic problems is the convexity approach which can be used as a risk-management tool to measure and manage the amount of risk [38]. A wide range of optimal selection problems are formulated as non-linear constrained optimization problems. One of the most common characteristics of these problems is the presence of non-convexities in their modelling representations. Non-convexities complicate solution methodologies since most existing optimization algorithms rely on identifying stationary points in the feasible space. Locating the global minimum solution of a general non-convex optimization models remains of a primary importance. A common characteristic of all global optimization approaches is their increased computational requirement as the size of the problem increases [39].

Different 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 [40]. Heuristic algorithms are responsible for meeting the set criterion. The criteria are implemented to either maximize the production output or minimize the lost flow capacity of the logistic system or minimize the tool replacement time. Equations of state are given in order to represent the flow of material through the logistic system [41]. The problem of modelling also consists in determining the best order realization sequence in order to minimize the total production time. The idea of time scaling by means of the simulation method should be implemented in order to determine the best possible order realization time. A possibility of simulation of such production systems must be outlined [42].

Methods of mathematical modelling supported by heuristic approaches can be implemented in a lot of fields of contemporary experiments e.g. in modelling sustainable environment tasks [43]. Another aspect worth considering remains implementing RFID methods in order to support manufacturing tasks. These methods lead to minimizing service time of manufacturing processes. As the key innovative solution it automatically captures and tracks the movement of material items throughout an entire supply chain [35]. In multi stage job problems, simple priority dispatching rules such as shortest processing time and earliest due date can be used to obtain solutions of minimum total processing time, but may not sometimes give sequences as expected that are close to optimal [44].

From the programming point of view, algorithms can be classified as follows:

i) *Non-modifying* algorithms change neither the order nor the value of the elements they process. These algorithms operate with input and forward iterators; therefore they can be called for standard containers.

ii) *Modifying algorithms* change the value of elements. Such algorithms might modify the elements of a range directly or modify them while they are being copied into another range. If elements are copied into a destination range, the source range is not changed.

iii) *Removing algorithms* are a special form of modifying algorithms. They can remove the elements either in a single range or while these elements are being copied into another range. An associative or unordered container cannot be used as a destination because the elements of these containers are considered to be constant.

iv) *Mutating algorithms* change the order of elements by assigning and swapping their values which is not changed. An associative or unordered container cannot be used as a destination because the elements of these containers are considered to be constant.

v) *Sorting algorithms* are a special kind of mutating algorithm because they also change the order of the elements. However, sorting is more complicated and therefore usually takes more time than simple mutating operations. Sorting algorithms usually have worse than linear complexity and require random-access iterators for the destination. Time is often critical for sorting elements.

vi) *Sorted-range* algorithms require that the ranges on which they operate be sorted according to their sorting criterion. As for associative containers, these algorithms have the advantage of a better complexity. The result of these algorithms is also sorted.

vii) *Numeric algorithms* combine numeric elements in different ways. These algorithms are more powerful and flexible.

To obtain a satisfactory solution, there is a need to test all available heuristic algorithms. Each order is specific and requires testing control procedures as it is never known which of them can bring the expected solution meeting the stated criterion. The diagram in Fig. 2. shows the general idea of controlling the proposed information logistic system. After implementing the structure of the system and the leading criterion, it is necessary to set the heuristic algorithm. Then the order must be specified which requires adjusting the charges in the next step. The life of the tools, production and replacement times are determined. The above is followed by choosing the number of units of the specified order, which is realized consequently. Orders are realized completely and then another heuristic algorithm is set. The whole procedure is repeated. As a result, the report is generated in which the course of action satisfying the set criterion is proposed. Moreover, if there are more heuristic algorithms invented, they can be tested in the same described way.

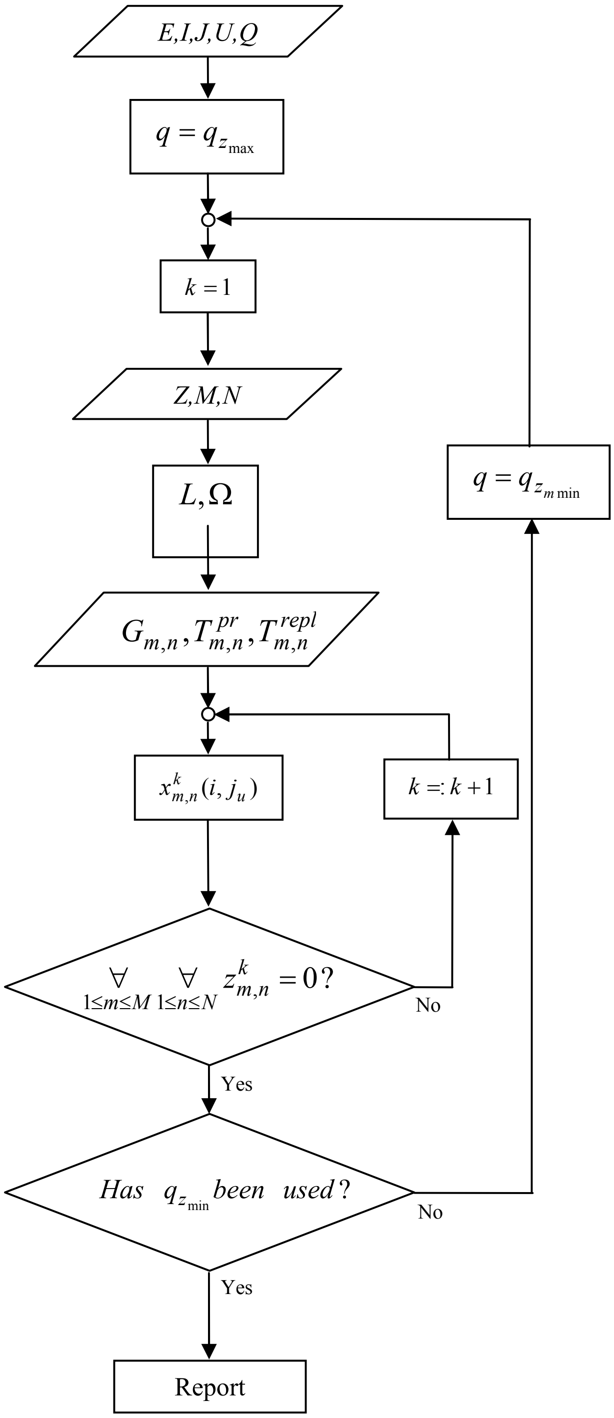


Fig. 2: The diagram of control for the logistic system

*B. Implementation of heuristics algorithms for control of our manufacturing system*

The control of the our complex of manufacturing systems consists in implementing heuristic algorithms which choose an order from the matrix of orders $Z^k$, *k=0, 1, ..., K* for manufacturing.

*1) The algorithm of the maximal order*

This algorithm chooses the order matrix element characterized by the maximal value of $z^k_{m,n}$. To produce the order $z^k_{\mu,\eta}$, $1\leq \mu \leq M$, $1\leq \eta \leq N$ the condition in the form (20) must be met, where $\gamma^k_{m,n} = z^k_{m,n}$.

$$(q^k_{z_{\max}} = z^k_{\mu,\eta}) \Leftrightarrow \left[ \gamma^k_{\mu,\eta} = \max_{\substack{1\leq m\leq M\\ 1\leq n\leq N}} \gamma^k_{m,n} \right] \tag{20}$$

*2) The algorithm of the minimal order*

This algorithm chooses the order matrix element characterized by the minimal value of $z^k_{m,n}$. To produce the order $z^k_{\mu,\eta}$, $1\leq \mu \leq M$, $1\leq \eta \leq N$ the condition in the form (21) must be met, where $\gamma^k_{m,n} = z^k_{m,n}$.

$$(q^k_{z_{\min}} = z^k_{\mu,\eta}) \Leftrightarrow \left[ \gamma^k_{\mu,\eta} = \min_{\substack{1\leq m\leq M\\ 1\leq n\leq N}} \gamma^k_{m,n} \right] \tag{21}$$

*3) The minimal tool replacement time criterion*

The minimal tool replacement time criterion in the form (22) is reduced to the flow capacity bound specified in the form (23) and the order bound (24).

$$Q = \sum_{k=1}^{K} \sum_{i=1}^{I} \sum_{j=1}^{J} y^k_{repl}(i,j) \cdot \tau_j^{repl} \rightarrow \min \tag{22}$$

$$\forall_{1\leq i\leq I} \forall_{1\leq j\leq J} \; y^k_{pr}(i,j) \cdot p^k_{m,n}(i,j_u) \leq g_{m,n}(i,j_u) \tag{23}$$

$$\sum_{m=1}^{M} \sum_{n=1}^{N} x^k_{m,n} \leq z^k_{m,n} \tag{24}$$

## VII. Simulator – Tool for Searching the Satisfactory Solution of Manufacturing System Control

This section focuses on possibilities of searching for the satisfactory solution of manufacturing system output by means of simulation optimization. This approach consists in designing a general simulator illustrating the manufacturing process in these types of manufacturing systems. There is a wide range of commercial products offering an extremely wide spectrum of possibilities for the modelling and simulation of manufacturing, logistical and other queuing systems [45], [46].

The results of a survey of the most widely used discrete event simulation software (carried out for 100 people working in the field of simulation) are presented in [47]. These results help modellers in DES software selection.

Historically, one of the main disadvantages of simulation was that it was not an optimization technique. An analyst would simulate a relatively small number of system configurations and select the one that appeared to provide the best performance. However, the availability of faster PCs and improved heuristic optimization search techniques (evolution strategies, simulated annealing, tabu search, etc.) are important pieces of evidence indicative of the new marriage between optimization and simulation in practice. At present, nearly every commercial discrete-event simulation software package contains a module that performs some sort of "optimization" rather than just pure statistical estimation. The goal of an "optimization" package is to orchestrate the simulation of a sequence of system configurations so that a system configuration is eventually obtained that provides an optimal or near optimal solution.

### *A. Simulation optimization in the Witness environment*

Our workplace is equipped with the Witness environment in which we have, in close cooperation with industrial partners, conducted a number of simulation studies that have led – at least in part, to increases in the productivity of manufacturing, queuing and logistical systems [32]. This section presents the possibilities available when using the Witness environment, and especially the Witness Optimizer package.

The Witness simulation environment is one of the most successful world-class environments for the simulation of manufacturing, queuing and logistics systems. It is used in support of the senior management decision-making process when resolving organisational, technical and operational problems associated especially with the restructuralization and upgrading of an enterprise´s processes. Models in the Witness environment programme depict the movement of materials or customers within the system, the states of individual elements, the operations performed as well as the actual use of resources.

Simulation is not, in and of itself, an optimization procedure, but a means to model different scenarios and compare the results. Because the number of variable factors in a model can be very large, Lanner Group provides the plug-in module Witness Optimizer which can intelligently test different combinations of changes within a model and indicate the "best" model based on an objective function provided by the model builder [48]. This objective function quantifies the objective of the optimization. In addition, users provide information on any constraints within the system i.e. factors within the model which can vary and what their range of variation is. The Witness Optimizer provides several optimization methods, ranging from simply running all possible combinations to more complex algorithms [49].

The Witness environment is used for the optimization of manufacturing, logistics and queuing systems in a whole range of simulation studies. The results that were obtained from applying Witness Optimizer to a manufacturing example with seven decision variables are presented in [50].

### *B. Design of the model of the serial manufacturing system in the Witness environment*

It is obvious that it is possible to use the Witness environment and especially the Witness Optimizer package for the simulator design for our type of the manufacturing system. The production orders can be modelled as the element of the *Part* type with various parameters (characteristics or features of a part). In our case we can create the attribute specifying the number of order units, the attribute for the production times of the production order in each production stand or the attribute specifying the stands where the order is realized. Each machine (workstation) in the production system can be modelled in the Witness environment with help of the element *Machine of Single* type. Moreover, it is possible to model tool centers with the use of the elements *Labor*. Additionally, we can model requirement for replacement of a tool by means of the *Setup* page of the element *Machine*. The *Setup* page enables us to model times that the machine needs to set up or retool.

The sample model in the simulation environment of Witness is shown in Fig. 3. This model represents a manufacturing line with two dedicated workstations. Each workstation consists of a centre for two tools (e.g. for drilling and grinding). The drilling centre contains two kinds of drills and the grinding centre contains three kinds of grinding discs. The attribute *Usage_tool* specifies the number of units realized by the specific type of tool. The production orders are modeled as the element of the *Part* type (*Order*) with four attributes specifying the number of order units (*Number_of_unit*), production times of the production order in each production stand (*Production_time*), the attribute specifying the stands where the order is realized (*Stand*) and the kind of the implemented tool (*Tool*). The charge material is modeled as the element of the *Part* type (*Charge*) with the attribute specifying the type of material. The machine *Assigment_order_charge* provides assignment of charge material to the order.

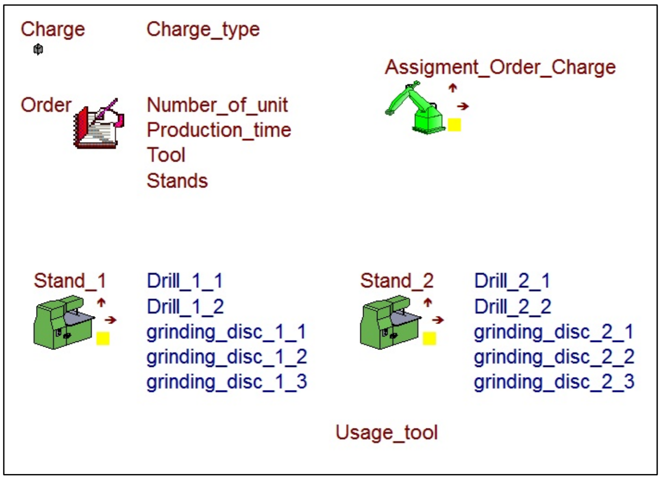


Fig. 3: The scheme of the sample model in Witness

## VIII. CONCLUSIONS

Manufacturing process in a production company must always be prepared thoroughly as it consists in the use of machines, tools and labour to realize the order for the defined product set by a customer at any time. The challenge for manufacturers is to try to protect their customer base, while carefully managing costs and cash flows. However, as demand often weakens this has become progressively more difficult. Nevertheless, knowing the type of the product which is to be realized within the specified period of time enables us to prepare the sequence of decisions which lead to meeting the manufacturers' expectations as well as the customers' demands. Monitoring the change of the system and orders after each decision about either production or replacement of worn out tools lets the operator of the system to alternate the course of production in order to meet the stated criterion. Control of the complex manufacturing system consists in implementing heuristic algorithms. The algorithms of the maximal and minimal orders are proposed in the paper in order to meet the minimal tool replacement time criterion which is accompanied by the defined constraints of the flow capacity as well as the order bound. The proposed algorithms are to set an example how to control production process by determining the order elements for realization. All the assumptions stated in the paper are to result in creating the simulator which will search for the satisfactory solution in accordance with the implemented minimal tool replacement time criterion. The number of orders can be immense which may lead to big losses during the manufacturing process. Such losses may result from e.g. replacing a tool which has not been worn out completely, the wrong sequence of production decisions and not implementing the control elements properly. If the use of the proposed heuristic algorithms fails to deliver the expected satisfactory result data, their combination may lead to obtaining the cost saving procedures. However, this can be achieved only by means of a simulation method. Implementing other criteria e.g. the cost minimization criterion or the output maximization criterion, requires another kind of approach to control the manufacturing system. After making a decision about which criterion is valid, the solution focusing on the preferred way of minimizing costs should be sought for. Another aspect worth highlighting is the priority of criteria. The priority-based control should be sought for as well in order to adjust the cost reducing procedures to satisfy the need of realizing the order. The analytical way of searching for a satisfactory solution cannot be implemented.

The work presented in the paper forms the basis for building a simulator which lets us make the proper decisions about production. The simulator which is to be created on the basis of the designed model is to allow both a "screening" or worst-case analysis and more detailed assessments. However, searching for the satisfactory solution remains the priority in further works.

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