Calculation of transport system in flexible manufacturing

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Abstract
Modern enterprises deal with a number of different material fluxes with respect to the transportation and storage systems, which can be considered as two parts of a whole warehouse system in a flexible manufacturing. At that, the warehouse system is considered as a regulator of the flows to compensate the uneven production in the enterprise or uneven delivery from outer suppliers. Up to date, the methods of the warehouse design rely mostly on the average indicators; however, they require the statistical data that are not always available, especially at the preliminary design stage. As a result, insufficient storage or transport capacity can form a 'bottle neck' that decreases the effective output of the enterprise.
Thus, the implementation of the methods that considered the probabilistic character of the storage and delivery processes is necessary to avoid the miscalculation. Using the methodology of theory of mass service like the queuing theory, the capacity of the transport system can be determined without preliminarily collecting statistical data on the materials flows of arrival and departure, as well as processing these materials by methods of mathematical statistics and probability theory.

1. Introduction
A factory planning involves a lot of problems that should be solved to avoid critical mistakes, which hinder the effective exploitation of the flexible manufacturing systems [1]. For the purpose, statistical methods of analysis of such systems, like queuing theory [2] powered by simulation [3] are applied, as was successfully demonstrated for theoretical calculations of flow-type [4] and flexible manufacturing systems [5], as well as for industry applications [6-9].
However, the problem is far from being solved due to the large variety of FMS. In our previous work, the application of queuing theory was demonstrated with respect to a particular type of a system that incorporates CNC cutting machines provided with the machine-bound buffer magazines and large inter-operational storage for workpieces. At that, the methods of calculating the capacity of the buffer magazines and inter-operational storage were developed [10], as well as methods of calculation of the number of lines for robots to provide CNC machines with tools, and method of calculation of the capacity of a section in the central tool storage [11]. However, since flexible manufacturing systems are a highly integrated systems, where the relation between components is very complex, various mathematical programming approaches are in-demand.
Generally, the methodologies developed for optimization of robocar transport systems are categorized into mathematical methods (exact and heuristics), simulation studies, meta-heuristic techniques and artificial intelligent based approaches [12]. Suri et al. represented one of the first works in automated manufacturing of parts

with mid-volume demand, where a computer program based on mean-value analysis of queues was developed [13]. An algorithm proposed by Mahdavi et al. [14] was dedicated to solution of major challenges in the domain of autonomous transportation systems, which are trajectory planning and collision avoidance. In the first phase, the lowest cost path is planned by a modified Dijkstra algorithm; in the second phase, the head-on collisions can be foreseen and avoided, and finally, the task assignment and scheduling algorithm allocated different tasks. A distributed Petri net was applied by Herrero-Perez et al. [15] for solving task allocation and traffic control problems. Petri nets and algorithm with a heuristic function represented by a neural network, were also proposed by Nie et al. [16] to simulate an operation of a robotic system in the numerical experiments to estimate a minimal time that should be taken to complete all planned tasks. A method based on use of the graphical language Sequences of Operations (SOP), was applied by Magnusson et al. [17] to automate transport planning for FMS. The method was composed of three iterative steps, which require create operations, add local execution conditions and extend the execution conditions to achieve a correct global behaviour. In the work conducted by Kumar et al. [18], an implementation of Flexsim model for measuring and analysis of FMS performance was tested. The approach developed by Fazly et al. [19] was concentrated on the design and optimization of FMS layout, where ARENA simulation software was employed. A mathematic model for integrated scheduling of a specific type of FMS with single robocar and single buffer area was developed by Lv et al. [20]. Unfortunately, the numerical experiments are time consuming, while the simulations of a separate systems lack generality.

In this paper, we report about the method of calculation of a transport system intended to serve CNC machines with a purpose of changing the processed workpieces to blanks by use of transport robocars. A developed mathematical model is based on the well-known model of death and reproduction that describes the states of the transport system according to the degree of loading of the storage area with transport consignments. Each of the states describe a certain probabilistic situation that is characterized by a fixed set of CNC unit engagement, rate of arriving requirements for CNC service, and service rate. The research question is formulated as following: what have to be the number of robocars of the

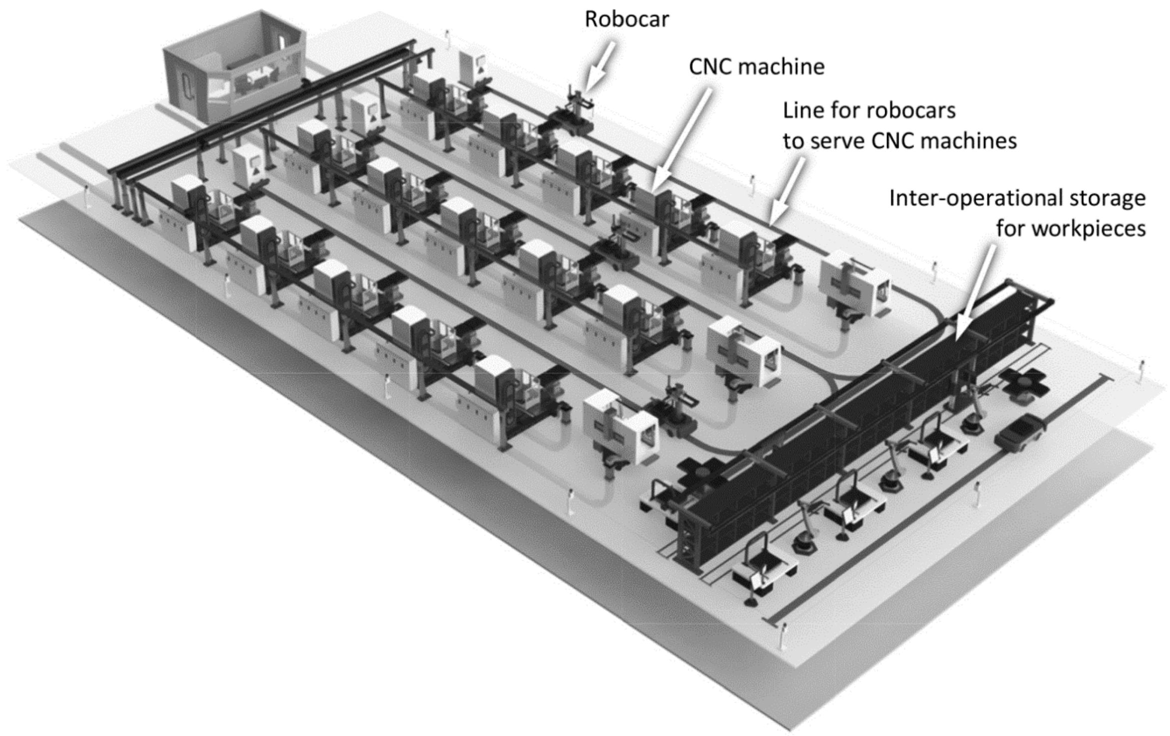

Figure 1: General view of a machining flexible manufacturing system (FMS) with n CNC machines (n = 18) that are served by m robocars, which is considered in the paper

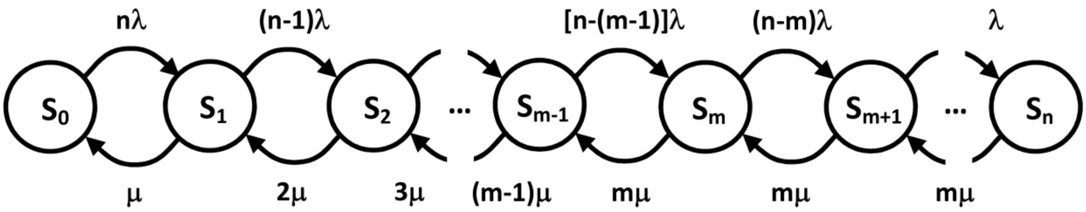

Figure 2: Labeled graph of Markov process of the queuing system discussed in the paper

transport system to fit the production rate of FMS of a specified design?

2. Methods

A flexible manufacturing workshop of a specified layout is considered. It includes CNC machines, and produces a certain number of workpieces of a wide nomenclature. A general view of the workshop provided with n CNC units (n = 18) is shown in Figure. 1.

To make a supply chain between the CNC machines and an inter-operational storage, the production and storage are connected by transportation lines for robocars, and the number of the robocars is m. At that, each of n CNC machines requires servicing at a frequency λ (workpieces/h), while each of m robocars can serve the CNC machines at a rate μ (machines/h). It is assumed that each service requirement from the CNC machines equals to the delivery of one workpiece by use of one robocar. In a case when the robocar can deliver several workpieces in one transport consignment, the rate λ of arriving requirements should be decreased by N_{cs} times, where N_{cs} is the number of workpieces in one transport consignment.

To determine the dependence of the average number N_{ru} of robocars-on-duty on the number m of robocars employed in the production system, as well as the robocar utilization K_{ru}, the average number of served CNC machines A_{serv} (absolute service capacity of the transportation system), and the average number of idle CNC machines $N_{CNCidle}$, a dependence of probability p_k of a certain state k of the production system on the number of CNC machines n at the number of employed robocars m should be determined. For the purpose, a system of Kolmogorov equations is set to describe a process illustrated in Figure 2. The figure presents a labeled graph of Markov process of the queuing system, where S_0 is a state when all CNC machines operate, and all robocars are not on duty. At that, the total flow of requirements for service is $n\lambda$, since each of the CNC machines can produce the requirement. S_1 is a state when one CNC machine does not operate, and one robocar is on duty. The rate of transfer from S_1 to S_0 state is determined by the total service rate that is μ, if the system stays in S_1 state (only one robocar is on duty); the rate of transfer to S_2 state is $(n\text{-}1)\lambda$, since one CNC machine has already produced the requirement for the service to a robocar, and cannot generate new requirement. S_2 is a state when two CNC machines do not operate, and two robocars are on duty, so the rate of transfer to S_1 state is 2μ, and the rate of transfer to S_3 state is $(n\text{-}1)\lambda$. S_m is a state when m CNC machines do not operate, and m robocars are on duty. After all m robocars are on duty, the total service rate $m\mu$ stays constant even if the number of CNC machines requiring service increase from m to n.

Thus, the following set of differential equations that determines the rates of change of probabilities p_k (k=0, 1, …, n) at the dependence on probabilities p_{k-1} and p_{k+1} can be written: (1)

$$\begin{cases} \frac{dp_0}{dt} = -n\lambda p_0 + \mu p_1, \\ \frac{dp_1}{dt} = n\lambda p_0 - [(n-1)\lambda + \mu]p_1 + 2\mu p_2, \\ \frac{dp_2}{dt} = (n-1)\lambda p_1 - [(n-2)\lambda + 2\mu]p_2 + 3\mu p_3, \\ \dots \\ \frac{dp_k}{dt} = \begin{cases} [n-(k-1)]\lambda p_{k-1} - [(n-k)\lambda + k\mu]p_k + \\ +(k+1)\mu p_{k+1}, \ k < m \\ [n-(k-1)]\lambda p_{k-1} - [(n-k)\lambda + m\mu]p_k + \\ +m\mu p_{k+1}, \ k \geq m \end{cases} \end{cases}$$

From a practical point of view, a stationary mode of the manufacturing system is usually a matter of interest, so the equations can be simplified by implying the following condition:

$$\frac{dp_k}{dt} = 0. \quad (2)$$

To solve system (1), a normalization condition should also be implied, which states that a sum of the probabilities p_k should equal unity:

$$\sum_{k=0}^{n} p_k = 1. \quad (3)$$

To simplify further the final set of equation, a utilization factor is introduced

$$\alpha = \frac{\lambda}{\mu}, \quad (4)$$

and the probabilities p_k of a certain state k at the dependence on the number n of CNC machines at the number m of robocars employed in the production system and probability p_0 are expressed from system (1):

$$p_k = \begin{cases} \frac{\alpha^k}{k!}\frac{n!}{(n-k)!}p_0, \ k < m, \\ \frac{\alpha^k}{m!m^{k-m}}\frac{n!}{(n-k)!}p_0, \ k \geq m. \end{cases} \quad (5)$$

To determine the probability p_0 that is the probability of the state when all CNC units operate, and all robocars are not on duty, the last expression is substituted into (3), which yields:

$$\sum_{k=0}^{m-1} \frac{\alpha^k}{k!}\frac{n!}{(n-k)!}p_0 + \\ + \sum_{k=m}^{n} \frac{\alpha^k}{m!m^{k-m}}\frac{n!}{(n-k)!}p_0 = 1, \quad (6)$$

and p_0 is determined:

$$p_0 = \begin{pmatrix} \sum_{k=0}^{m-1} \frac{\alpha^k}{k!}\frac{n!}{(n-k)!} + \\ + \sum_{k=m}^{n} \frac{\alpha^k}{m!m^{k-m}}\frac{n!}{(n-k)!} \end{pmatrix}^{-1}. \quad (7)$$

Thus, final expressions for the probabilities p_k are obtained:

$$p_k = \begin{cases} \frac{\frac{\alpha^k}{k!}\frac{n!}{(n-k)!}}{\sum_{k=0}^{m-1}\frac{\alpha^k}{k!}\frac{n!}{(n-k)!} + \sum_{k=m}^{n}\frac{\alpha^k}{m!m^{k-m}}\frac{n!}{(n-k)!}}, k < m, \\ \frac{\frac{\alpha^k}{m!m^{k-m}}\frac{n!}{(n-k)!}}{\sum_{k=0}^{m-1}\frac{\alpha^k}{k!}\frac{n!}{(n-k)!} + \sum_{k=m}^{n}\frac{\alpha^k}{m!m^{k-m}}\frac{n!}{(n-k)!}}, k \geq m. \end{cases} \quad (8)$$

After determining the probability of the states of the manufacturing system, other characteristics can be found. The average number N_{ru} of robocars-on-duty is:

$$N_{ru} = \sum_{k=1}^{m-1} kp_k + m \sum_{k=m}^{n} p_k. \quad (9)$$

The robocar utilization is:

$$K_{pu} = \frac{N_{ru}}{m}. \quad (10)$$

The average number of CNC machines served by the robocars that is the absolute service capacity of the transportation system, is:

$$A_{serv} = \mu N_{ru}. \quad (11)$$

The average number of idle CNC machines, i.e. the machines that do not operate while waiting the service from the robocars, is

$$N_{CNCidle} = \sum_{k=1}^{n} kp_k. \quad (12)$$

3. Results of calculations

The proposed model was employed to calculate the efficiency of FMS with n = 18 CNC machines with an average production capacity of 4 items/h; thus, each of the machines requires servicing with the parameter λ = 4 workpieces/h. At that, rough estimation allows obtaining the number of robocars necessary to satisfy the requirements at the known service capacity μ of a robocar. In the example, the capacity was set to μ =24 workpieces/h that correspond to the average service time of 60 min/24 workpieces = 2.5 minutes to change a workpiece in CNC machine. This value is quite reasonable, when considering typical length of transportation line of a few dozen meters, robocar velocities of about 30 m/min, and times of changing positions in the buffer storages near CNC cutting units. Thus, the average number of the robocars at such parameters should be $\lambda n/\mu$ = 4·18/24 = 3 robocars, which are engaged for 100 % at that, so the robocar utilization is unity. With such a high degree of utilization robocars cannot be exploited, their number have to be increased, which, in turn, leads to increase of production cost. However, application of the proposed mathematical model allows obtaining more accurate results.
The results of calculations by use of expressions (8) of the dependence of probability p_k of a certain state k of the production system on the number of CNC machines at the number of robocars m_{rc} = 3 and m_{rc} = 4 are shown in Figures 3 and 4, respectively.

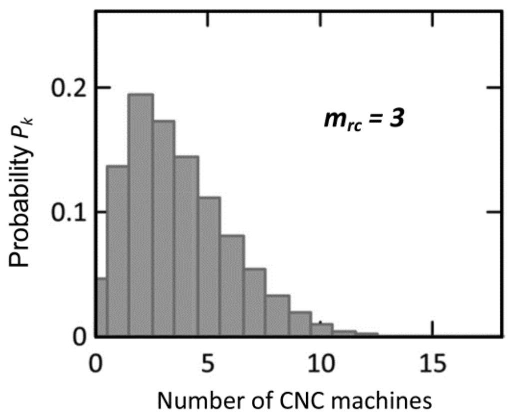

Figure 3: Dependence of probability of a certain state of the production system on the number of CNC machines at the number of robocars m_{rc} = 3

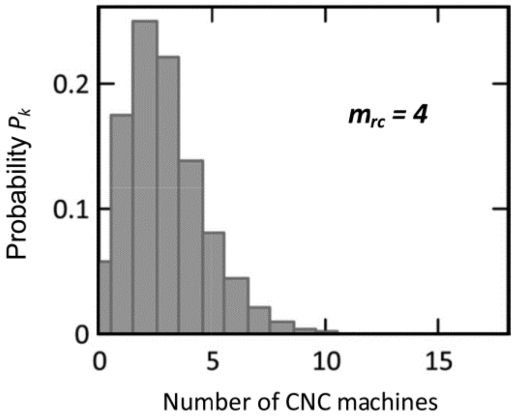

Figure 4: Dependence of probability of a certain state of the production system on the number of CNC machines at the number of robocars m_{rc} = 4

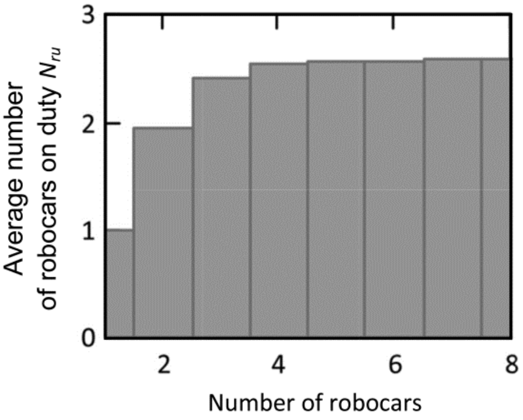

Figure 5: Dependence of the average number of robocars-on-duty on the number of robocars employed in the production system

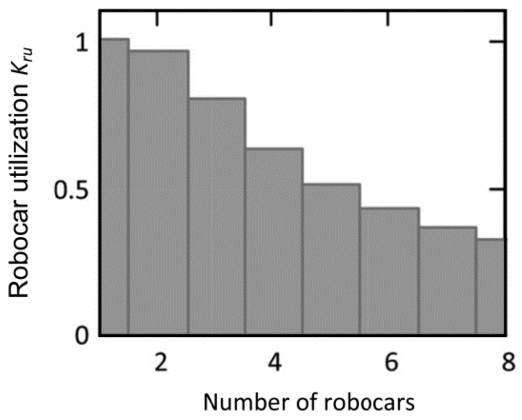

Figure 6: Dependence of the robocar utilization on the number of robocars employed in the production system

As it can be seen, for the fixed number of CNC machines n = 18, the distribution becomes sharper at m_{rc} = 4, while the most probable state is still the same, namely S_3. Moreover, if the number of robocars is increased further, the average number of robocars-on-duty does not change significantly, as it can be seen from the results shown in Figure 5. At that, the utilization factor shown in Figure 6, is satisfactory even for two robocars employed in the system, $K_{ru}(2)$ = 0.8, while the served number of CNC machines is not so far from saturation, as it can be seen in Figure 7, since $A_{serv}(2)$ = 57.6 (in the saturation limit this value reaches 61.7 machines/h). The average number of idle CNC machines in this case is $N_{CNCidle}(2)$ = 3.6 machines, as it follows from Figure 8. The robocar utilization for the cases m = 1, 3, and 4 are $K_{ru}(1)$ = 0.966, $K_{ru}(3)$ = 0.632, $K_{ru}(4)$ = 0.512; the average number of served CNC machines are $A_{serv}(1)$ = 46.4, $A_{serv}(3)$ = 60.7, $A_{serv}(4)$ = 61.5; the average number of idle CNC machines are $N_{CNCidle}(1)$ = 6.4, $N_{CNCidle}(3)$ = 2.8, $N_{CNCidle}(4)$ = 2.6.

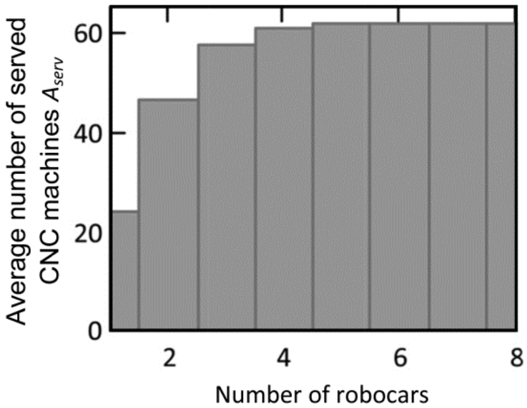

Figure 7: Dependence of the average number of served CNC machines on the number of robocars employed in the production system

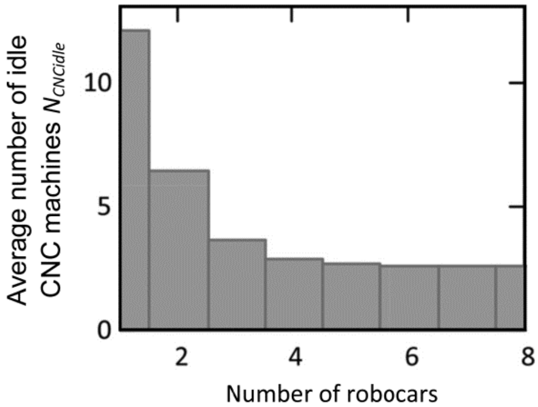

Figure 8: Dependence of the average number of idle CNC machines on the number of robocars employed in the production system

Thus, even two robocars can satisfy the requirements from CNC machines in this system; however, it is appropriate to use tree robocars to increase reliability.

4. Summary

The developed model was used to calculate the parameters of efficiency of a storage system of a flexible manufacturing by use of methods of queuing theory. It was shown that the calculations allows solving a problem of estimation of a number of robocars employed to serve CNC cutting machines in flexible manufacturing. For a specified number of CNC machines, the necessary number of the robocars is lesser that obtained by use of average values of productivity μ of the robocars, and λ – for CNC machines. In turn, the economy obtained due to more accurate calculations, results in increase of the cost-efficiency of the whole production cycle.

In future, the methods of the queuing theory are planned to be used to predict the efficiency of the whole transportation and storage system of such FMS, including the states of the large inter-operational storages with their transport facilities.

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