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for a Virtual Enterprise**

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# COMPUTER-AIDED PROTOTYPING OF PRODUCTION FLOWS FOR A VIRTUAL ENTERPRISE

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## Abstract

This paper presents a logistics framework to cope with the problem of planning and control of production flows processed on a set of work cells distributed among component firms of a Virtual Enterprise (VE). The Constraints Theory framework is employed to study constraint-based production flow coordination rules. The article discusses relationships linking structural parameters (e.g., buffer capacity, machine tool efficiency, and automated storage/retrieval systems) of VE components with material flow control guaranteeing efficient completion of work orders, and specified by such parameters as batch delivery periods, work-in-process (WIP) and make-span. The results are summarized in the form of a performance evaluation scheme. Examples using a software package that implements the proposed flow coordination methodology are provided.

**Keywords:** Virtual enterprise, production flow, constraints theory, performance evaluation, logistics, modelling

## 1. INTRODUCTION

Modern manufacturing is characterized by short schedule horizons and small-batch production. Nowadays, the speed of decision-making is crucial [Hendry, Kingsman, 1989]. Large Manufacturing Requirements planning (MRP II) systems are implemented only in big factories with stable production, since they cannot cope with the robust character of a shop floor. Being competitive depends upon the method of organizing production flow, and, first and foremost, the time at which the method is chosen and applied. The need is observed in most small and midium batch production companies, where allocation of tasks to the resources is made according to local information. Recently, widespread interest has been shown in distributed control implementation [Perkins, Humes, Kumar, 1994]. Distributed control is characteristic of biological and holonic manufacturing [Vaario, Ueda, 1996], [Tonshoff, Winkler, Ehrnmann, 1998]; [Kawamura 1997]. The manufacturing problems addressed by those approaches can be compared to production problems in the Virtual Enterprise (VE), understood as a network of companies (supplier, concurrent firm, clients, etc). The Virtual Enterprise phenomenon has been studied extensively [Teixeira, Makatsoris, Besant, 1997], [Gornev et al., 1997], [Medina-Mora, Wong, Flores, 1992], [Sihn, von Briel, Rost, 2000], [Balic, Tusek, 2001]. Enterprise-spanning workflows that can be

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treated as a generalization of production flows require coordination encompassing specific application needs, such as those resulting from the virtual enterprise structure. Considering the complex nature of VE systems it is impossible to satisfy the requirements (such as manufacturing cycle time, delivery time and batch size limitations) of several simultaneously processed work orders and, at the same time, to decide on optimal routing, workload balancing, scheduling rules and control strategies.

Today, the central aim of producers is to increase profits and consumer satisfaction, and not to assure the satisfaction of manufacturing technology requirements. Efficient modeling and management methods (i.e., planning, scheduling and control) are needed, first to balance production tasks and manufacturing system capacity, and second, to guarantee disturbance-free utilization of resources [Hendry, Kingsman, 1989], [Kouvelis, 1992], [Ulfby, 1990], [Balic, Pahole, Cus, 2001]. The first objective is a necessary condition, while the second is a sufficient condition for assuring quick validation of market demands and reacting to them through the execution of the production tasks in a timely way. Recently, a research approach has been developed to provide a generalized framework for considering all these issues in a unified manner. This approach offers a broader perspective for evaluating system performance and for describing possible schemes for managing the workflows within a VE paradigm [Bremer, 2000].

A workflow (also called business process) consists of a set of activities that need to be executed in a particular controlled order over a combination of heterogeneous database systems and legacy systems [Leymann, Roller, 2000], [Hollingsworth, 1995]. Simply speaking, a workflow specifies a set of activities that achieve a goal and their order of execution. In particular, workflow activities display production flow characteristics determined by the parameters of VE components such as storage/retrieval, transportation, and workshop subsystems, as well as production plans encompassing batch sizing and batch delivery periods, master schedule, dispatching rules, and so on. Material flows are a prime concern within the domain of production flows. The main coordination problem is establishing the order of execution of activities and the flow of data and materials among the activities.

The objective of this paper is to present a study of coordination mechanisms for distributed production flows using a constraint theory paradigm [Goldratt, Cox, 1987], [Cox, Spencer, 1998], [Coughlan, Darlington, 1993], [Lepore, Cohen, 1999]. We focus on material flows as our main consideration. The aim is to define the relationship linking structural parameters (e.g., buffer capacity, machine tool efficiency, automated storage/retrieval systems, and so on) of Flexible Manufacturing Systems (FMS) that can be treated as VE components (enterprises, work-cells, etc.) with material flow control, guaranteeing efficient completion of work orders, and specified by such parameters as: batch delivery periods, WIP, make-span and so on. The relationship is studied within the framework of the constraint theory. The so-called critical resources (i.e., bottlenecks, or resources that are used non-stop) and critical processes (i.e., where no one operation is waiting for the execution of that particular process) are the primary constraints. In this context, the results obtained can be treated as a continuation of our earlier work [Banaszak et al., 2000], [Zaremba et al., 1999], [Zaremba, Banaszak, 1995], [Skolud, 2000].

The paper first describes the application in which the production flow modeling and management problems occur. Next, it reviews the constraint-based production flow-planning scheme. Third, flow control generation and its correctness are discussed. Fourth, implementation of the scheme proposed for the design and operation of the software package developed is

introduced. The results of computer-based experiments are presented. Finally, the possibility of evaluation of VE integration and further research questions are discussed.

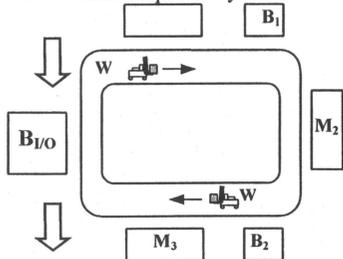
## 2. PRODUCTION FLOW MANAGEMENT

### 2.1. Concurrent flow coordination

Efficient planning and scheduling methods are needed that would balance production tasks and the manufacturing system capacity, and assure quick validation of market demands and reaction to them by execution of the production tasks in a timely manner [Pinedo, 1995], [Vandaele, 1997]. For the sake of simplicity, further consideration is restricted to production flows observed on an FMS level.

The illustrative example presented below shows production flow coordination and the influence of constraints (resource constraints such as resource capacity, and buffer space allocation, as well as logistic constraints, e.g., transport frequency and vehicle capacity) on production flows, their rhythmic character and the production system efficiency.

**Illustrative example.** Let us consider an FMS composed of a set of machine tools  $\{M_1, M_2, M_3\}$ , a set of buffers  $\{B_{I/O}, B_1, B_2\}$ , and a set of automated guided vehicles  $\{W_1, W_2\}$ , as is shown in Fig. 1. Given a production order determined by a production volume  $Q = 100$  items (each one processed along the production route  $B_{I/O} - M_1 - B_1 - M_2 - B_2 - M_3 - B_{I/O}$ ), and expected realization time  $T = 650$  units of time. Let us assume that operation times are equal to 3, 6, and 4 units of time respectively on machine tools  $M_1, M_2$ , and  $M_3$ . Pre-set times are equal to zero.



Legend:

$M_i$  – the  $i$ -th machine tool

$B_i$  – the  $i$ -th buffer

$W_i$  – the  $i$ -th automated guided vehicle

Fig. 1. An FMS structure.

**Case.1.** Consider the case where the capacities of buffers  $B_1$  and  $B_2$  are equal to zero. The transportation times are also equal to zero. The corresponding production flow is shown in a Gantt's chart in Fig. 2 (a). It is easy to see that  $M_2$  represents a bottleneck limiting the production flow. The corresponding production time is equal to 1 item  $\times$  3 units + 100 items  $\times$  6 units + 1 item  $\times$  4 units = 607 units of time. However, production capacity is still available on  $M_1$  and  $M_3$ . The question is how to exploit this available capacity, for instance to process a production order (with a volume of 50 items) specified by the production route  $B_{I/O} - M_1 - B_1 - B_2 - M_3 - B_{I/O}$ , and operation times lasting 5 and 4 units of time, respectively.

Because buffer capacity is equal to zero, the only allowed batch size is equal to 1. The reason the conditions assumed do not allow another production order to be accepted is the occurrence of two new bottlenecks, in that machine tools  $M_1$  and  $M_3$  limit the production cycle to a period of 8 units of time. This results in a delay of the first production order time (50 items  $\times$  8 units + 50 items  $\times$  6 units = 700 units of time). Note that such minimal period can be obtained only under the assumption that the capacity of buffer  $B_2$  is greater than zero. The buffer capacity constraint and the bottleneck period thus limit the batch sizes of a production flow.

**Case 2.** Consider the situation when the buffer capacity constraint is released, i.e., assume that each buffer's capacity is equal to 1. The production flow for a batch size of two items is

considered as in Fig. 2 (b). This time, the bottleneck period is the same as in Case 1 (equal to 6 units); however, the time slots available on machine tools  $M_1$  and  $M_3$  are twice as long. This results in a new admissible organization of two production flows, see Fig. 2 (c).

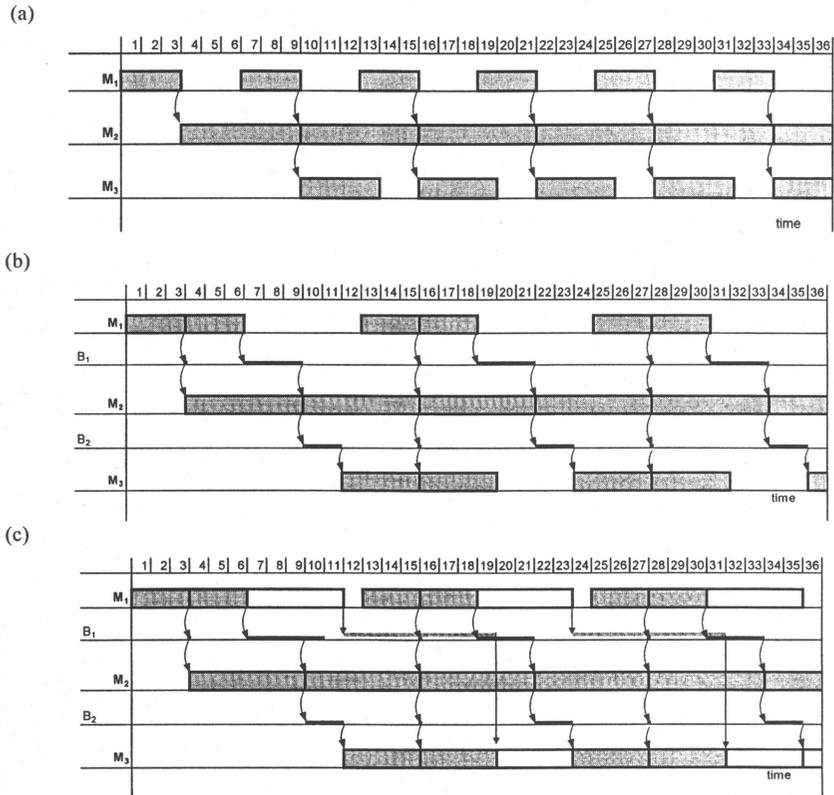


Fig. 2. Gantt's charts for production flow organization.

In order to summarize the example considered let us note the following:

- The occurrence of bottlenecks implies that the production flow has a rhythmic character. So, the assumption imposing rhythmic (i.e., cyclic) batch delivery implies a smooth (i.e., deadlock-free and starvation-free) production flow, but can result in a lower rate of system resource utilization.
- Planned (i.e., scheduled) production flows can be executed either in centrally supervised (i.e., according to a master schedule) or in distributed (i.e., according to assigned dispatching rules) regime. When manufacturing process disturbances occur (i.e., there is a delay or acceleration of technological and/or material transportation/handling operations), the centrally supervised production flow control enables better utilization of system resources.

In further considerations, the distributed control of production flows is assumed [Gausemeier, Gehnen,1997], [Kim, et al., 2001]. By a procedure of distributed flow control, we mean a set of dispatching rules each of which is assigned to a resource shared by processes (flows)

competing for access to it. Thus when we speak of a **dispatching rule**  $\sigma_i$  regulating access to the  $i$ -th shared resource, we mean the finished, repetitive sequence of operations  $\sigma_i = (Pa_1, Pa_2, \dots, Pa_j, \dots, Pan)$  that determines the number of processes executed on the  $i$ -th shared resource, where  $Pa_j$  denotes process,  $i \in \{1, 2, \dots, m\}$ ,  $m$  – the number of resources,  $a_j \in \{1, 2, \dots, n\}$ ,  $n$  – the number of processes. For the purpose of illustration, let us consider processes  $P_1$ ,  $P_2$  and  $P_3$  that compete for access to resource  $M_1$ , see Fig. 3 a). Given dispatching rule  $\sigma_1 = (P_1, P_1, P_3, P_2)$  guarantees access to resource  $M_1$  twice for process  $P_1$ , once for process  $P_3$  and once for  $P_2$ , as in Fig. 3 (b).

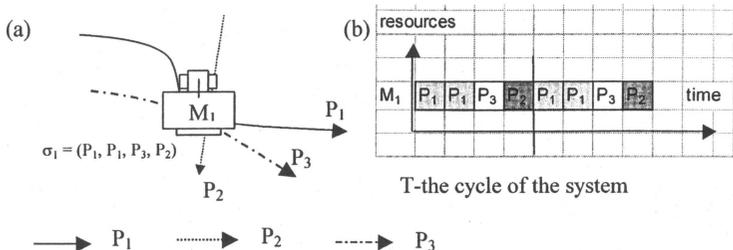
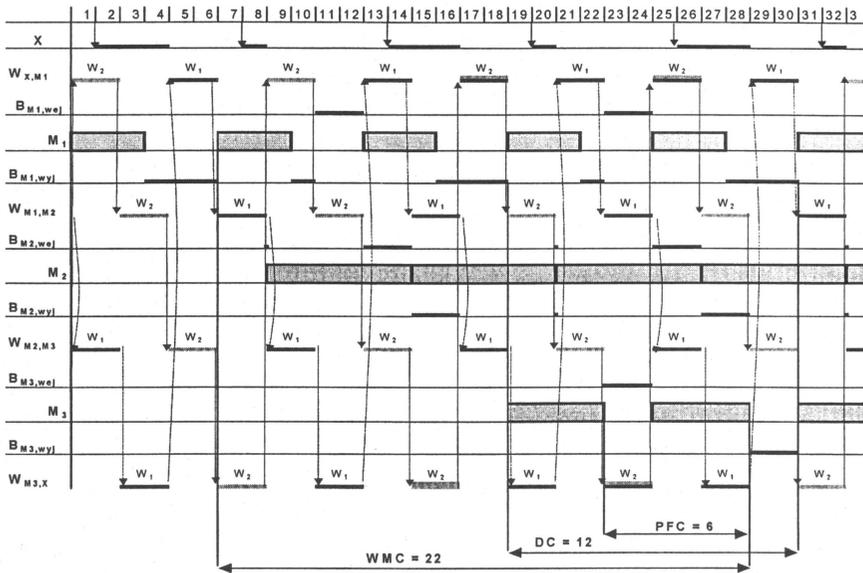


Fig. 3. Dispatching rule assigned to resource  $M_1$ .

Let us note that the selection of buffer capacity and batch sizes provides a way to control the time slots of production capacity available at a particular (non-critical) resource. By a critical resource we mean a resource processing non-stop, i.e., limiting the system throughput [Marcus P., Meleton Jr., 1986]. So, if a given system throughput cannot be changed and yet available production capacity has to be rearranged (so that a new production order can be handled), buffer capacity and batch sizes can be appropriately determined. Moreover, as a consequence of bottlenecks, the resultant material flows have a rhythmic character, determined by the cycle of bottleneck occurrences [Fawcett, Pearson, 1991].

This observation implies the assumption that a steady-state periodic behavior is imposed on the whole FMS. At the same time, however, batch sizes are limited by delivery constraints, i.e., by delivery periods, and delivery batch sizes. In order to evaluate an FMS performance in terms of admissible cyclic steady-state behavior, let us introduce the concepts of a critical resource and a critical process [Zaremba, Banaszak, 1995]. By a critical resource we mean a resource being processed non-stop, i.e., one limiting the system throughput. It is assumed that component operations of the critical process are not suspended. So, performance evaluation measures such as the cycle time or the rate of system resource utilization can be seen as a function of the above-mentioned constraints.

**Illustrative example.** Now, let us take into account the equipment responsible for batch delivery. Consider the case where two AGVs, each with a capacity of one item, are employed. The issue here is designing the AGVs delivery timetable determined by critical resources. Suppose the production flow is as shown in Fig. 2 (a). Assuming a given time (the same for both AGVs) required to pass between  $B_{I/O}$  and  $M_1$ ;  $M_1$  and  $M_2$ ;  $M_2$  and  $M_3$ ;  $M_3$  and  $B_{I/O}$  that is equal to 2 units of time, it is quite easy to find the relevant cyclic AGVs' timetable (see Fig. 4).



Legend:

$W_{M_i, M_j}$  – a part of path linking  $M_i$  and  $M_j$ ,  $M_i$  – the  $i$ -th machine tool,  $W_j$  – the  $j$ -th AGV,  $B_{M_i, i}$ ,  $B_{M_i, 0}$  – the input and the output buffer of the  $i$ -th machine tool,  $X$  – the system storage, PFC – production flow cycle, WMC – work piece manufacturing cycle (WIP), DC – delivery cycle.

Fig. 4. Gantt's chart for delivery flow for the production order from Fig. 2 (a).

Each vehicle is loaded and unloaded at the resources (machine tool and/or buffer) placed along the production route. To simplify the computations, the load/unload operations are assumed to be equal to 0. Moreover, in the case considered it is easy to see that each AGV services the system resources rhythmically, with a cycle time equal to 8 units. The phase between the AGVs is equal to 4 units, i.e., each resource can be serviced every 4 units. It should be noted that this transportation process can be treated as a critical one. Moreover, the critical process provides transportation service in accordance with production flow requirements imposed by a critical resource.

To summarize, it is clear that material flows are limited by the efficiency of machine tools (processing items) and logistics constraints of the available transportation/storage facility. In terms of constraints, the above situation can be seen as a case dominated by a resource bottleneck (delivery processes are not critical), as a case dominated by critical delivery processes (no critical resources) or as a case where both critical resources and critical processes co-exist with each other.

In the rest of the paper, it is assumed that the delivery process has higher priority. This means that the solution obtained for the problem stated below is valid for cases dominated by the delivery systems.

## 2.2. Modeling

The main activity of the partners co-operating within a VE is the execution of their own production orders. Usually, only a part of the production capability is available for common use in the VE.

**Resources and orders.** Let us consider a set of  $K$  independent firms,  $F_1, F_2, \dots, F_K$ . Each firm consists of a set of resources  $N_i$ , where  $i \in \{1, 2, \dots, K\}$ .  $R_{ik}$  denotes the  $k$ -th resource from the  $i$ -th firm, where  $i \in \{1, \dots, K\}$ ,  $k \in (1, \dots, N_i)$ ,  $N_i$  – number of resources. The partner firms co-operating within a VE are described by  $V_j = (v_{1j}, \dots, v_{hj}, \dots, v_{Bj})$ , i.e., a vector of resources belonging to the set of resources  $C_p$ . The set  $C_p$ ,  $p \in \{1, \dots, L\}$  contains the resources necessary to complete the  $O_j$ -th production order. Each set  $C_p$  consists of subsets containing elements relating to the same kind of operation, e.g., milling, assembly, transportation, storage, etc. Elements of each subset can be alternatively used in order to execute a relevant operation from the  $n$ -th production routing  $MR_n = (OP_{n1}, \dots, OP_{ni}, \dots, OP_{nK})$ , where  $OP_{ni}$  is the  $i$ -th operation executed in the workshop of the  $n$ -th firm.

### Logistics constraints

Logistics constraints take into account both the traffic route network, and the storage/transportation facility at a shop level. This means that material flows among the co-operating firms are constrained by route network parameters (e.g., network topology and capacity) and transportation means including tracks, containers, supply/delivery timetables, etc. Similar constraints can be considered at the shop level, where certain facility limits, derived for instance from an Automated Guided Vehicle System (AGVS) or a warehouse/buffer subsystem, have to be taken into account.

The resultant VE is created to complete a set of production orders  $\{O_j, j \in \{1, 2, \dots, M\}\}$ , where  $M$  is the number of production orders. Each production order is defined by the transportation routing  $TR_i = (F_1, \dots, F_i, \dots, F_K)$ , i.e., a sequence of firms in which production order  $O_j$  has to be processed, where  $F_i$  is the  $i$ -th component firm. Each production flow can thus be treated as a sequence of alternately executing transportation-delivery and manufacturing actions. The manufacturing actions, in turn, can be seen as the execution of particular work orders.

In other words, each transportation (production) routing is specified by a sequence of firms involved in the execution of a given production order (a sequence of subsets of shop resources required on a given stage of a transportation routing) and an operational time required for the execution of particular stages in the transportation (production) routing.

**Model specification.** Finally, it is assumed that each production order is specified by the following parameters:

$TB_j$  – the beginning time of work order  $O_j$ ,

$TE_j$  – the completion time of the work order  $O_j$ ,

$Q$  – production quantity,

$I_j$  – the size of production series processed for the production order  $O_j$ ,

$TR_i = (F_1, \dots, F_i, \dots, F_K)$  – the transportation route, where  $F_i$  is the  $i$ -th component firm.

The requirements imposed by storage/transportation facilities are characterized by the following parameters:

$C_{i/I}, C_{i/O}$  – the capacity of the input and the output storage  $B_{i/I}, B_{i/O}$  of the  $i$ -th firm

$T_{F_i, F_j}$  – the transportation time required for delivery between  $F_i$  and  $F_j$ .

$TC_{F_i, F_j}$  – the track capacity servicing delivery between  $F_i$  and  $F_j$ ,

$DS_{F_i, F_j}$  – the size of the delivery batch between  $F_i$  and  $F_j$ .

Similar assumptions apply to each work order  $W_n$  executed in a particular component firm, i.e., the  $n$ -th work order is specified by:

$MR_n = (OP_{n1}, \dots, OP_{ni}, \dots, OP_{nK})$  – the  $n$ -th manufacturing routing, where  $OP_{ni}$  is the  $i$ -th operation executed in the  $n$ -th firm's shop,

$Z_{ni} = (z_{ni1}, \dots, z_{nip}, \dots, z_{niL})$  – the vector of operation times  $z_{nip}$  associated with the  $p$ -th machine tool  $M_p$  that is used to execute the  $i$ -th operation occurring along the  $n$ -th production routing.

The requirements imposed by the storage/transportation facility at the shop level are characterized by the following parameters:

$T_{Mi,Mj}$  – the transportation time required for delivery between  $M_i$  and  $M_j$ ,

$TC_{Mi,Mj}$  – the track capacity servicing delivery between  $M_i$  and  $M_j$ ,

$C_{i/I}, C_{i/O}$  – the capacity of the input and the output buffers  $B_{i/I}, B_{i/O}$  of the  $i$ -th machine tool

$J_j$  – the batch size of the  $i$ -th work order  $W_i$ ,

$D_{Mi,Mj}$  – the size of the delivery batch between  $M_i$  and  $M_j$ .

The two-level model of a VE presented above requires specification of the structural data describing the set of firms (including storage facilities), sets of machine tools (including buffers), and the transportation/delivery system (including vehicle capacity) as well as a specification of production orders (including such requirements as the order cycle and the transportation and production routings). The answer to the question whether the requirements imposed by a production order specification can be met within the structure of a given VE depends on the possible organization of the production flow and the local work flows at individual firms. That is because the resulting order cycle depends on flow management, i.e., series and batch sizes as well as transportation batch sizes (at both inter-company and inter-workstation levels).

It has been shown that system performance (such as throughput rates and order cycle) depends not only on the effectiveness of the component elements (firms, machine tools, transportation/delivery means), but also on the synchronization of their interconnections. Such constraints can be seen as specific bottlenecks limiting the flows. As a consequence of the bottleneck occurrence, the flows have a rhythmic character, determined by bottleneck constraints. This observation implies the assumption of a steady-state periodic behavior imposed on the whole VE.

An important question now facing us is: How can we evaluate whether a storage and transportation means on hand could be arranged in a way that will not limit the system throughput? The key issue is how to evaluate whether such storage and transportation means could be organized so that available production capacity could be rescheduled to accept a new work order.

Answers to these questions depend on synchronization between two critical processes: material flow (specified by a relevant batch size and a period of access to a critical resource), and transportation flow (specified by delivery batch sizes, delivery period, number of pallets, and number of AGVs and their capacity). The approach proposed here assumes that an admissible synchronization has to balance a given system throughput rate with material handling capacity.

### 2.3. Problem formulation

The main objective of a production flow management system is the co-ordination of processes and activities related to work order processing, transportation, inventory management, warehousing and production. In other words, the goal is to achieve a well-synchronized behavior of dynamically interacting components, where the right quantity of the right material is provided

in the right place, and at the right time. In order to meet these objectives, however, many different aspects of production flow relating, for instance, to the capacity of available AGVs and/or local buffers, allocation of working cells and warehouses, production routings and guide paths, have to be taken into account.

The following problem can be now considered. Take a manufacturing system providing spare production capacity while processing some work orders. Only a part of the production capability is available for use in the VE system. Given that the repetitive character of production flow results from a critical resource and/or critical process occurrence, how can we determine whether a particular production order can be completed within the prescribed order cycle in the given system while guaranteeing that the due time of already executed work orders will remain unchanged?

Note that the assumption imposing repetitive, cyclic delivery implies smooth (i.e., deadlock-free and starvation-free) traffic flow, but limits the production flow. So, in order to guarantee the required quality flow, let us assume that only critical resources and/or critical processes limit the material flows. In other words, let us assume that the material flows are limited by the efficiency of machine tools (processing items) and logistics constraints of the available transportation/storage facility. That is, because the constraints such as buffer capacity, technological equipment output and AGVs have to be treated as bottlenecks limiting the system throughput and resulting in a kind of repetitive material flow with the cycle time constrained by a bottleneck cycle time, i.e., specified by the batch size and its delivery period.

From the above perspective, the problem under discussion can be seen as a problem of synchronizing critical resources and processes constraining the production flow.

**Flow synchronization.** Besides the above-mentioned quantitative requirements of production flow synchronization, some qualitative requirements have to be taken into account. Our assumption concerning the periodic character of material and transportation means that a deadlock-free and starvation-free process execution is guaranteed, however, we still have to deal with the problem of how to find such periodic processes.

The computational complexity of the problem is the same as for a task-scheduling problem under limited buffer-capacity constraints. So, because the problem is NP-hard, the approach proposed assumes that the transportation/delivery processes have higher priority.

AGVs move along their particular transportation routes periodically (i.e., each AGV has its own route, and a period determined by the available speed, the route length, the number of load/unload operations and the specific operation time required). Of course, the routes and periods are planned so as to guarantee the required quality of AGV traffic, namely that it should be simultaneously collision-free and deadlock-free. In other words, the transportation/delivery processes dominate over material flows. Consequently, the production batch sizes are selected in order to match delivery batch sizes and delivery periods.

An alternative approach to the above, assuming that delivery periods play a crucial role in the production flow co-ordination, is to assign a leading role to local (i.e., characteristic of the particular machine tools or work-cells) bottlenecks that synchronize the delivery/transportation flows. Other factors that have to be taken into account in the course of flow synchronization are buffer capacity allocation and vehicle capacity. It is easy to see that different capacity allocations may result in the same throughput rate, e.g., large buffer capacity can be replaced by more frequent AGV servicing. Moreover, capacity allocation restricts the scope of possible delivery and production batch sizes.

### 3. PRODUCTION PLANNING

#### 3.1. Production capability validation

The balancing of production capability and work order requirements, i.e., an available production capacity of component firms as well as a material delivery transportation system linking them, plays a crucial role in the course of validation of possible VE configuration variants. In order to present the conditions guaranteeing such a balance let us consider the VE configuration as shown in Fig. 5.

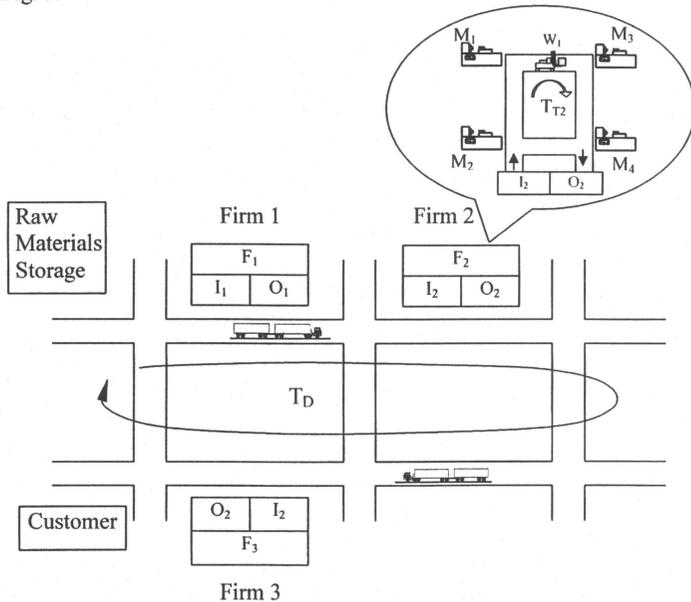
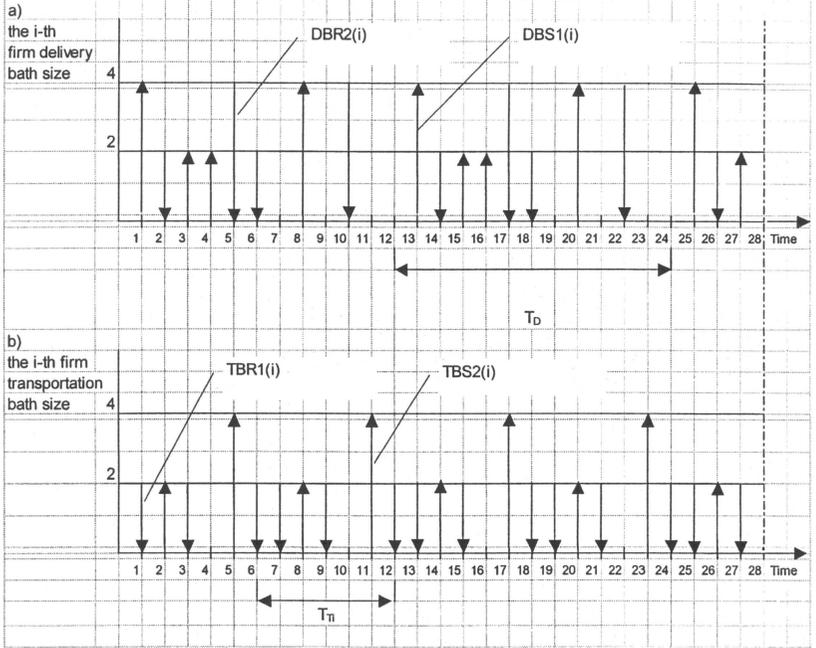


Fig. 5. An example of two-level production flow structure.

A repetitive, track-based transportation system supports a production flow following the material transportation routing specified by the sequence of component firms  $F_1, F_2, F_3$ . Each  $i$ -th firm  $F_i$  is equipped with an input buffer  $I_i$  capacity of  $C(I_i)$ , and an output buffer  $O_i$  capacity of  $C(O_i)$ . Both kinds of buffers are shared by batch delivery (track-based transportation system) and the relevant AGV-based material handling system. It is assumed that the subsequent delivery batches can be of different volumes, however, they all have the same cycle equal to  $T_D$ . So, the possible structure of the cyclic, track-based transportation system can be graphically illustrated as shown in Fig. 6 (a). A similar assumption applies to a local, i.e., shop level, supported by an AGV system, and is specified by a cycle time equal to  $T_{Ti}$ . The relevant illustration of the possible transportation batches structure is shown in Fig. 6 (b).

It is easy to see that since the considered material transportation/delivery systems act periodically, hence the whole system (determining a production flow) has a cyclic character, and

its cycle  $T$  is determined by ECM of the component period, i.e., determined by the following formulae:  $T = \text{LCM}\{T_D, T_{T1}, T_{T2}, \dots, T_{Ti}, \dots, T_{Tn}\}$ , LCM – states for the lowest common multiple.



Legend:

$\text{DBS}_j(i)$  ( $\text{DBR}_k(i)$ ) – size of the  $j$ -th (the  $k$ -th) delivery batch sent by a track-based system (released from) to an input (output) buffer of the  $i$ -th firm

$\text{TBS}_m(i)$  ( $\text{TBR}_l(i)$ ) – size of the  $m$ -th (the  $l$ -th) transportation batch sent by an AGV system (released from) to an input (output) buffer of the  $i$ -th firm

$j, k$  ( $m, l$ ) – state of indices determining the relevant batch number within the period  $T_D$  ( $T_{Ti}$ )

Fig. 6. Schedule of delivery batch sizes; (a) track-based transportation system, (b) AGV-based material handling system.

Moreover, the cycle time  $T$  can be treated as balancing time horizon. The following conditions have to hold for each firm  $F_i$  in order to guarantee that the same quantity of goods have been sent to and released from  $F_i$  within the given time horizon  $T$ .

$$(i) \quad T/T_{Ti} \sum \text{DBR}_k(i) = T/T_D \sum \text{TBS}_m(i), \quad k \in \{1, \dots, K\}, \quad m \in \{1, \dots, M\},$$

$$(ii) \quad T/T_{Ti} \sum \text{DBS}_j(i) = T/T_D \sum \text{TBR}_l(i), \quad j \in \{1, \dots, J\}, \quad l \in \{1, \dots, L\},$$

$$(iii) \quad T/T_D \sum \text{DBR}_k(i) = T/T_D \sum \text{DBS}_j(i),$$

where:

$K, J$  ( $M, L$ ) – states for a number of batches released from and sent to the  $i$ -th firm, respectively within the period  $T_D$  ( $T_{Ti}$ ).

Due to condition (i), the number of items released from the output buffer and sent to it within the planning horizon have to be the same. Similarly, due to condition (ii), the number of items sent to the input buffer and released from it within the planning horizon have to be the same. The quantity of items sent and released has to be the same due to condition (iii).

In order to take into account limitations imposed by the buffer capacity constraints let us consider the time horizon T. Consider a set of events of cardinality of IE associated with input buffer  $I_i$ . Let  $u \in \{1, \dots, IE\}$  be the number of an event corresponding either to sending of a delivery batch or to releasing of a transportation batch or to both simultaneously.

The following condition has to hold for every i-th firm in order to guarantee that the i-th input buffer capacity will not be overloaded within the time horizon T.

$$C(I_i) \geq \begin{cases} f_j(I_i) & \text{if the } j\text{-th event corresponds either to sending or to releasing of a batch} \\ f_{j-1}(I_i) + DBS_j(i) & \text{if the } j\text{-th event corresponds simultaneously to delivery and releasing of a batch} \end{cases}$$

where

$$f_j(I_i) = f_{j-1}(I_i) + \begin{cases} DBS_j(i) & \text{if the } j\text{-th event corresponds to sending of a batch} \\ - TBR_j(i) & \text{if the } j\text{-th event corresponds to releasing of a batch} \end{cases}$$

$f_j(I_i)$  - means the j-th state of the input buffer corresponding to the j-th event within the time horizon T.

A similar condition has to hold, of course, for each output buffer.

$$C(O_i) \geq \begin{cases} f_j(O_i) & \text{if the } j\text{-th event corresponds either to sending or releasing of a batch} \\ f_{j-1}(O_i) + TBS_j(i) & \text{if the } j\text{-th event corresponds simultaneously to delivery releasing of a batch.} \end{cases}$$

where

$$f_j(O_i) = f_{j-1}(O_i) + \begin{cases} - DBR_j(i) & \text{if the } j\text{-th event corresponds to sending of a batch} \\ TBS_j(i) & \text{if the } j\text{-th event corresponds to releasing of a batch} \end{cases}$$

$f_j(O_i)$  - means the j-th state of the output buffer corresponding to the j-th event within the time horizon T.

The presented conditions have an iterative form encompassing dynamic changes of buffer occupation.

In the general case, i.e., for a given VE configuration, the above conditions have to hold simultaneously for each component firm's buffer along a transportation routing. However, when such a balance cannot be achieved, some adjustments regarding for instance a buffer capacity change, and/or delivery batch sizing and/or batch delivery periods, still can be undertaken. It should be noted, however, that delivery batches on an inter-company level are limited by constraints of means (e.g., their number, their capacity and speed), and batch sizes and delivery periods are limited by the AGVS constraints as well as production batch characteristics stemming from both the productivity of the machine tools and the capacity of their local buffers.

### 3.2. Flow control

This section discusses a modelling framework for design of the distributed control procedure based on the concept of dispatching rule assignment is discussed [Skolud, Banaszak, Zaremba, 2000]

**Priority rules' assignment.** The problem we face now is the following one. For a given manufacturing system of concurrent processing of given work orders, the production is characterised by a cyclical behaviour with cycle  $T$  at steady state. To avoid the starvation problem the local dispatching rule (see par.2.1) should be allocated to each common resource. However arbitrary allocation of the rule to resources may provoke a deadlock. Only when the balance of the process flow in the system and sufficient buffer capacity are achieved will the deadlock not be provoked in the system at steady state.

The procedure for designing a dispatching rule for a given steady-state production flow consists of the following steps:

1. *Given a system composed of  $m$  resources where  $n$  processes have to be concurrently executed,*
2. *Assign each process once to each rule allocated to resources along the production route,*
3. *Check the balance constraint.*

The balance condition assures that the number of processes entering the system is equal to the number of processes leaving the system in one cycle. The balance of the system is achieved if for any shared resource the following equations hold:

$$\begin{aligned} \chi_1 n_{1,1} &= \chi_2 n_{2,1} = \dots = \chi_i n_{i,1} = \dots = \chi_m n_{m,1}, \\ \chi_1 n_{1,2} &= \chi_2 n_{2,2} = \dots = \chi_i n_{i,2} = \dots = \chi_m n_{m,2}, \\ &\dots \\ \chi_1 n_{1,j} &= \chi_2 n_{2,j} = \dots = \chi_i n_{i,j} = \dots = \chi_m n_{m,j}, \\ &\dots \\ \chi_1 n_{1,n} &= \chi_2 n_{2,n} = \dots = \chi_i n_{i,n} = \dots = \chi_m n_{m,n}, \end{aligned}$$

where:

$\chi_i$  – repetitiveness of the dispatching rule allocated to the  $i$ -th resource,

$n$  – number of processes operating in the system,

$m$  – number of resources in the system,

$n_{i,j}$  – repetitiveness of the  $j$ -th process in the dispatching rule allocated to the  $i$ -th resource.

4. *Check the buffer capacity constraint.*

The buffer capacity constraint requires that the capacity  $C_{S_{i,k}}$  of any buffer allocated between two subsequent resources  $M_i$ , and  $M_k$  satisfy the following condition:

$$C_{S_{i,k}} \geq n_{i,j} \cdot \chi_i,$$

where:

$C_{S_{i,k}}$  – capacity of the buffer,

$n_{i,j}$  – repetitiveness of the  $j$ -th process in the dispatching rule allocated to the  $i$ -th resource.

5. *Determine the cycle time  $T$ .*

$$T = \text{MAX}(\chi_1 \tau_1, \chi_2 \tau_2, \dots, \chi_i \tau_i, \dots, \chi_m \tau_m.)$$

6. *Check the constraint of due time production order completion.*

The constraint of due time production order completion requires that the following condition is satisfied:

$$tz_j - \left( to_j + \frac{I_j T}{Q_j} \right) \geq 0,$$

where:

$to_j$  – the beginning moment of the  $j$ -th order realization,

$tz_j$  – the expected realization time,

$I_j$  – the number of elements,

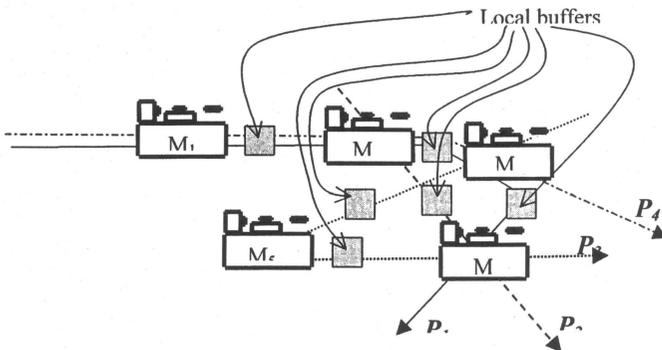
$Q_j = n_{i,j} \chi_i$  – the number of elements executed during  $T$ .

7. If the process cannot be executed in due time, increase the number of appearance of processes in rules allocated to resources on its production route and go to step 3. STOP if the condition in step 6 applies.

In order to illustrate the above procedure, let us consider a manufacturing system composed of 5 machine tools  $M_1, M_2, M_3, M_4, M_5$ . Assume the production orders  $Z_1, Z_2, Z_3, Z_4$  are specified by processes  $P_1, P_2, P_3, P_4, P_5$  and queued for execution by the system. Assume that the system is not busy. The production routes are illustrated in Fig 7. Process parameters are specified in Table 1.

Table 1. Production orders

Production order	Series size	Expected completion time	Number of operations
$Z_1$	20	250	4
$Z_2$	10	150	2
$Z_3$	20	250	3
$Z_4$	30	250	3



Legend:

$M_1, M_2, M_3, M_4, M_5$  – machine tools;

---▶ production route of the work order  $P_1$ ;

.....▶ production route of the work order  $P_2$ ;

.....▶ production route of the work order  $P_3$ ;

Fig. 7. System of concurrently executed production flows.

Between each pair of subsequent resources there exists a buffer with a capacity equal to 2. The following matrices describe processes expected to be performed in the system:

$$MP_1 = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 2 & 4 & 3 & 2 \\ 1 & 1 & 0 & 0 \end{bmatrix} \quad MP_2 = \begin{bmatrix} 2 & 4 \\ 2 & 2 \\ 1 & 1 \end{bmatrix} \quad MP_3 = \begin{bmatrix} 3 & 5 & 4 \\ 2 & 3 & 1 \\ 0 & 0 & 0 \end{bmatrix} \quad MP_4 = \begin{bmatrix} 1 & 2 & 3 \\ 2 & 2 & 1 \\ 0 & 0 & 1 \end{bmatrix}$$

The first row of the matrix describes the number of the resource (the process route), the second row represents operations time and the third row represents pre-set time.

According to the procedure, each process is assigned once in dispatching rules allocated to resources along its route. Rules are the following:  $\sigma_1(P_1, P_4)$ ,  $\sigma_2(P_1, P_2, P_4)$ ,  $\sigma_3(P_1, P_3, P_4)$ ,  $\sigma_4(P_1, P_2, P_3)$ ,  $\sigma_5(P_3)$ . Both the system balance and the buffer capacity conditions are satisfied. For such dispatching rules the cycle time is  $T=10$ . Realization times for each production order are:  $t(Z_1) = 200$ ,  $t(Z_2) = 100$ ,  $t(Z_3) = 200$ ,  $t(Z_4) = 300$ . Because  $Z_4$  is slower than expected, increasing the  $P_4$  repetitiveness in rules allocated to resources occurring along its manufacturing route is proposed. New dispatching rules are:  $\sigma_1(P_1, P_4, P_4)$ ,  $\sigma_2(P_1, P_2, P_4, P_4)$ ,  $\sigma_3(P_1, P_3, P_4, P_4)$ ,  $\sigma_4(P_1, P_2, P_3)$ ,  $\sigma_5(P_3)$ . Both the system balance and the buffer capacity conditions hold here. In this case the cycle time is  $T=12$ . Realization times of each production order are:  $t(Z_1) = 240$ ,  $t(Z_2) = 120$ ,  $t(Z_3) = 240$ ,  $t(Z_4) = 180$ . This means that due time realization of all processes is possible. The Gantt's chart (see Fig.8) illustrates the steady-state behaviour of the system when processes are realized according to the assigned dispatching rules

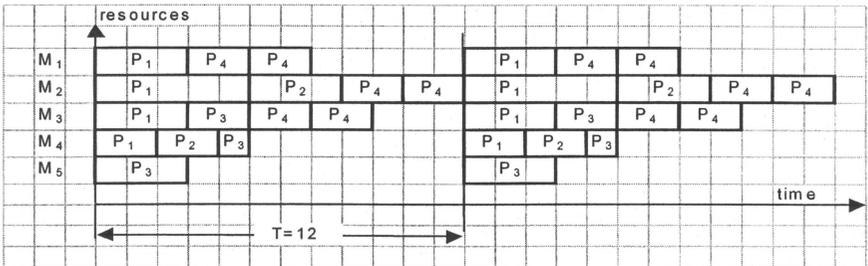


Fig. 8. Gantt's chart illustrating the steady state of the production flow

### Procedure for construction of the starting-up dispatching rule

The procedure presented in the previous section makes it possible to validate the capacity of the production system for due time realization of given production orders. However, we must be aware that starting the system functioning according to such allocated dispatching rules without considering any starting phase (starting conditions) may provoke a cycle of mutual expectations and in consequence provoke a deadlock.

In order to illustrate this problem, let us consider a system composed of 3 machine tools  $M_1$ ,  $M_2$ , and  $M_3$ , where processes  $P_1$ ,  $P_2$ ,  $P_3$  follow the production routes as shown in Fig. 9. Operating time for each operation is equal to 2 units of time. The following dispatching rules  $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$  are allocated.

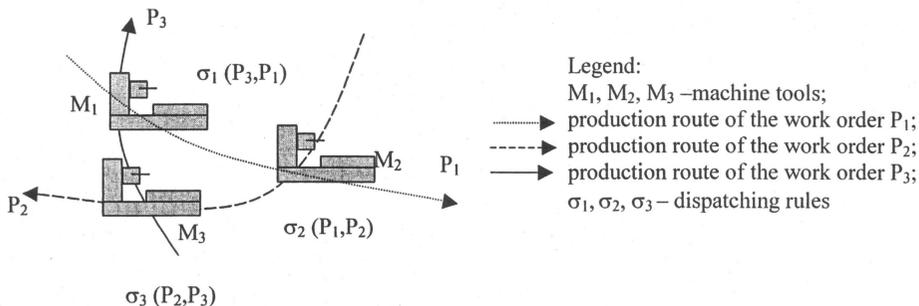


Fig. 9. Production flow structure

It is easy to see that the processes cannot operate according to the established dispatching rules. That is because on resource  $M_1$ , the process  $P_3$  should be executed as the first process. The operation should be then preceded by the operation realised on the machine tool  $M_3$ . In turn, the operation processed by  $P_3$  on the  $M_3$  should be preceded by  $P_2$  (see the dispatching rule). So, the preceding operation along the  $P_2$  production route is realized on  $M_2$ , but its execution on  $M_2$  is possible only if  $P_1$  has been executed. As a consequence, process  $P_1$  cannot continue because of the dispatching rule structure assigned to machine tool  $M_1$ . Finally, a closed cycle of mutual waits appears, that results in a deadlock.

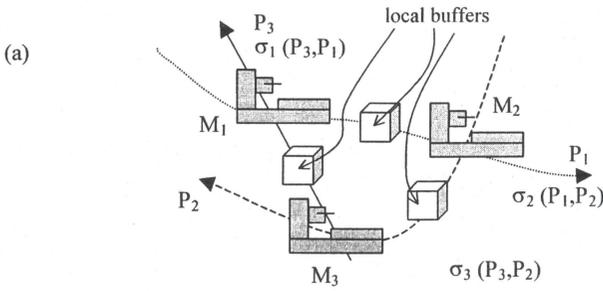
In order to avoid such cases the relationship between an initial production flow allocation and assumed dispatching rules should be considered. The problem is how to find a synchronization mechanism guaranteeing a system the start-up conditions to reach the desirable steady-state cyclical behaviour.

Note that in the general case, execution of a process takes as long as the number of production cycles, i.e., the number of operations in a manufacturing route. Consequently, for each pair of machine tools ( $M_i, M_k$ ), the number of work pieces (in different phases of manufacturing) should be initially assumed to be equal to the number realized in one cycle. Thus the allocation of buffers and their capacity assure that each dispatching rule can be executed independently of its structure.

Let us assume that the manufacturing system is composed of 3 machine tools, where processes  $P_1, P_2, P_3$  operate concurrently, see Fig.10 (a). For each pair of resources, an intermediate buffer with the required number of work pieces is allocated. The way processes are executed is shown in Fig. 10 (b).

In this case, buffers and their capacity allocation guarantee the desired system synchronization according to the given dispatching rule.

Creating of the start-up rule provides a way to automatically synchronize of an initial system state (i.e., initial process allocation) to the expected cyclic steady-state flow [Skolud, Krenczyk, 2001].



Legend:  
 $M_1, M_2, M_3$  – machine tools,  
 ..... → production route of the work order  $P_1$  ,  
 ---- → production route of the work order  $P_2$  ,  
 — → production route of the work order  $P_3$  ,  
 $\sigma_1, \sigma_2, \sigma_3$  – dispatching rules.

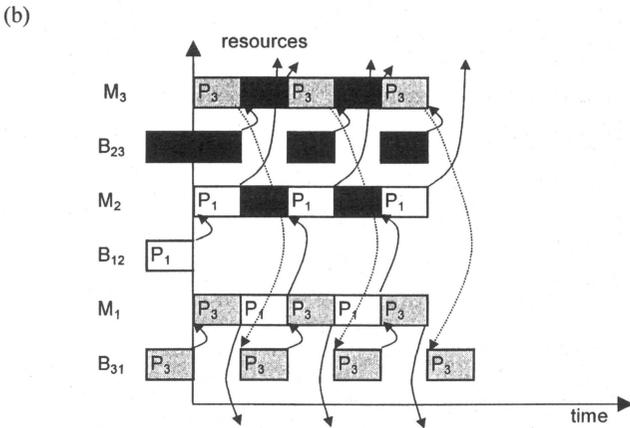


Fig. 10. Realization of concurrent processes; (a) production flow structure, (b) Gantt's chart illustrating the production flow.

**Generation of a start-up dispatching rule**

1. Given the dispatching rule  $\sigma_i(p_{i1}, p_{i2}, \dots, p_{i\theta_i})$ ,  $i=(1, \dots, m)$  allocated to the  $i$ -th resource.
2. Given the rank of processes  $P_{p_{i1}}, P_{p_{i2}}, \dots, P_{p_{i\theta_i}}$  according to their increasing numbers  $N_{p_{iw}}$ ,

where:

$N_{p_{iw}}$  - successive number of the operation in process  $P_{p_{iw}}$  executed in the  $i$ -th resource.  
 $P_{p_{iw}}$  - successive occurrence of the process in the  $i$ -th resource, where  $w=1, 2, \dots, \theta_i$ .

3. To ensure process succession, assign the repetitiveness of each process in the start-up rule allocated to the  $i$ -th resource  $K_{i1}^R, K_{i2}^R, \dots, K_{i\theta_i}^R$  according to the following equation:

$$K_{iw}^R = (O_{iw} - N_{p_{iw}}) \cdot \chi_i,$$

where:

$K_{iw}^R$  - the product of operation numbers of process  $P_{P_{iw}}$  remaining for execution after the  $i$ -th resource and the rule repetitiveness allocated to the  $i$ -th resource,

$O_{iw}$  - the number of operations of  $P_{P_{iw}}$ ,

$\chi_i$  - the repetitiveness of the dispatching rule allocated to the  $i$ -th resource.

According to the presented procedure, the start-up rule has the following structure:

$$\sigma_i \left\{ \underbrace{(K_{i1}^R \cdot P_{i1}, K_{i2}^R \cdot P_{i2}, \dots, K_{io_i}^R \cdot P_{io_i})}_{\text{start-up rule}}; \underbrace{(P_{i1}, P_{i2}, \dots, P_{io_i})}_{\text{dispatching rule}} \right\}$$

### Procedure for construction of the cease dispatching rule

Like the start-up rule design, discussed in the previous section, termination of a production requires the application of a special procedure. The procedure to cease production is created according to the number of work pieces executed during the start-up rule realization (surplus of work pieces entering a system in a start-up phase). The designed cease rule should assure smooth termination of production without the appearance of any deadlock and/or starvation.

If the expected realization time for each process should be the same, and the given system start-up procedures are applied, then the following procedure for designing the cease rule can be considered.

### Procedure for generating cease dispatching rule

1. Given the dispatching rule  $\sigma_i(P_{i1}, P_{i2}, \dots, P_{io_i})$ ,  $i=(1, \dots, m)$  allocated to the  $i$ -th resource.
2. Rank processes  $P_{P_{i1}}, P_{P_{i2}}, \dots, P_{P_{io_i}}$  according to decreasing numbers  $N_{iw}$ ,

where:

$N_{iw}$  - successive number of the operation in process  $P_{P_{iw}}$  (according to the accepted meta-rule) executed in the  $i$ -th resource.

$P_{P_{iw}}$  - successive occurrence of the process  $P_{P_{iw}}$  in the  $i$ -th resource, where  $w=1, 2, \dots, o_i$

3. For a given succession assign the repetitiveness of each process in the finishing rule  $K_{i1}^W, K_{i2}^W, \dots, K_{io_i}^W$  according to:

$$K_{iw}^W = (N_{iw} - 1) \cdot \chi_i,$$

where:

$N_{iw}$  - number of operations in process  $P_{P_{iw}}$ , executed on the  $i$ -th resource,

$\chi_i$  - the repetitiveness of the dispatching rule allocated to the  $i$ -th resource.

According to the presented procedures, the cease rule has the following structure:

$$\sigma_i \left\{ \underbrace{(P_{i1}, P_{i2}, \dots, P_{io_i})}_{\text{dispatching rule}}; \underbrace{(K_{i1}^W \cdot P_{i1}, K_{i2}^W \cdot P_{i2}, \dots, K_{io_i}^W \cdot P_{io_i})}_{\text{cease rule}} \right\}$$

The above considerations inspire and motivate toward the construction of dispatching rules allocated locally to the system resources, called *meta-rules*. The meta-rule consists of three parts.

The first part of a rule is the start-up, executed one time and assuring the synchronization of the system with regard to the expected (desirable) cycle. The second part is executed repetitively so as to guarantee a cyclic, steady-state production flow execution. The third one governs the ceasing of production. The most important aspect is that the dispatching rule should result in the self-synchronization of the system due to achievement of the expected cyclical behaviour.

**Illustrative example.** Let's assume a system composed of 4 machine tools  $M_1, M_2, M_3,$  and  $M_4$ . The following production orders  $Z_1, Z_2, Z_3$  wait for realization in the system. No other processes operate in the system up to this moment (the system is empty).

The manufacturing route of  $P_1$  lies through resources  $M_1, M_3, M_4$ , process  $P_2$  is executed on resources  $M_4, M_3, M_1, M_2$ , and process  $P_3$  is executed on resources  $M_2, M_1$ . The manufacturing routes are illustrated in Fig. 11.

Matrices specify processes considered; the first row of the matrix describes the number of operations, the second row contains the number of resources, and the third row of the matrix represents operations time.

$$M_{P_1} = \begin{bmatrix} 1 & 2 & 3 \\ 1 & 3 & 4 \\ 4 & 2 & 3 \end{bmatrix}, \quad M_{P_2} = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 4 & 3 & 1 & 2 \\ 5 & 6 & 5 & 4 \end{bmatrix}, \quad M_{P_3} = \begin{bmatrix} 1 & 2 \\ 2 & 1 \\ 4 & 3 \end{bmatrix}$$

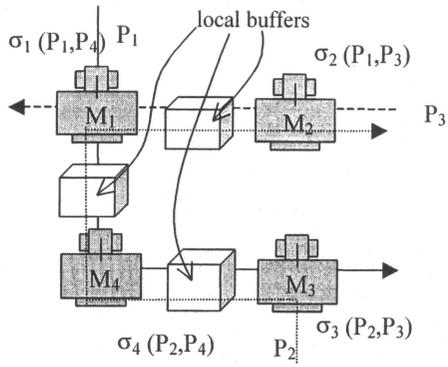
Dispatching rules allocated to shared resources are as follows:

$$\sigma_1(P_3, P_2, P_2, P_1), \quad \sigma_2(P_2, P_2, P_3), \quad \sigma_3(P_1, P_2, P_2), \quad \sigma_4(P_2, P_2, P_1).$$

The repetitiveness of the rules allocated to the resources is as follows:  $\chi_1 = \chi_2 = \chi_3 = \chi_4 = 1$ .

According to the procedure presented in the previous section, the meta-rules allocated to resources are the following:

$$\begin{aligned} \sigma_1 & \{ (P_1, P_1, P_2, P_2); (P_3, P_2, P_2, P_1); (P_2, P_2, P_2, P_2, P_3) \}, \\ \sigma_2 & \{ (P_3); (P_2, P_2, P_3); (P_2, P_2, P_2, P_2, P_2, P_2) \}, \\ \sigma_3 & \{ (P_1, P_2, P_2, P_2, P_2); (P_1, P_2, P_2); (P_1, P_2, P_2) \}, \\ \sigma_4 & \{ (P_2, P_2, P_2, P_2, P_2, P_2); (P_2, P_2, P_1); (P_1, P_1) \}. \end{aligned}$$



Legend:  
 $M_1, M_2, M_3, M_4$  – machine tools;  
 ———▶ production route of the work order  $P_1$ ;  
 .....▶ production route of the work order  $P_2$ ;  
 - - - -▶ production route of the work order  $P_3$ ;  
 $\sigma_1, \sigma_2, \sigma_3, \sigma_4$  – dispatching rules.

Fig. 11. System of concurrent processes.

The behaviour of the system in the case of meta-rules application is presented in Fig. 12 and Fig. 13. It can be easily noted that the rule application assures deadlock-free and starvation-free production flow execution.

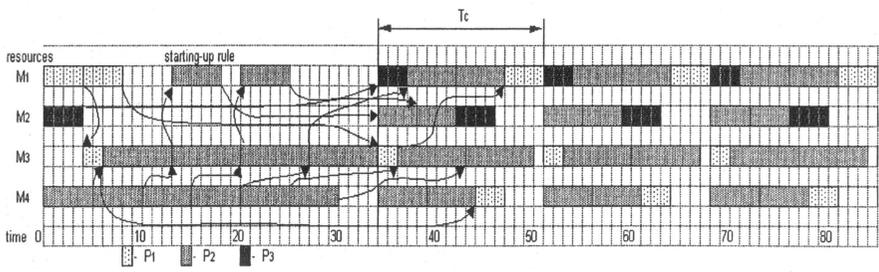


Fig. 12. Gantt's chart illustrating the application of start-up rules.

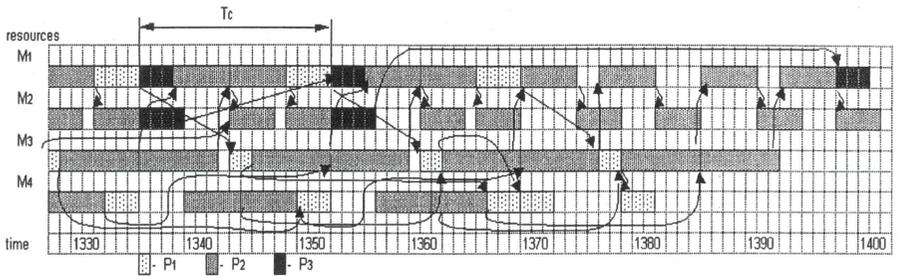


Fig. 13. Gantt's charts illustrating the application of cease rules.

The cycle is synchronized according to the critical resource. The cycle of the system is 17 time units. In a similar way, the relevant dispatching rules can be designed for transportation means, i.e., for AGVs as well as for both transportation and manufacturing flows.

#### 4. COMPUTER-BASED EVALUATION OF VIRTUAL ENTERPRISE INTEGRATION

The answer to the question whether the requirements imposed by a production order specification can be fulfilled within a given manufacturing system depends on the possible production flow organization. A solution would enable one to balance production tasks and the manufacturing system capacity.

##### 4.1. Rapid prototyping of production flows

In order to determine whether a given work order can be processed in an FMS possessing some unused production capacity, an approach based on constraint propagation has been implemented. This approach requires examination of a set of necessary conditions. Each condition encompasses a relationship between a particular constraint and a production order and/or FMS parameters.

Given an FMS characterized by a steady state of production flow, and given a specification of a newly introduced (prototyped) work order, the following conditions are examined:

ZW - time slots determining periods when a production capacity is available at a particular resource. The condition checks whether the capacity available is greater than required by the new work order.

TN - admissibility of a production routing. The condition examines whether the production routing of a new work order can be executed without changes to already processed production flows.

WS - availability of AGVs. The condition examines whether the AGVs is available to serve all required transportation operations.

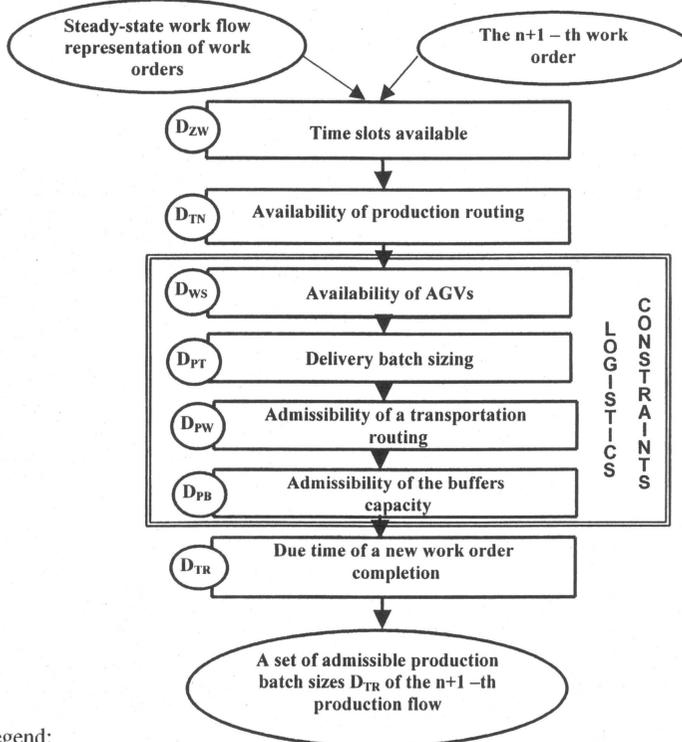
PT - delivery batch sizing. The condition checks whether available capacity of the AGVs supports the delivery batches required by the newly considered work order while preserving delivery batch servicing of already processed work orders.

PW - admissibility of a transportation routing. The condition examines whether the capacity of the AGVs guarantees execution of all transportation operations corresponding to the new work order.

PB - admissibility of the buffer capacity. The condition checks whether the capacity assigned to each buffer corresponds to the requirements imposed by assumed sizes of production and delivery batches.

TR - due time for completion of a new work order. The condition examines whether the order time of the new work order is equal to or shorter than the assumed work order completion period.

Through examination of the above conditions, a set of admissible production batch sizes is determined (see Fig. 14). It means that each condition can be treated as a kind of filter eliminating the production batches that cannot occur (cannot be realized) in the final production flow [Banaszak, Saniuk, Zaremba, 2001].



Legend:

$D_Y$  – a set of admissible batch sizes following the Y-th examined condition.

Fig. 14. Scheme of constraints filtering

The concept of constraint propagation has been implemented in a Computer Aided Production Planning software package (CAPP for short) [<http://www.iiz.pz.zgora.pl>]. The package makes it possible to assess whether a work order of a given volume can be completed within a requested order cycle in a system with a given amount of available production capability. A positive response provides the batch size as well as the volume and the period of deliveries that guarantee realization of the planned production flow.

## 4.2. Experiments

In this part of the paper, two experiments are presented that were carried out using the CAPP package. The objective of these experiments is to explore the influence of resources and logistic

constraints on system functioning. The first experiment relates to the flow-shop level and the second one relates to the higher (virtual enterprise) level.

**Flow-shop level experiment.** In order to illustrate a possible application of the approach developed, let us consider an FMS as shown in Fig. 5. In the system consisting of a set of machine tools  $\{M_i | i = 1, \dots, 3\}$ , and a set of buffers  $\{B_k | k = 1, \dots, 3\}$ , each with a capacity equal to 1, and a set of AGVs  $\{W_z | z = 1, \dots, 2\}$ , and a warehouse X, the work order  $Z_1$  is planned to be processed. It is assumed that the transportation paths are one-way routes, and all the AGVs move in the same direction and at the same speed. Vehicles move periodically with the same cycle time equal to 8 units. Consider an order specified by a production volume of 100 items, and a work order period equal to 800 units of time. The production route is determined by the following sequence of machine tools:  $M_1$ - $M_2$ - $M_3$ . The operating times are equal to 3, 8 and 4 units, respectively. The considered production flow structure is shown in Fig. 15.

In order to simplify further considerations, let us suppose the warehouse is always ready to provide a new batch of items as well as to store the completed items. So, it is assumed that only items currently required occupy the warehouse, and do so just in the moment they are required. It is arbitrarily assumed that the production batch size is equal to 3 items, and the initial phase between vehicles is equal to 4 units. Since the machine tool  $M_2$  constitutes a bottleneck, each production batch has to be delivered in the same period of time equal to  $8 \text{ units} \times 3 \text{ items} = 24$  units of time. Because the delivery batch sizes are limited by a vehicle's capacity and are equal to 1 item, some buffer capacity greater than zero is required.

Moreover, since each machine tool is served by an AGV in any 4 units of time, i.e., 6 times within the period of 24 units, within the resulting cycle of the production flow (equal to 24 units) the same amount of delivered and processed items is handled. This means that a material balance condition holds.

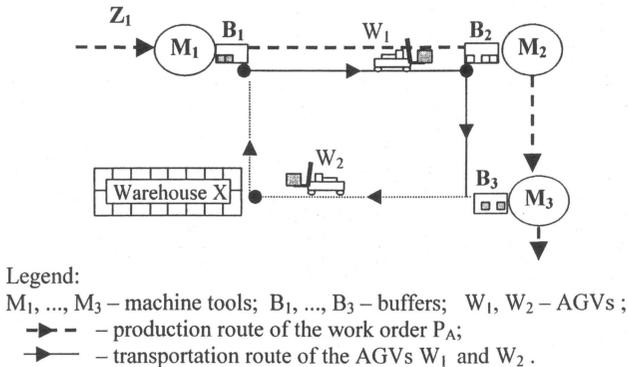
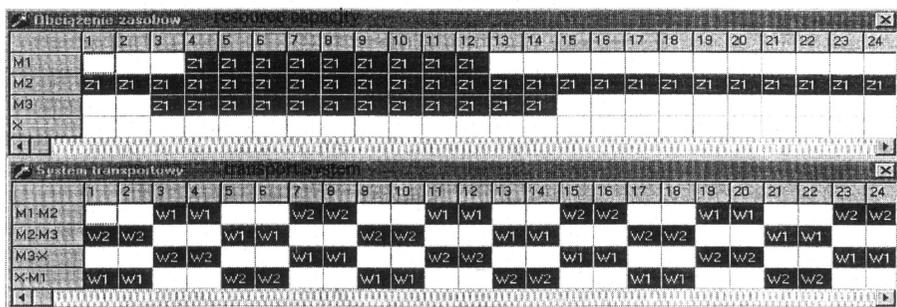


Fig. 15. Material and production flow structure.

The Gantt's charts illustrating both the material and the AGV flows are shown in Fig. 16. The corresponding Gantt's chart illustrating the items stored within the production flow cycle is shown in Fig. 17.

It is easy to observe that besides the bottleneck machine tool  $M_2$ , a number of AGVs, their capacity and period as well as phases among them in an initial state satisfy the constraints limiting the system throughput. This means that when only one vehicle is available, its cycle time cannot be less than the one determined by a bottleneck resource. Moreover, if it is allowed to pass empty, the relevant cycle should be equal to a multiple of a bottleneck cycle.

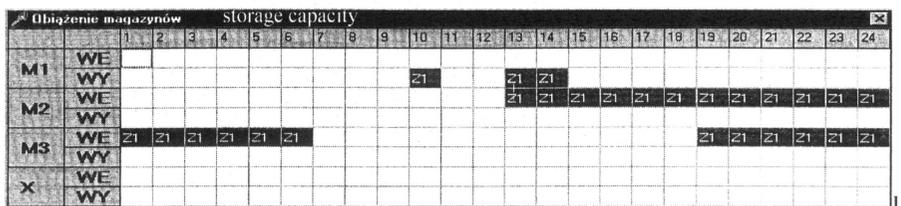
In the case where two AGVs are available, their relative phases start to play a crucial role. The phases decide how the buffers are utilized within the production flow cycle, i.e., determine the regularity of the volume of stored items. In the considered case, assuming that the relative phase between two vehicles has been decreased to 2 units (see Fig.18) more usage of the regular system's storage capacity has been obtained (see Fig. 19). The difference obtained in the considered cases is shown in Table 1.



Legend:

$M_1, M_2, M_3$  – machine tools;  $W_1, W_2$  – AGVs;  $M1-M_2$  – a transportation path section;  
 $Z_1$  – Gantt's chart of a steady-state production flow of the  $Z_1$  work order.

Fig. 16. Gantt's chart for the production flow for work order  $Z_1$ .



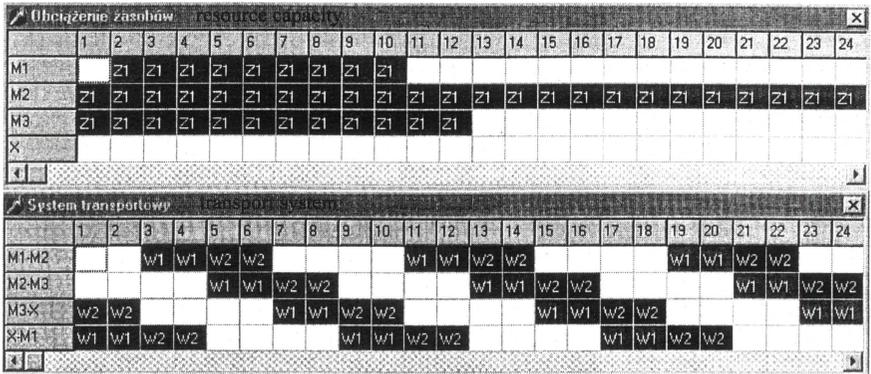
Legend:

$M_1(WE,WY), M_2(WE,WY), M_3(WE,WY)$  – the input/output buffers allocated to a machine tool;  
 $X$  – warehouse;  $Z_1$  – a steady-state item allocation in the production flow of work order  $Z_1$ .

Fig. 17. Gantt's chart for steady-state item allocation for work order  $Z_1$ .

Table 2. Items stored in the system during the production flow cycle.

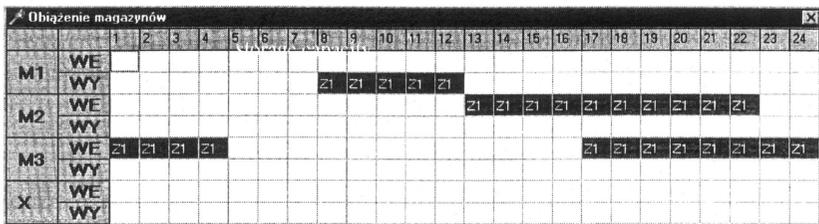
Phase\Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
4	1	1	1	1	1	1	0	0	0	1	0	0	2	2	1	1	1	1	2	2	2	2	2	2
2	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	1	1



Legend:

M<sub>1</sub>, M<sub>2</sub>, M<sub>3</sub> – machine tools; W<sub>1</sub>, W<sub>2</sub> – AGVs; M<sub>1</sub> – M<sub>2</sub> – a transportation path section; Z<sub>1</sub> – Gantt’s chart for a steady-state production flow of work order Z<sub>1</sub>.

Fig. 18. Gantt’s chart for the production flow for work order Z<sub>1</sub>.



Legend:

M<sub>1</sub>(WE, WY), M<sub>2</sub>(WE, WY), M<sub>3</sub>(WE, WY) – the input/output buffers allocated to a machine tool; X – warehouse; Z<sub>1</sub> – a steady-state item allocation in the production flow of work order Z<sub>1</sub>.

Fig.19. Gantt’s chart for steady-state item allocation in Z<sub>1</sub> production flow.

The above observation allows one to manage effectively such system resources as storage capacity. In other words, if there is a shortage of available capacity, the alternative scenarios of vehicle flow has to be examined.

It should be pointed out, however, that production batches of other sizes could be considered as well as other capacity of the vehicles. The CAPP package makes it possible to evaluate different variants of transportation and storage/delivery designs and/or different production flow organization. Its efficiency follows from examination of a given set of sufficient conditions.

As a consequence, the question “whether...or not” can be mainly considered. Besides questions such as: Could a given work order be completed within assumed period or not? Could a given AGV system capacity be enough to service an assumed production flow? Other questions may arise, such as how to examine whether allocation of a given buffer capacity makes it possible

to process a given work order, or how to check whether an assumed work order cycle could fit into a desired period.

Besides steady-state production flows, transition periods (i.e., system start-up and cease) can be analysed as well. For further details see [Banaszak, Zaremba, 2001], [Banaszak, Józefczyk, 2001].

### Virtual enterprise level experiment

A Virtual Enterprise is initiated by a single-partner company  $P_i \in \{P_1, \dots, P_i, \dots, P_K\}$  that prepares the specification for the production of a new product. First, the selected company has to determine what sets of resources are necessary to complete the work order. Then, operations of the manufacturing processes, i.e., production routings, have to be established. Finally, on the basis of a given operation time and cost of resource utilization, the relevant resources are selected. The following problem can be now considered. Given a set of partner companies that provide a structure allowing the set-up of a VE aimed at a given production order, How can we determine whether a given production order can be completed within the prescribed order cycle in a given variant of a VE?

The presented approach permits the selection of resources (partners of a VE) that guarantee the completion of work orders within a fixed time limit and at a relatively low cost. In order to illustrate the problem of an evaluation of due-date work-order completion, let us examine a VE consisting of four companies: A, B, C, and D (see Fig. 19). Consider the work order  $O_p$  determined by its production volume of  $Q = 300$  items, and the order time of  $T_E = 5800$  units of time.

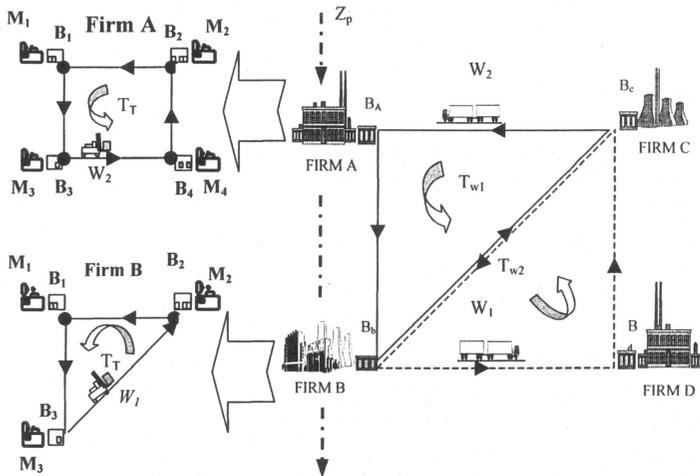
Let us assume a production routing of the work order passing through the company A, and then the company B. Suppose the capacities of warehouses  $B_a$  and  $B_b$  are the same and equal to 8 items. Deliveries are provided by tracks  $W_1$  and  $W_2$  of the same capacity equal to 9 items. The transportation routings and the track delivery times are specified in Table 3.

In order to answer the question whether a given volume work order can be completed within a requested order cycle in a company with a given amount of available production capability, let us use the CAPP package. A positive response provides the batch size as well as the volume and the period of deliveries that guarantee realization of the planned production flow.

Table 3. The transportation routings and delivery times.

Track	Transportation routing (transportation time)
$W_1$	Company B – Company D (10)
	Company D – Company C (10)
	Company C – Company B (10)
$W_2$	Company A – Company B (10)
	Company B – Company C (10)
	Company C – Company A (10)

Let us assume that the time  $t_a$  an item has to spend in company A equals 5, and suppose the same time for company B is  $t_b = 6$  units of time. The storage capacity allocated to companies A and B is equal to 6 and 8 units, respectively. To simplify the computations, the set-up times are assumed to be equal to 0. For a series consisting of 10 items, the delivery period is equal to 60 time units. Moreover, the CAPP software determines the delivery batches of volumes 1, 6, and 3, and their delivery periods.



Legend:

- $Z_p$  – the work order,  $B_a, b_a, B_c, B_d$  – warehouses of the companies A, B, C, and D, respectively,  $W_1, W_2$  – delivery tracks,  $T_T, T_{w1}, T_{w2}$  – delivery cycles,
- $M_1, \dots, M_4$  – machine tools,  $B_1, \dots, B_4$  – buffers;  $W_1, W_2$  – AGVs,
- >----- - the transportation route of truck  $W_1$ ,
- >----- - the transportation route of truck  $W_2$ ,
- >----- - the production routing of work order  $Z_p$ ,
- >----- - transportation route of AGVs  $W_1$  and  $W_2$ .

Fig. 20. Structure of production flows in a virtual enterprise.

This means that each company is able to process the series of 10 items within a time period not exceeding 60 units of time.

The analysis of the production flow synchronization can be performed using the Gantt's chart, shown in Fig. 21. The diagram represents a steady state of the production flow. Its cycle is determined by the cycles of the transportation components used on the two levels of the VE structure. A similar analysis can be done at a company level.

Let us consider a company A which on its shop level has four machine tools,  $M_1 - M_4$ , and one AGV. Each machine tool  $M_i$  is equipped with an input buffer  $B_{i/2}$  and an output buffer  $B_{i/2}$ . The required production routing passes first through machine tool  $M_3$ , and then  $M_4$ . The capacities of input buffers  $B_{3/1}, B_{4/1}$  and output buffers  $B_{3/2}, B_{4/2}$  are the same and equal to 1. For the sake of simplicity, let us assume that the set-up times are equal to 0. In this case, for operation times associated with the machine tools  $M_3$  and  $M_4$  equal to 1 and 3 time units, respectively, and the transportation time required to link  $M_3$  and  $M_4$  being equal to 1 time unit, the calculated batches consist of 1 item and the obtained batch delivery period equals 5 time units.

Let us now suppose that the shop level of company B is equipped with three machine tools,  $M_1 - M_3$ , and one AGV. Each machine tool has an input and an output buffer. The required production routing passes through machine tool  $M_1$ , and then  $M_3$ . The capacity of input buffers  $B_{1/1}, B_{3/1}$  and output buffers  $B_{1/2}, B_{3/2}$  is the same and equals 2 units. Let us assume null set-up

times. In this case, for operation times associated with machine tools  $M_1$  and  $M_4$  equal to 1 and 4 units of time, respectively, and the transportation time required to link  $M_1$  and  $M_4$  being equal to 1 time unit, the calculated batches consist of 1 item and the batch delivery period is equal to 6 time units.

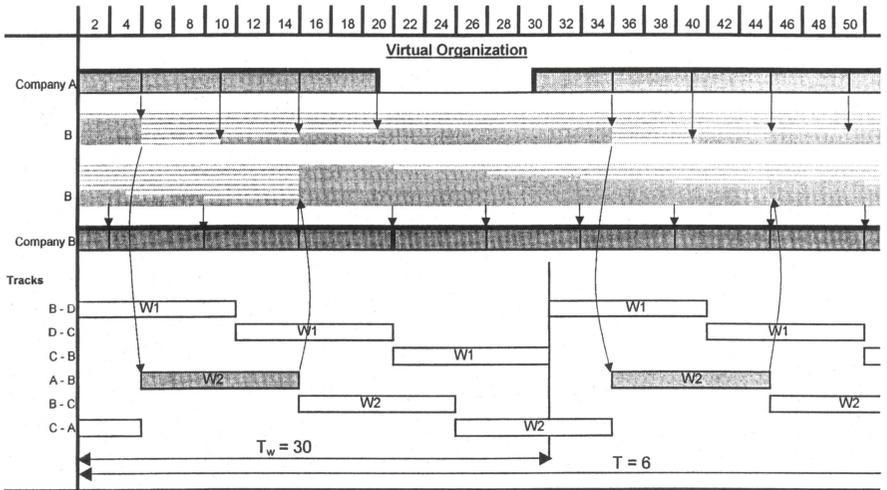


Fig.21. Gantt's chart for the delivery flow.

It is now easy to observe that company B experiences a bottleneck in the production flow. The relationship between the delivery period and the production flow cycle can be observed as well. Finally, the order cycle can be calculated providing an answer to the main question stated at the beginning.

In the case considered above, there co-exist both the critical series delivery process and the critical resource (company B). This means that maximal throughput can be obtained for given logistics constraints. This can be done, however, for specific sizes of the production series, of the batches, and of the delivery batches. How they are calculated is critical to verifying whether a balanced – in terms of material flow and production capacity - production plan can be realized.

The obtained production flow provides a pattern for a production plan design. Such plans can be directly defined either in the form of a master schedule or in the form of a set of dispatching rules. The CAPP design package presented above offers distributed control procedures, i.e., a set of dispatching rules that control the access of competing processes to shared resources.

## 5. CONCLUDING REMARKS

Based on the concepts of a critical resource and a critical process, the Constraint Theory approach was adopted. It was shown that system performance (such as throughput rates and product cycle times) depends not only on the effectiveness of the component elements, but also on the synchronization of their interactions. In addition to issues of balancing system capability and customer requirements, production flow control problems were discussed. The results obtained

relate to the procedures for generating the starting-up and the cease dispatching rules, which control production flows during these transition periods.

The theoretical results obtained have been implemented in a software package that permits the user to investigate the effect of a new work order on the performance of a manufacturing system. In other words, the software answers the question whether a given work order can be accepted for processing in a virtual enterprise, i.e., whether its completion time, batch size, and its delivery will satisfy the customer requirements, while at the same time satisfying constraints imposed by the enterprise configuration and the process of manufacturing other products. Besides a production planning capability, i.e., the ability to determine batch sizes and batch delivery periods of production flows, the package provides a distributed control procedure, i.e., a set of dispatching rules and procedures for their assignment to the shared resources. The dispatching rules supervise the execution of both transition (i.e., starting-up and cease periods) and steady-state periods of the production flow. Application of the package to the problem of production flow verification was presented.

Apart from the above-presented approach that assumes that a crucial role in the production flow co-ordination in a VE is played by delivery periods, an alternative approach can be considered, which is based on the leading role of local (i.e., characteristic of the particular company) work flows that synchronize the delivery/transportation flows. We believe that this alternative, as well as workflow oriented VE management, can be considered within the presented framework.

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