QUEUE ALGORITHMS ANALYSIS IN FLEXIBLE MANUFACTURING SYSTEMS INCLUDING VARIABLE CHANGEOVER TIMES

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Summary: In this paper, the ways of application of a simulation model based on Hierarchical Timed Coloured Petri Nets (HTCPN) for an analysis of queue algorithms in flexible manufacturing systems (FMSs) were presented. The characteristic feature of the model proposed is the consideration of variable changeover times necessary for preparing the machines for processing of a new set of items. A method of defining variable changeover times based on the comparison of the current machine equipment code with the machine equipment code required for a given technological process was proposed. The changeover diagram was made, which allowed for an explicit assignment of machine changeover time depending on the scope of necessary exchanges of the processing tools or other tools. An exemplary flexible manufacturing system was defined in which the items were transported automatically without a conflict of resources. In order to queue the orders in the simulation model, four queue algorithms were used: EDD, SPT, LPT, TR. The simulation was done using an exemplary list of existing production orders. The study revealed a necessity for consideration of variable changeover times in the analysis of queue algorithms in flexible manufacturing systems. In the majority of the cases studied, the introduction of changeovers bore a considerable influence on the increase in the delays in order processing which are of great significance to the customer. The consideration of changeover time in the simulation model enables one also to determine the influence of this process on the total order processing time.

Keywords: Petri nets, queue algorithm, flexible manufacturing systems, variable changeover times.

1. Introduction

Improving the efficiency of manufacturing is the main goal of both the designers and users of the manufacturing systems. According to the marketing paradigm, products must fulfil the expectations of the receivers, be cheap and reach the customers as quickly as possible. These requirements bring about a need for a change in planning and execution manufacturing systems. Efficient planning of manufacturing processes becomes especially important in case of flexible manufacturing systems that deal with rapidly-changing and strictly customer-oriented production. Computer-aided modules become an inherent feature of modern flexible manufacturing systems, because they allow for efficient planning and queuing of successive customers' orders. One of the most important elements of such modules are simulation models that allow for the analysis of production processes taking place in production zone, allow rapid reaction to ever changing business environment and also provide a prediction how resolved decisions will affect the future prosperity of an enterprise [1, 2, 3].

The range of problems related to event prediction in business reality is an extremely complex issue but also absorbing at the same time. Modern implementations of IT systems which provide support in decision making processes (Decision Support Systems - DSS) are applicable, among others, in Business Intelligence (BI) software class [4, 5, 6], which is often implemented as a part of advanced Enterprise Resource Planning (ERP) systems [1]. With regards to production enterprises, where manufacturing processes are crucial for business continuity, making decisions without any previous analysis, in extreme cases may lead manufacturing processes to a deadlock. In order to provide a supportive tool in decision making process on this level, one should reach for professional IT solution called Advanced Planning and Scheduling (APS) system. This software can be considered as a subsystem of ERP or as an additional module which extends functionality of Manufacturing Execution System (MES) [7, 8, 9].

Production planning with decision support, which is provided by APS, is essential in modern manufacturing when flexible manufacturing systems are considered with sort batches, agile manufacturing or variant production and all of above multiply complications. For in opposite to traditional planning, actual range of regarded factors is extended significantly. Therefore the object of the latest production planning systems is not only a proper sequence of actions planning but to develop efficient strategy which will evolve with the time and will be depend on current production indexes, variable market demands, costs or time preferences, balanced job coverage or machine loading indicators. In a such compound work environment any act of decision making, usually results worsen the secondary indicators in a given time horizon [7, 10].

One of the key subsystem in APS solution is an order's queue management system. Sequence of orders delivered to production may have significant impact on tardiness of orders, overall production time and even on machines malfunctions. Due to the aims assigned during production scheduling process, there are possibilities to create queues to minimize overall production time, minimize tardiness or to maximize machine utilization. This narrow scope of production scheduling problem will be introduced in following points of this paper and simulation studies will determine how order queue sequences impact on specific production indicators. Petri net formalism used in conducted studies has been verified in many research projects [11, 12, 13, 14, 15].

2. Description of the issue

One of the main tasks of the work control module of the flexible manufacturing system is to determine the sequence of production order execution. According to the paradigm of flexible manufacturing systems functioning, this task should be done automatically using efficient queue algorithms. In this paper the possibilities of application of a simulation model based on Petri nets to an analysis of queue algorithms in flexible manufacturing systems are presented. The characteristic feature of the model presented is the consideration of variable changeover times necessary for preparing machines for processing a new set of items.

Figure 1 shows the schematic diagram of the analysed manufacturing system. The system consists of numerically controlled machines (M_1, M_2, M_3, M_4) connected by an automated transportation subsystem. Machines M_1, M_2, M_3 perform such typical technological operations as: turning – machine M_1, milling – machine M_2, grinding – machine M_3. Machine M_4 symbolises quality control workstation in the analysed manufacturing system. At the system input there is a list of orders described by technological routes. Technological routes define the order of machines (machine tools) on which the processing of the items assigned to a given order is to take place. Furthermore, processing times for individual machines, required machine equipment and due date are also assigned to the orders.

The characteristic feature of a flexible manufacturing system is its routing flexibility that manifests itself in the possibility of simultaneous manufacturing of the items of different technological routes. Figure 1 shows all possible transport directions during production process. One of the following seven possible technological routes is assigned to an order:

- Technological route RT1: $M_1 – M_4$,
- Technological route RT2: $M_2 – M_4$,
- Technological route RT3: $M_3 – M_4$,
- Technological route RT4: $M_1 – M_2 – M_4$,
- Technological route RT5: $M_1 – M_3 – M_4$,
- Technological route RT6: $M_2 – M_3 – M_4$,
- Technological route RT7: $M_1 – M_2 – M_3 – M_4$.

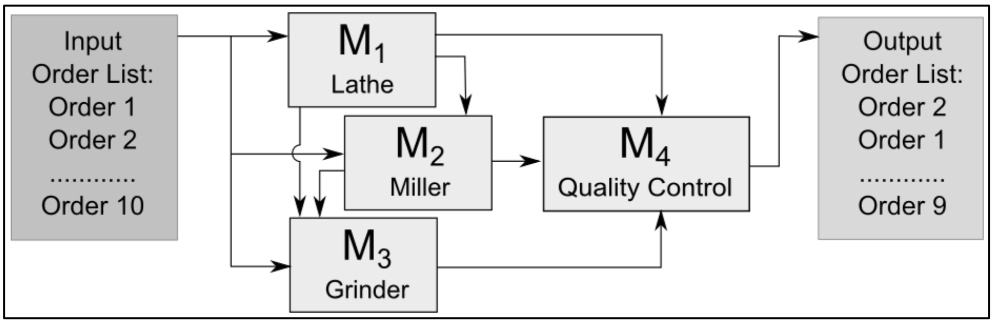

Fig. 1. Simplified schematic diagram of a production system

To each order the due date is assigned. The date is fixed at the stage of production planning with the customer and should be categorically kept. Most frequently, the due date is defined as an explicitly set date, the missing of which will be subject to contractual penalty. It may happen, however, that the date is not explicitly set: the customer can define a time span for an order to be processed. In such a case the order should be processed neither too early nor too late.

In case of piece and small batch production, the consideration of times necessary for equipping the machine tools with proper tools and fixing proper tool posts is a very important issue. In simulation models a fixed changeover time is very often assumed for simplification. The time is, in fact, variable and depends not only on the type of items to be processed but also on what was processed by a given machine before. Sometimes in order to prepare the machine for processing of a new set of items all tools need to be exchanged, and sometimes only one.

In this paper a method for defining the variable changeover times necessary for preparation of the machine for the processing of an order Z_i is proposed. For each order a code of the required equipment of all the machines in the technological route of that order is defined as $K_{UMj}(Z_i)$. For example, for an order Z_k with an assigned technological route $MT(Z_k)$ = RT1 one may define the code of the required machine equipment M_1 - $K_{UM1}(Z_k)$

and the code of the required machine equipment M_2 - $K_{UM2}(Z_k)$. For each machine in the system the code of the current machine equipment is defined K_{UMj}. The time needed for the preparation of the machine for the processing of the items from Z_k depends on the required machine equipment described by the code $K_{UMj}(Z_k)$ and its current equipment described by the code K_{UMi}. If the current machine equipment is exactly the same as the required equipment, it may be assumed that the changeover is not necessary and the changeover time $T_{przez}(M_h,Z_k)$ is 0. If the code of the required equipment is different than the code of the current machine equipment, the changeover must take place, and the time needed for it depends on the scope of the necessary tasks to be done. Table 1 shows the way of calculating changeover times for a machine M_1 for three different equipment codes (A, B, C).

Tab. 1. M_1 machine changeover times

Required equipment	Current equipment of M_1 machine	Changeover time $T_{przez}(M_1,Z_k)$ [s]
A	A	0
A	B	300
A	C	800
B	A	300
B	B	0
B	C	400
C	A	800
C	B	400
C	C	0

Table 2 shows the way of calculating changeover times for M_2 machine for three different equipment codes (A, B, C).

Tab. 2. M_2 machine changeover times

Required equipment	Current equipment of M_2 machine	Changeover time $T_{przez}(M_2,Z_k)$ [s]
A	A	0
A	B	500
A	C	200
B	A	500
B	B	0
B	C	600
C	A	200
C	B	600
C	C	0

Table 3 shows the way of calculating changeover times for M_3 machine for three different equipment codes (A, B, C).

Tab. 3. M_3 machine changeover times

Required equipment	Current equipment of M_3 machine	Changeover time $T_{przez}(M_3,Z_k)$ [s]
A	A	0
A	B	100
A	C	800
B	A	100
B	B	0
B	C	600
C	A	800
C	B	600
C	C	0

Figure 2 shows schematic diagram of changeovers that indicates possible changeovers for each machine.

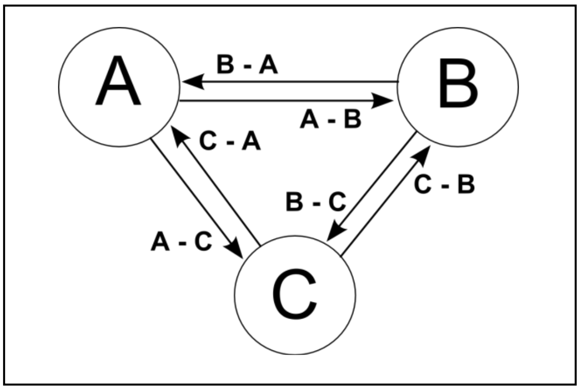

Fig. 2. Changeovers diagram

For research purposes, a specific order list, based on actual production data, was adopted. In this order list ten production orders were defined. Characteristic feature in this list is presence of six orders following technological route RT6 and one order with long processing time in comparison to other orders.

In order to set a sequence of production orders that are available on input list, various sorting algorithms may be used. Four implemented algorithms are described below:

- EDD algorithm, Earliest Due Date – list of orders is searched for an order with a closest due time, such an order is designated as number one. As a result of next searching, successive order is designated as number 2. The last searching designate number 10 to an order with the farthest due time,
- SPT algorithm, Shortest Processing Time – sorting of a list is dependent on sum of processing times for each order and is sequenced from the shortest one,
- LPT algorithm, Longest Processing Time – sorting of a list is dependent on sum of processing times for each order and is sequenced from the longest one,
- TR algorithm, Time Reserve – sorting is done on basis of minimal time reserve factor (T_{rc}) described as:

$$T_{rc} = T_{zk} – T_{obr} \quad (1)$$

where: T_{rc} – time reserve value,
T_{zk} – due time of order,
T_{obr} – sum of processing times of an order,
and the sorting itself is done from the lowest, to the highest T_{rc} factor.

3. Simulation model

In order to construct a simulation model, IT tool named "CPN Tools" was used. This software is used to build advanced systems on basis of Hierarchical Timed Coloured Petri Nets (HTCPN) with usage of Standard Meta Language (SML). One of the essential features of coloured Petri net is the ability to assign colours (attributes) to tokens. This ability was used to define a production order token which contains substantial information, regarding the objectives of conducted studies. The construction of the production order token is shown in formula 2.

1`(s, rt, c1, t1, c2, t2, c3, t3, t4, dl, ord)@ts (2)

where:
s – number from 1-10 range, describing the sequence of entering production zone,
rt – number from 1-7 range, describing technological route of an order,
c1 – number from 1-3 range, describing required equipment of M_1 (A or C),
t1 – number from 0-4000 range, describing processing time on M_1,
c2 – number from 1-3 range, describing required equipment of M_2 (A, B or C),
t2 – number from 0-4000 range, describing processing time on M_2,
c3 – number from 1-3 range, describing required equipment of M_3 (A, B or C),
t3 – number from 0-4000 range, describing processing time on M_3,
t4 – number from 0-4000 range, describing processing time on M_4,
dl – number from 200-16000 range, describing due time of an order,
ord – identification number of an order,
@ts – individual time stamp of an order.

The construction of the production order token, introduced in formula 2, makes it possible to gather all important information of an order in one place and to trace its changes during a simulation of production process. Variable "s" is assigned a value during sequencing orders by a given queue algorithm. Value "dl" defines due date of an order and it is dictated by the customer after the confirmation made by production planning unit. The "ord" value defines ID number of an order and it is inherited from the superior system. Other attributes (route - rt, processing times - t_i, equipments - c_i) are related to specific technological processes which are essential for proper processing and assigned by the technology-construction department.

Considering the feature of hierarchical Petri net, the whole model was divided into three layers, shown in figure 3 along with flow directions of production orders.

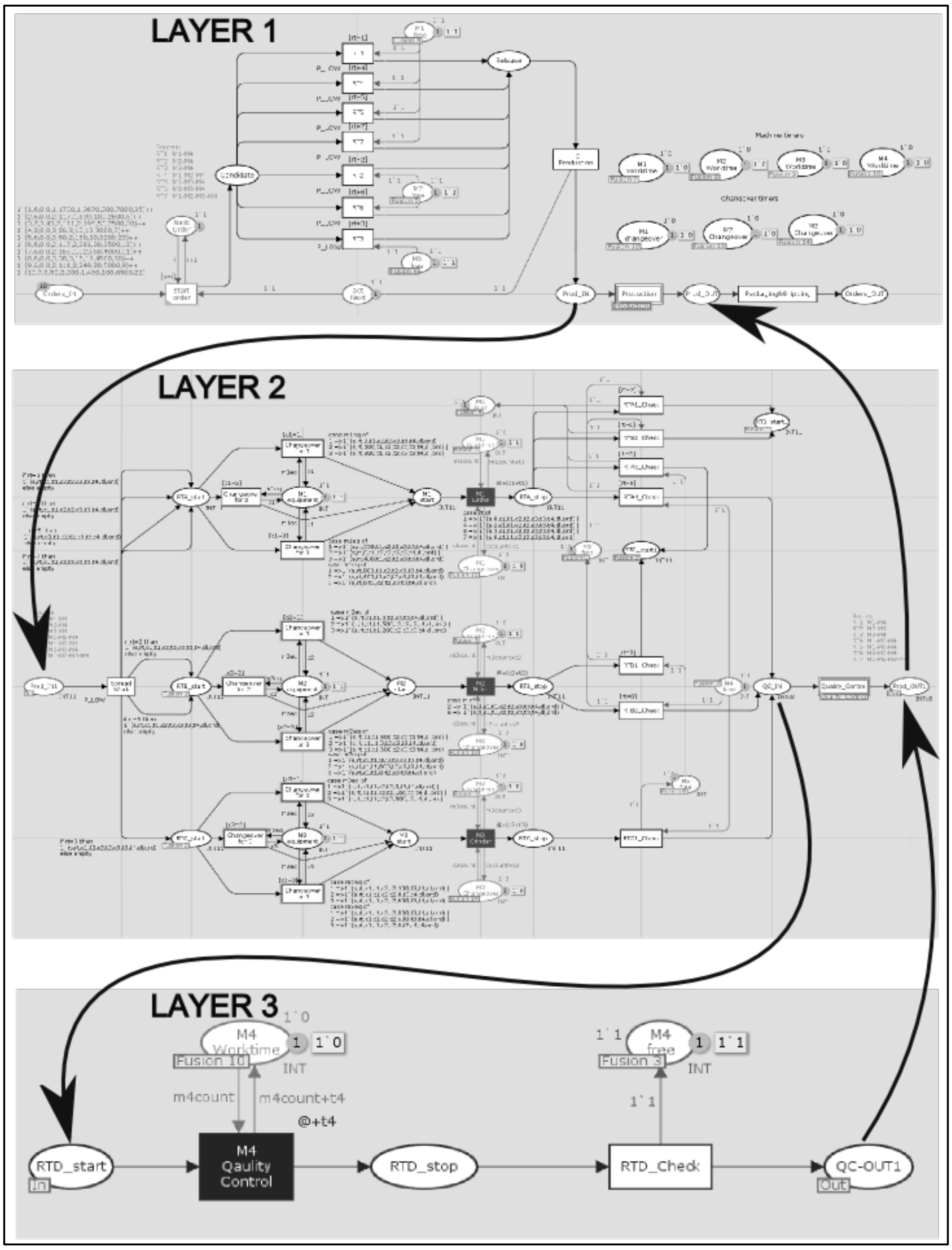

Fig. 3. Hierarchical construction of simulation model

Layer 1 is responsible for the selection of the next order from an input list and, depending on workstations' status, grant or deny the introduction of the selected order to the production zone. A fact worth consideration is that the transitions in layer 2 have higher priorities than the transitions in layer 1. It means that in case of an order conflict concerning the access to the machine M_2 or M_3, the order which is already in the production zone has priority over the order waiting for introduction. Layer 2, production sub layer, is responsible for proper processing in workstations M_1, M_2 and M_3 including correct priorities and technological routes constraints. Layer 3 models quality control station M_4.

The third specific feature of HTCPN is time. Considering time implications in the examined model, two methods are employed: global simulation clock analysis and individual time stamps analysis. Due to the analysis of individual time stamps of tokens, it is possible, for instance, to determine the working time of each workstation and, after correlating it with the global simulation clock, to define machine utilization coefficients.

Figure 1 shows the module of simulation model responsible for M_1 machine changeover. Other functions provided by this module are: adding the changeover time to the processing time according to the M_1 machine changeover time table, adding the processing time to the counter of M_1 processing times, adding the changeover time to the counter of M_1 changeover times and also replacing "rt" index in accordance with current production status. For each machine involved in the technological process, an individual changeover module was defined. All the modules are the part of production layer (layer 2).

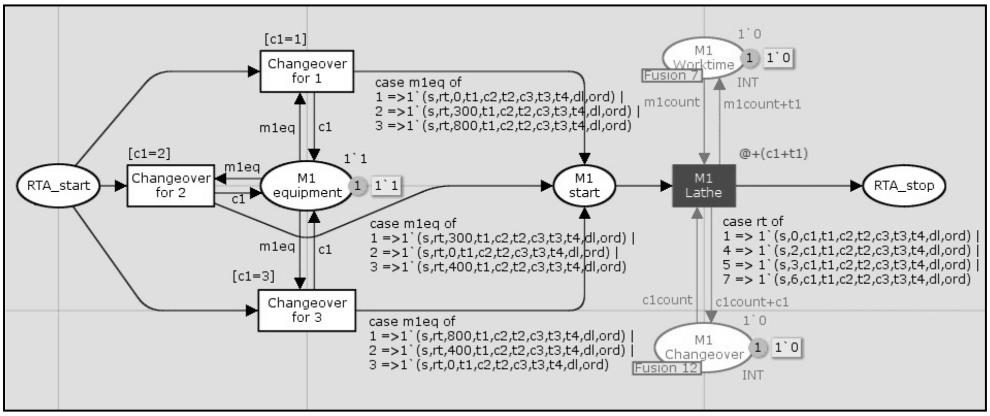

Fig. 4. Module of simulation model responsible for M_1 machine changeover

The example of changeover simulation for M_1 machine is described below. Let us presume that the production order token Z_4 described as 1`(4, 7, 3, 50, 2, 200, 1, 450, 100, 6500, 22)@0 is going to be processed on M_1 machine. The token appears in "RTA_start" where the variable c1 is checked. The c1 index describes the requested equipment of M_1 for order Z_4. Due to Z_4 request, the equipment of M_1 needs to be marked as C; it means the c1 index equals 3 (c1=3). The production order token Z_4 is moved to transition "Changeover for 3" whose fire condition is described as [c1=3]. Current M_1 equipment is stored in "M1 equipment" and equals 1; it means that the current M_1 equipment is A. Transition "Changeover for 3" collects the production order token Z_4 and the current M_1 equipment. As a result, after the "Changeover for 3" transition is fired, two tokens are created. The first one goes to "M1 equipment" and changes the M_1 equipment for C (token has the value 3). The second one is the new order token Z_4 where the value c1 is changed for changeover time $T_{przez}(M_1,Z_4)$=800. The new order token Z_4 appears in the place "M1 start" in the following way 1`(4, 7, 800, 50, 2, 200, 1, 450, 100, 6500, 22)@0. During the simulation process transition "M1 Lathe" reads and sums up the changeover time and the processing time. The indication is shown above the transition as @+(c1+t1). Meanwhile, the same value is added to the individual time stamp of the order. Additional places "M1 Changeover" and "M1 Worktime" calculate changeover times and working times for M_1 machine for further data mining. As a result, after the transition "M1 Lathe" is fired, the new order token Z_4 1`(4, 6, 800, 50, 2, 200, 1, 450, 100, 6500, 22)@850 is created in "RTA_stop". The new token has new technological route rt=6 and new individual time stamp @850.

4. Simulation studies

The objective of the simulation studies conducted was to analyse the production process in flexible manufacturing environment. Simulation studies were focused on ten orders put on the order list which was described in chapter 2. In the light of the collected data, it was possible to define the following parameters:

- overall production time for different queuing algorithms,
- the sum of processing times for each machine,
- the sum of changeover times for each machine,
- the number of orders delayed,
- the sum of tardiness for all orders,
- machine utilization coefficient,
- the fraction of changeover times in overall production time.

Taking into consideration the figure 5, it is possible to state that changeover times have significant impact on overall production time. A good example with regent to the production time, is the LPT algorithm, which results in shortest changeover times. Unfortunately, using this algorithm causes the longest delays, which may result in worsening of the relationships with the clients. It is clearly visible that LPT algorithm that sorts orders according the longest processing time is able to reach high machine utilization coefficient but it cannot be recommended in case of strict due date constraints. Taking into account the uncompromising customers' demands fulfilment, it is highly recommended to choose SPT or EDD algorithm, as the ones that generate minimal sum of tardiness. Nevertheless, in that case, the shortest production time is not guaranteed. In particular, the usefulness of SPT algorithm was proved, reaching the minimal sum of tardiness of all other algorithms.

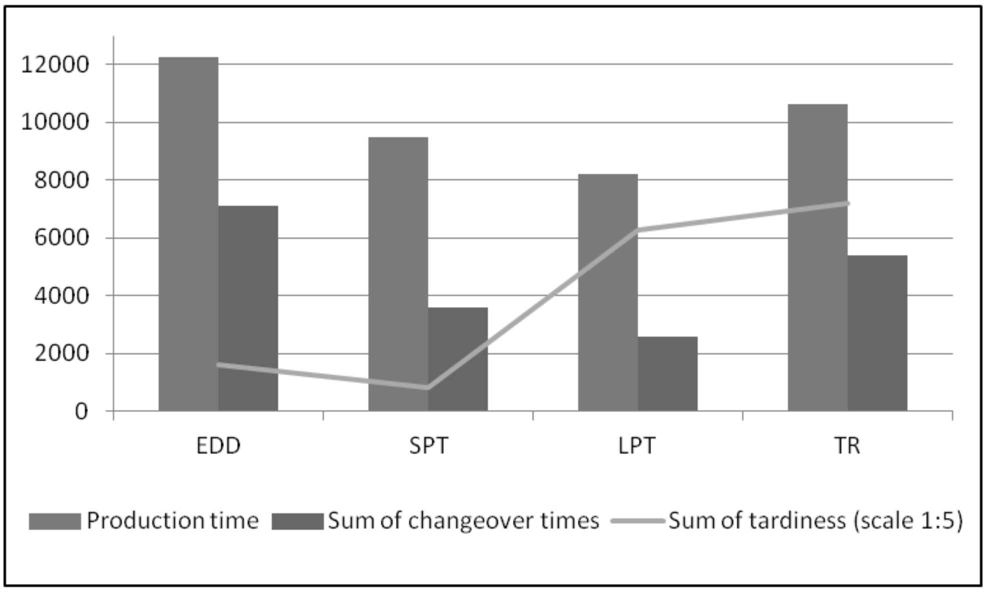

Fig. 5. Production time, sum of changeover times and sum of tardiness

Figure 6 shows the impact of the changeovers on the sum of tardiness. The results achieved shown in figure 6 should be treated as ambiguous. In case of LPT algorithm which causes large sum of tardiness, similar sum of tardiness was reached, regardless of the presence or absence of changeover times. Three other cases indicate that changeover times have significant impact on the increase in the sum of tardiness.

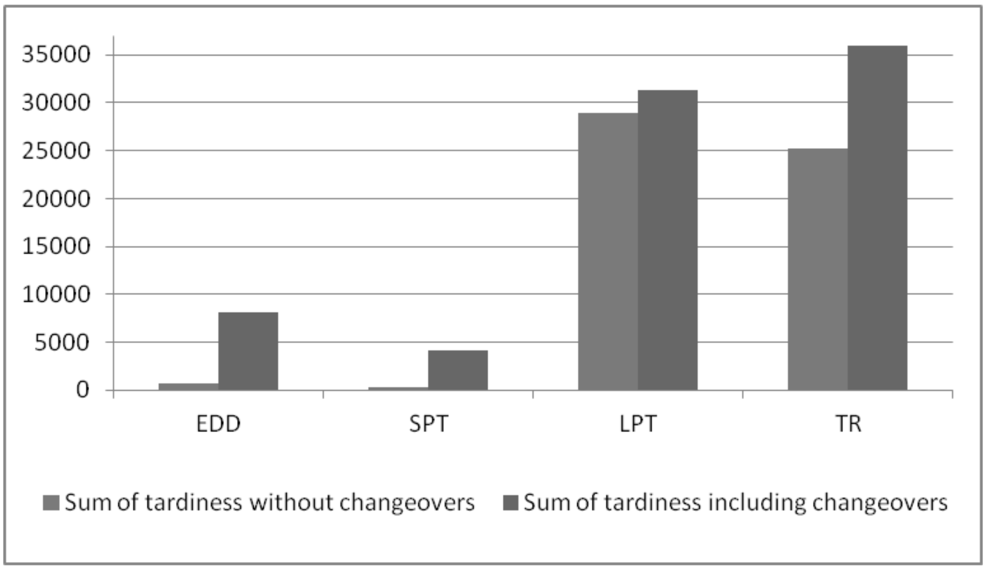

Fig. 6. Impact of changeovers on sum of tardiness

5. Conclusion

According to the paradigm of operation of flexible manufacturing systems, the task of determining the sequence of order processing should be done automatically, using efficient queue algorithms.

In this paper, the ways of application of a simulation model based on Hierarchical Timed Coloured Petri Nets for an analysis of queue algorithms in flexible manufacturing systems were presented. The characteristic feature of the model proposed is the consideration of variable changeover times necessary for preparing the machines for processing of a new set of items. By means of the functional programming language Standard Meta Language the 12-parameter token of an order was defined. Such token structure allows for monitoring of all important information of an order during the time of the simulation process.

A method of defining variable changeover times based on the comparison of the current machine equipment code with the machine equipment code required for a given technological process was proposed. The changeover diagram was made, which allowed for an explicit assignment of machine changeover time depending on the scope of necessary activities connected with the exchange of the processing or other tools.

An exemplary flexible manufacturing system was defined in which the items were transported automatically without a conflict of resources. In order to queue the orders in the simulation model, four queue algorithms were used: EDD, SPT, LPT, TR. The simulation was done using an exemplary list of existing production orders. The list features typical changeover times, characteristic of machine processing.

The study revealed a necessity for consideration of variable changeover times in the analysis of queue algorithms in flexible manufacturing systems. In the majority of the cases studied, the introduction of changeovers bore a considerable influence on the increase in the delays in order processing which are of great significance to the customer. The consideration of changeover time in the simulation model enables one also to determine the influence of this process on the total order processing time. The occurrence of big time losses connected with machine changeover prompts the intensification of research timing at arriving at such an order list that would guarantee the minimisation of the total changeover time. Further research assumes the use of a computer system based on evolutionary algorithms for that purpose.

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