PROBLEMS OF CONTROL OF WORKPIECE FLOW IN A FLEXIBLE MANUFACTURING SYSTEM

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Summary

The paper presents problems arising during developing algorithms controlling workpiece flow subsystems in a flexible manufacturing system. The necessary signals as well as the general algorithm responsible for worpiece flow in a flexible manufacturing system were defined. On the basis of a structure of a flexible manufacturing system developed at the Institute of Manufacturing Engineering of Szczecin University of Technology the problems of selecting an appropriate pallet from a rack stacker and choosing the right transport operation of a horizontal transport carrier were defined. In order to choose an appropriate pallet to carry out a task a method based on fuzzy sets was proposed and applied. The linguistic variables used in the reasoning process and the structure of the process were also described. The operation of Fuzzy Logic module was depicted on the basis of simulation studies. The investigations confirmed the possibility of applying Fuzzy Logic reasoning in developing complex algorithms controlling automated manufacturing systems.

Keywords: workpiece flow control, FMS, Fuzzy Logic

Problemy sterowania podsystemem przepływu przedmiotów w elastycznym gnieździe obróbkowym

Streszczenie

W pracy przedstawiono wybrane problemy projektowania algorytmów sterowania podsystemem przepływu półwyrobów w elastycznym gnieździe obróbkowym. Zdefiniowano konieczne sygnały sterujące oraz omówiono ogólny algorytm pracy urządzeń odpowiedzialnych za przepływ przedmiotów w systemie obróbkowym, uwzględniając strukturę podsystemu sterowania elastycznego gniazda obróbkowego, zbudowanego w Instytucie Technologii Mechanicznej Politechniki Szczecińskiej. Zdefiniowano problemy wyboru odpowiedniej palety z magazynu regałowego i operacji transportowej wózka automatycznego. Do realizacji procesu wyboru palety zaproponowano metodę wnioskowania opartą na zbiorach rozmytych. Określono zmienne lingwistyczne stosowane w procesie wnioskowania oraz ich strukturę. Działanie modułu wnioskowania Fuzzy Logic obrazowano za pomocą eksperymentu symulacyjnego. Uzyskane wyniki badań potwierdziły możliwość stosowania wnioskowania typu Fuzzy Logic do budowy skomplikowanych algorytmów sterujących zautomatyzowanymi systemami obróbkowymi.

Słowa kluczowe: sterowanie przepływem materiałów, ESW, logika rozmyta

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1. Introduction

A dynamic development of Flexible Manufacturing Systems (FMS), which started in the 1980s aimed at cutting costs of manufacturing of various products particularly given the context of constantly growing customers' demands [1]. A constant tendency to lowering the number of manufactured products while at the same time increasing their variety led, in conventional systems, to a dramatic increase of setup time in the total work time. As a result manufacturing costs also kept increasing. Only owing to an application of technologically advanced means of production, such as FMS (Flexible Manufacturing Systems), it was possible to reduce the setup time necessary to adopt a system to dynamically changing demand while at the same time keeping a high level of automation of production process, which results in low production costs [2-4].

While analyzing FMS functioning, it should be noted that a system's effective operation to a large extend depends on the smooth running operation of control subsystem or to be more precise on control algorithms implemented in the system. Such algorithms are responsible for controlling processes of taking products from high storage container, for controlling automated guided vehicles (AGV) which transport products over to machining subsystem, and for control and diagnostics operations. Because of a very high number of various tasks performed by control system, it is usually divided into the following elements which are closely related to respective FMS subsystems [2]:

- workpiece flow control subsystem responsible for transport operations from high storage container to machining subsystem and vice versa (transport carriers, rack stackers, robots);
- machining process control subsystem responsible for machining of worpieces;
- workpiece storage control subsystem responsible for storing workpieces at various stages of machining;
- quality inspection control subsystem responsible for controlling and diagnosing a machining process;
- tooling flow control subsystem.

Many studies have focused on problems connected with developing effective algorithms controlling FMS. In [5], its author investigates the problem of choosing transport carriers' control rules and divides them into rules initiated by carriers and those initiated by workstations. The problem of optimal machine duty was discussed in [4] and [6] whereas the issue concerning the allocation of operations to workstations was investigated in [7] and [8]. Many papers focus on the problem of production task scheduling. Precise and approximate methods as well as methods based on Fuzzy Logic, artificial neuron networks and genetic algorithms are used in order to solve these problems [9-12]. An application of artificial intelligence methods makes it possible to build complex algorithms which control automatic systems using ambiguously defined expert knowledge or "intelligent" algorithms which have self-teaching properties.

The paper presents problems arising while designing algorithms which control workpiece flow control subsystem in a test flexible manufacturing system designed and assembled in the Institute of Manufacturing Engineering of Szczecin University of Technology.

The paper is organized as follows; in Section 2 a basic problem of effective control of workpiece flow control subsystem and its importance in a flexible manufacturing system has been defined. Section 3 presents the structure of workpiece flow control subsystem and defines the problem of effective control of both a rack stacker and a transport carrier. Section 3 also presents a general work operation algorithm of these two devices. Section 4 presents in detail a pallet selection module supported by Fuzzy Logic reasoning. This section also contains a description of both linguistic variables used in the reasoning process and the structure of the process. Section 5 contains a description of simulation experiment presenting how the developed algorithm of pallet selection actually works in a real manufacturing system. Section 6 presents conclusions and a plan of further research.

2. Problem Formulation

The analysis of problems arising in designing workpiece flow control subsystem was limited to a flexible manufacturing system of a job shop type, in which workpiece flow is carried out by automated guided vehicles (AGV) and industrial robots. An example of a configuration of the investigated group of manufacturing subsystems is presented in Fig. 1.

The basic elements of such systems include: a high-storage warehouse, flexible production cells and a transport subsystem connecting all respective production cells. Flexible production cells usually consist of two or three automatic machining stations connected by means of an internal transport subsystem and the cell's main containers. A distinctive feature of such systems is their technological flexibility, which allows them to effectively carry out various manufacturing tasks that require different technological routes. This very property of such systems, i.e. their ability to parallel conducting of different technological routes is a great challenge for transport subsystem control algorithms.

An effective control of workpiece flow subsystem is one of the most important requirements which are decisive for a smooth running operation of the whole flexible manufacturing system. This is due to the fact that in modern FMSs, their workpiece flow subsystems are fully automated. All transport operations carried out by either transport carriers (AGV – automated guided vehicles) or industrial robots are meticulously programmed or they should at least unambiguously follow from the developed algorithms. Even the most up-to-date and most efficient machines alone cannot possibly guarantee an effective operation of a production system without an efficient and "smart" workpiece flow subsystem, which makes it possible to both transport workpieces to machine tools and to collect them directly after machining has finished.

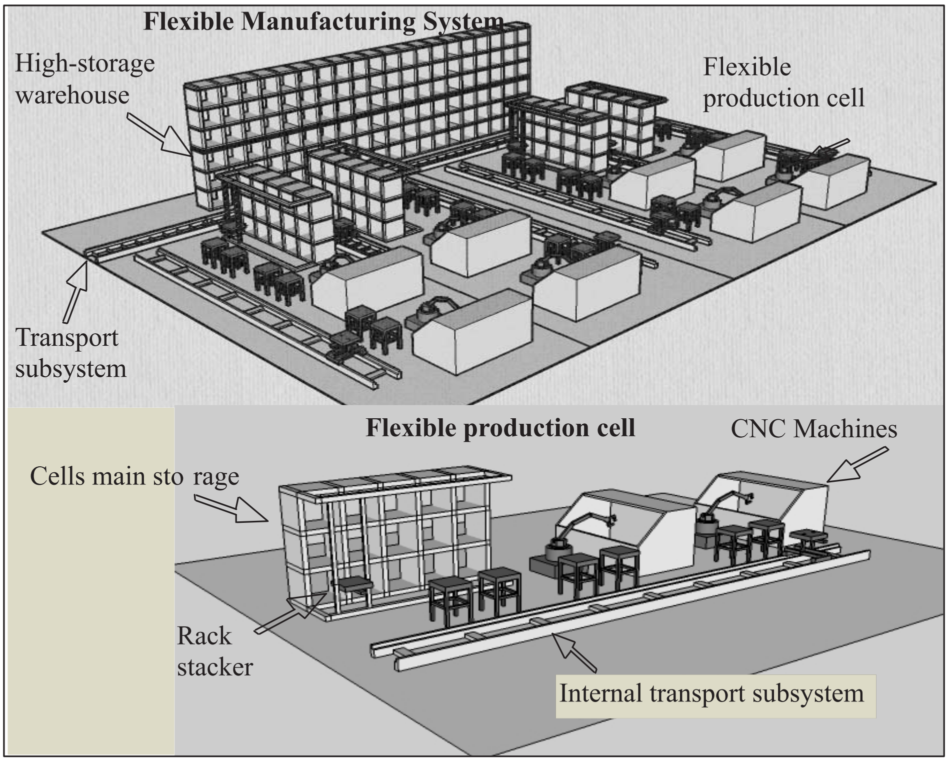


Fig. 1. A model configuration of a flexible manufacturing system of the job-shop type

The general problem of workpiece flow subsystem control can be defined as a problem of developing efficient algorithms which in turn control the operation of all transport devices that comprise the system and make it possible for the elements of the system to function logically and "smartly".

3. The control system of workpiece flow subsystem

The present paper discusses problems connected with how to control workpiece flow subsystems on the basis of a flexible manufacturing system designed and assembled in the Institute of Manufacturing Engineering of Szczecin University of Technology [1]. The system's basic technical elements, which are responsible for workpiece flow operations, are: rack stacker, carrier of horizontal transport and industrial robots. Workpieces to be machined in the system are transported on pallets. Every pallet has its own technological route which defines a sequence of technological machines on which workpieces on this particular pallet are to be machined. In the investigated system its pallets (or to be more precise worpieces stored on each pallet) can have the following technological routes:

MT1 = (M1, M2) – machining first on machine M1 and then on M2;
MT2 = (M2, M1) – machining first on machine M2 and then on M1;
MT3 = (M1) – machining only on machine M1;
MT4 = (M2) – machining only on machine M2;
MT5 = ([M1], [M2]) – machining on machine M1 or on M2.

Taking into consideration the structure and functions of the investigated manufacturing system the control system of workpiece flow subsystem was divided into four intelligent and autonomous agents:

1. System controlling the rack stacker making decisions about which pallet and its workpieces should be selected for machining.
2. System controlling the carrier of horizontal transport making decisions about the next operation depending on the status of storage containers next to the machines, technological routes of workpieces and the total work time of machining.
3. System controlling the industrial robot R1 (operating machine M1).
4. System controlling the industrial robot R2 (operating machine M2).

The structure of the control system governing workpiece flow subsystem is presented in Fig. 2. A distinctive feature of the system is the fact that all the modules controlling transport devices are totally autonomous. They are interconnected into one, logically operating, system by means of information transfer concerning a current status of machining process (i.e. the status of technological machines, transport and storage elements).

The basic function of the rack stacker is to serve the high storage container. The rack stacker picks up pallets from the container and transports them to the input station. Additionally, the rack stacker picks up pallets from the input station and places them at the high storage container. Figure 3 shows a diagram presenting the rack stacker with its rack container as well as store stations. From the technical point of view the rack stacker can pick up pallets in any order or sequence. As a result, pallets can be arranged and then machined in various ways. For instance, scheduling U_i can be defined by the numbers of subsequent pallets which are picked up from the high storage container. Every kind of scheduling precisely defines the order in which pallets enter the machining

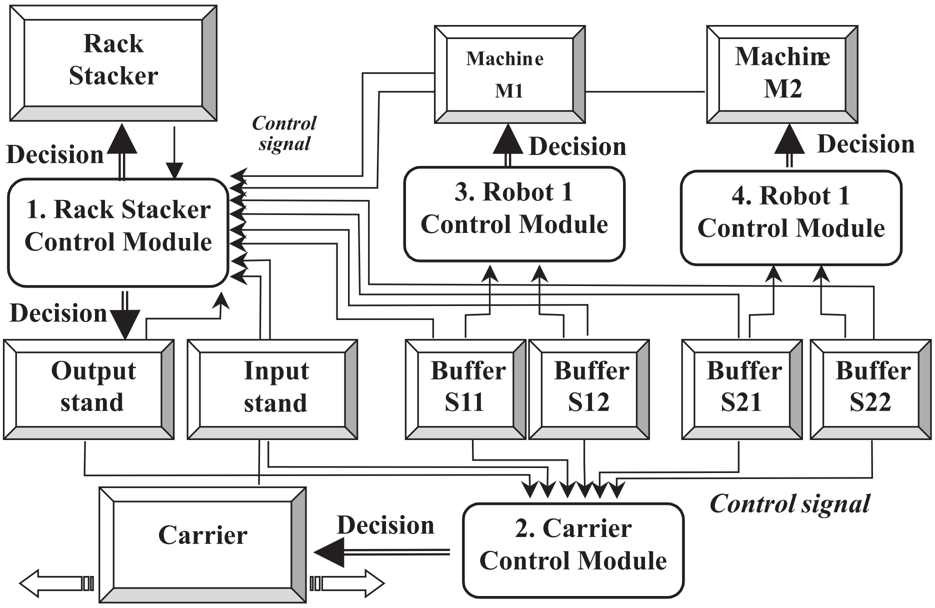


Fig. 2. The control system structure of workpiece flow subsystem

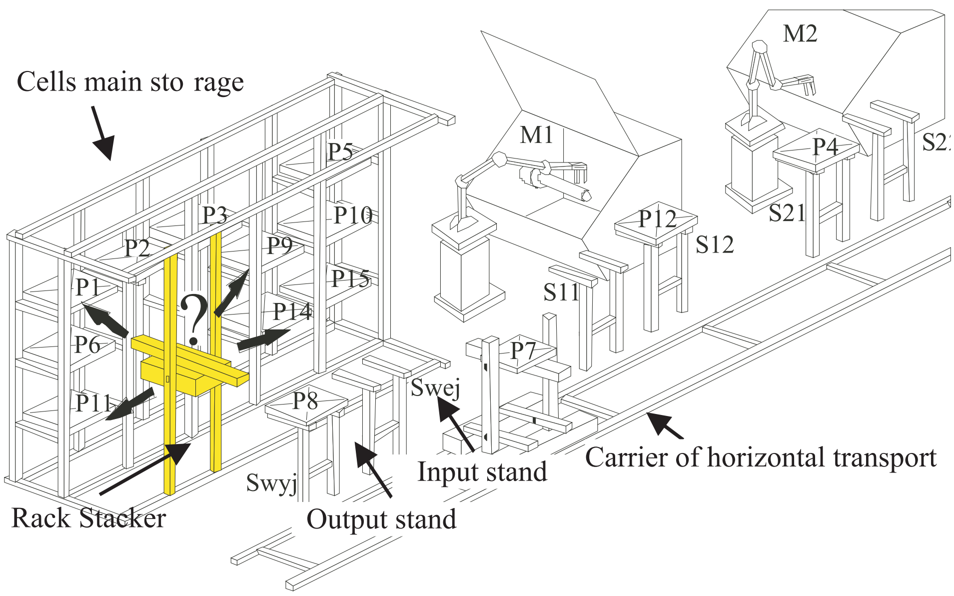


Fig. 3. The problem of choosing a pallet from a high storage container

process. If we assume that a store contains *n* pallets, then a scheduling $U_i = [P_1, P_2, P_3 \dots P_n]$ precisely describes the order of pallets $P_1, P_2, P_3 \dots P_n$, in which they will enter the machining process. The number of all the possible scheduling arrangements is equal to the number of permutations of a set of all pallets n: Per(n) = n! When the assumed number of pallets in the store equals 15, the number of all the possible arrangements of pallets equals 15! ≈ 1,30767E12.

The problem of an effective control of the rack stacker can be defined as a task of finding such an order of picking up pallets from the rack container that would allow to minimize the total working time of system *Tc*. By denoting the investigated scheduling as U_o and a set of all the possible arrangements as *ZU*, the below presented problem can be written as:

Task I:

$$\text{Find such } U_o \text{, that } Tc(U_o) = \min Tc(U_i);\ U_i \in ZU;\ i \in 1,2,3,\dots n! \tag{1}$$

where: U_o – is the sought-for arrangement, *ZU* – is the set of all possible arrangements, $Tc(U_i)$ – is the total working time of the machining system given arrangement U_i

In order to stress that a concrete time *Tc* refers to a certain arrangement U_i, the following notation will be used: $Tc(U_i)$.

When products on the pallets have a clearly defined deadline for finishing technological procedures $Tw(P_j)$, an effective control of the rack stacker can mean choosing such a scheduling that would allow to complete all the tasks by the predefined deadline (task IIa), or else to minimize a possible exceeding of this deadline (task IIb).

Task IIa:

$$\text{Find } U_i \in ZU \ \{ \underset{P_j}{\forall}\ Tr(P_j)_{Ui} < Tw(P_j) \} \tag{2}$$

Task IIb:

$$\text{Find } U_i \in ZU \ \{ \sum_{j=1}^{n} O(P_j)_{U_i} = \min \} \tag{3}$$

$$D(P_j)_{U_i} = \begin{cases} Tr\left(P_j\right)_{U_i} - Tw\left(P_j\right) gdy\, Tr\left(P_j\right)_{U_i} > Tw\left(P_j\right) \\ 0 \qquad\qquad\qquad gdy\, Tr\left(P_j\right)_{U_i} \le Tw\left(P_j\right) \end{cases} \tag{4}$$

where: U_i – is the sought-for arrangement, ZU – is the set of all possible arrangements, $Tw(P_j)$ – is the required deadline of finishing work on pallet P_j; $j \in 1,2,3,\ldots n$, $Tr(P_j)_{Ui}$ – is the real time of finishing work on pallet P_j; $j \in 1,2,3,\ldots n$ in scheduling U_i; $i \in 1,2,3,\ldots n!$, $D(P_j)_{Ui}$ – a delay of pallet P_j in scheduling U_i;

Controlling the rack stacker and the carrier of horizontal transport is conducted in a closed system, with a feedback loop which makes it possible to take into consideration any present state of the system (Fig. 4).

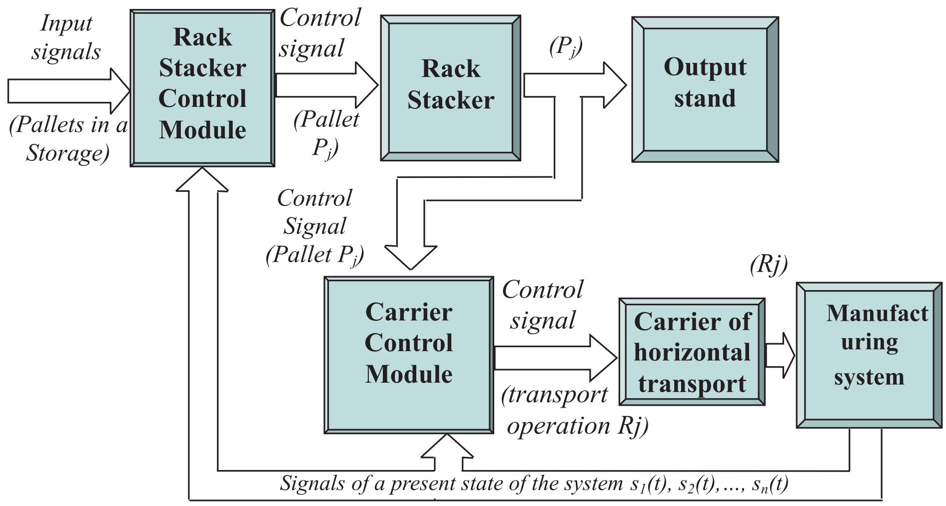


Fig. 4. A diagram of a system controlling the rack stacker and the carrier of horizontal transport

An algorithm implemented in the control system of the rack stacker generates control orders, which initiate taking subsequent pallets from the rack store, which in turn creates a certain pallet scheduling U_i. An act of taking a pallet P_j from the rack store and placing it on the output stand generates a control signal received by the control system of the carrier of horizontal transport. The system receives an order to transport pallet P_j , which is to be found at the input stand, to a machine defined in a route attributed to this pallet (or to be more precise to the buffer store at this machine).

Just as in the case of the rack stacker's control, the basic problem of effective control of the carrier of horizontal transport can be defined as a task of finding, at a present state of the system, such a transport operation R_i (the carrier's motion) that would make it possible to minimize the assumed criterion (the total working time of the system Tc or the sum of delays of carrying out all the orders O_{Pj}). Fig. 5 presents the transport carrier at the moment of selecting a transport operation. At a current status of the system the following transport operations are possible: a movement to input stand S_{out} to pick up pallet P_8 (movement R_{Sout}), a movement to a stand S12 to pick up pallet P_{12} (movement R_{S12}) or a movement to stand S21 to pick up pallet P_4 (movement R_{S21}).

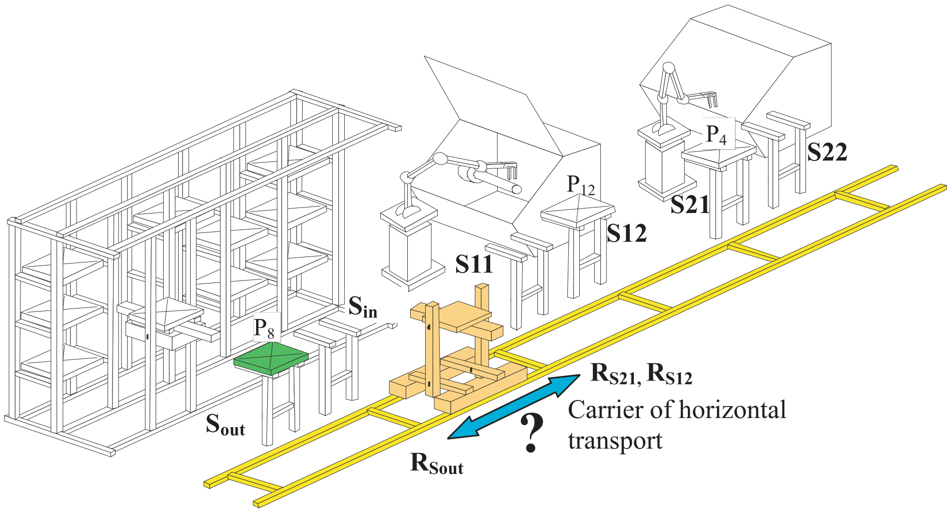


Fig. 5. The problem of selecting transport operations of the horizontal transport carrier

The details of the carrier of horizontal transport operations depend on the stock level of the stores near the milling machines, on the route attributed to a pallet selected by the rack stacker, on the routes of pallets found in the system and on the total working time of workpieces found on the pallets. When the store at a machine, to which a pallet should be transported, is free, the carrier should transport a pallet to it as quickly as possible (according to the FIFO rule). When there is no space in a store near a given stand, a pallet waits for a free space while at the same time blocking the input stand. Meanwhile, the carrier of horizontal transport performs other possible transport operations until an appropriate store is available. This kind of operation can lead to a lengthening of the total working time and to delays in conducting certain operations. In special circumstances (a very long estimated time of waiting for available free room in a store) the control algorithm of the horizontal transport carrier can decide that a wrong pallet has been put out. If this is the case, the carrier picks up from the output stand and transports it directly to the input stand without introducing it to the machining process.

Fig. 6 presents detailed algorithms of both the rack stacker and the horizontal transport carrier operations. The rack stacker in the first place checks whether station S_{out} is free, and if that is the case, it activates a module selecting a pallet which generates decisions about which pallet P_j should be placed on the stand S_{out}.

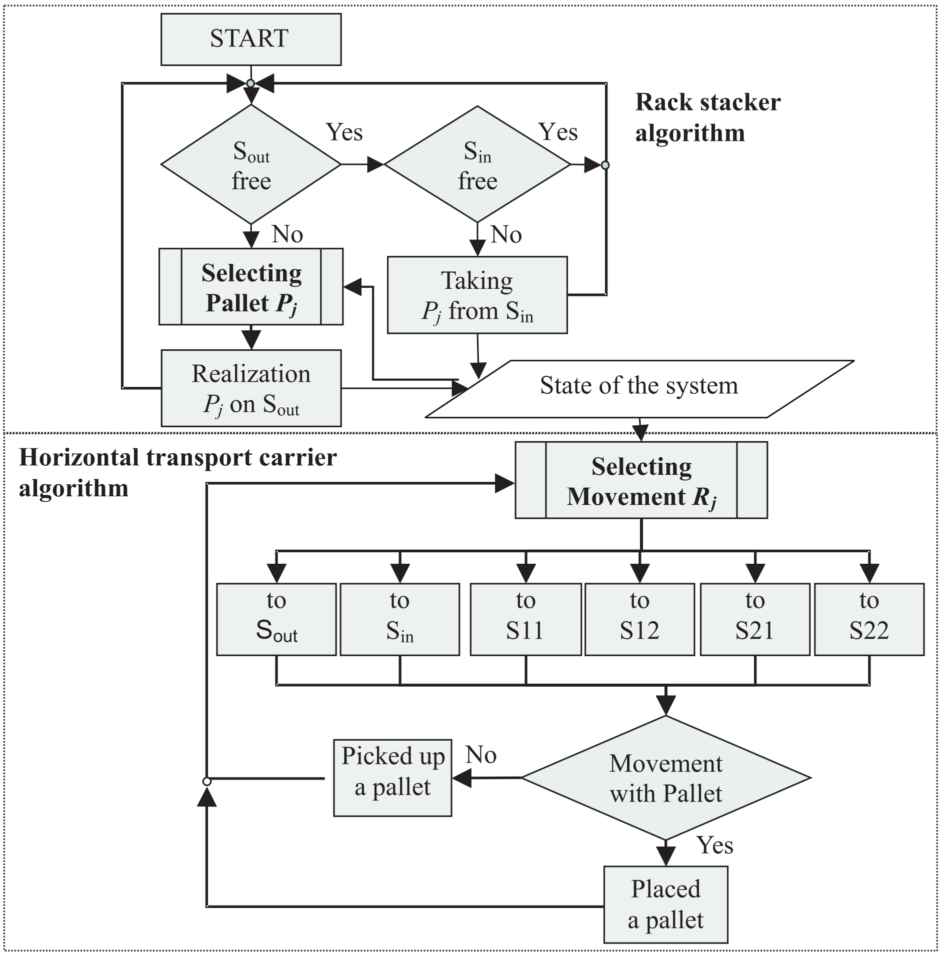


Fig. 6. The operation algorithms of the rack stacker and the horizontal transport carrier

The information about this operation is passed to a data base describing the status of the whole machining system. Having analyzed the data concerning the system's status, the algorithm controlling the horizontal transport carrier selects the optimal transport operation given the present conditions. The selected transport operation is executed, a pallet is either placed or picked up, and an inquiry information concerning the next transport operation is further transmitted.

4. Module of pallet selection supported by Fuzzy Logic reasoning

The most important and yet the most difficult element of the algorithms shown in Fig. 7 are selection modules (i.e. the pallet selection module in the rack stacker algorithm and the motion selection module in the horizontal transport carrier algorithm). Because of the difficulties in choosing an effective scheduling of pallets and transport operations, which were described in the previous section, as well as due to a necessity of finding quick and effective solutions in both modules, it was decided that Fuzzy Logic reasoning should be applied.

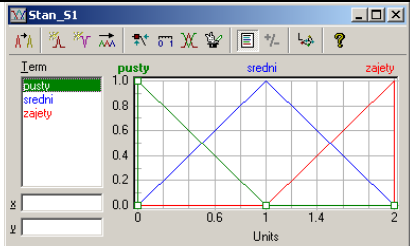
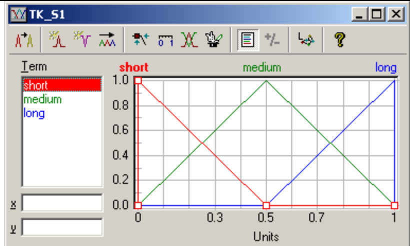
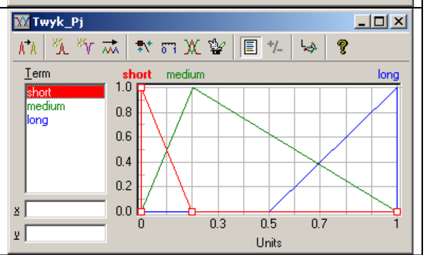
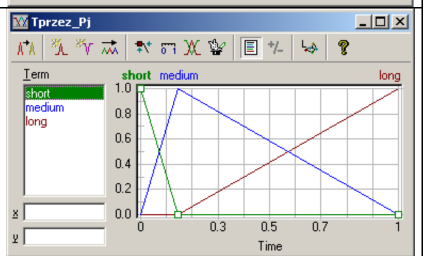
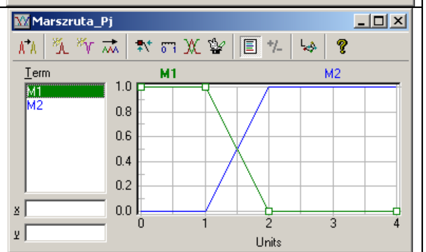
The modules based on Fuzzy Logic and selecting the "best", given the present conditions, pallet P_j and choosing the optimal transport operation consist of three stages: fuzzification, reasoning using a linguistic rule base and defuzzification. At the fuzzification stage, input variables are ascribed values of fuzzy sets that describe them. For every input variable linguistic membership functions were defined and described by means of fuzzy sets defined by triangular functions. Table 1 presents linguistic variables applied in the process of selecting a pallet as well as some model membership functions ascribed to those variables.

The application Fuzzy Logic reasoning in the algorithm controlling the operation of the rack stacker makes it possible to use linguistic rules in assessing every pallet in the rack store. Because of a high number of input variables a hierarchical structure of reasoning was applied (Fig. 7). At the first stage, on the basis of 9 variables concerning the current status of the system a decision is made whether at any given moment a pallet with a route to machine M1 or a pallet with a route to machine M2 should be selected. At the second stage, having considered such additional variables as the necessary setup time and the deadline a final selection of a pallet is conducted. A pallet with the highest final score is picked up by the stacker.

5. Simulation studies

In order to carry out simulation studies a complex model of the investigated machining system was created in eM-Planr environment. The algorithm controlling the rack stacker operation was written in Sim-Talk program language integrated with computer simulation system eM-Plant. Fuzzy-Tech program was used to develop a model based on fuzzy sets. Table 2 presents the results of simulation studies in the form of Gantt diagrams which show various situations

Table 1. Linguistic variables and membership functions ascribed to them

LP	Symbol	Description of linguistic variable	Membership functions
1	State_S1 State_S2 State_ S_{out}	State of buffers on machines: State_S1 – on M1 State_S2 – on M2. State_S_{out} – on S_{out} Values: empty, medium, occupied.	
2	TK_S1 TK_S2	Time of end of processing on: S1, S2 Values: short, medium, long	
3	Twyk_Pj	Required deadline of realization of estimated palette P_j ($j \in 1…15$) Values: short, medium, long	
4	Tprzez_ Pj	Time of rearming the machine necessary for starting the processing of palette P_j ($j \in 1…15$) Values: short, medium, long	
5	Route_Pj	Next forwarding operation of estimated palette P_j ($j \in 1…15$): M1 – movement to M1 M2 – movement to M2	

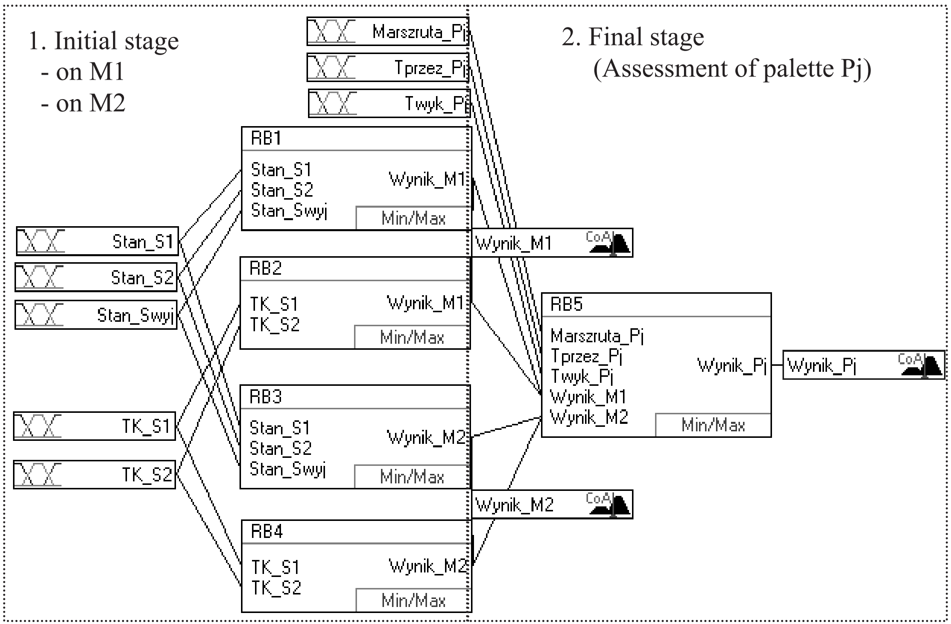


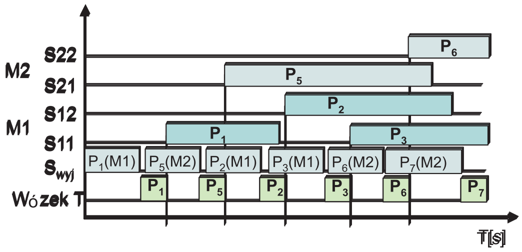
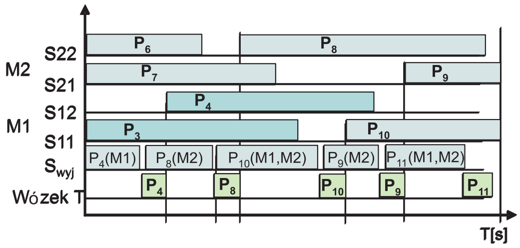
Fig. 7. The structure of Fuzzy Logic reasoning process (pallet selection)

taking place in the investigated machining system. On the basis of an analysis of the system operation it can be concluded that the module of pallet selection correctly reacts to any changes of the parameters during the system's operation. When the system starts its operation and when all the stores located near the machines are free, pallet P1 is chosen with a route to machine M1 and with the quickest performance time. Next, pallet P5 is selected with a route to machine M2 (although there are pallets with an earlier performance time, but with a route to machine M1). At the moment, when both machines are in operation, the module of pallet selection analyzes time remaining to operation completion and tries to ensure a smooth running operation of the system and meeting the deadlines.

Conclusions

The paper presents problems connected with developing algorithms controlling transport devices in flexible manufacturing systems. Within the investigated flexible manufacturing system four intelligent autonomous controlling agents have been singled out. The tasks of effective control of the rack stacker and horizontal transport carrier have been defined. The operation algorithms of these devices, which took into consideration their interrelations,

Table 2. Some results of simulation studies of the flexible manufacturing system

Lp.	Description	System's operation (Gantt chart)
1	Stage of starting. Order: P1 P5 P2 P6 P7 …	
2	Stage of stabilized work. Order: P4 P8 P10 P9 P11 …	

Set of pallets in store-house:			
Pallets	Route	Rearming time [s]	Deadline [h]
P1-P4	M1	120	8
P5-P9	M2	180	16
P10-P11	M1, M2	120, 180	24

have been presented. In the rack stacker's algorithm a particular attention was paid to the problem of selecting an appropriate pallet. In the process of selecting an appropriate pallet a fuzzy set method was proposed. Both the linguistic variables used in the reasoning process and the structure of the very process were described. The initial stage was defined, during which a preferable route is selected. Similarly, the second phase was defined, in which every pallet is assessed. The operation of Fuzzy Logic module was depicted by means of simulation studies. The investigations confirmed a possibility to apply Fuzzy Logic reasoning to develop complex algorithms controlling automated manufacturing systems. Further research should aim at developing a system that could take into consideration optional technological routes or possible machine failure.

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