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Re-scheduling of AGVs Steady State Flow

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Abstract: The paper's objective concerns assessing a mesh-like supply network of periodically acting local transportation modes from the perspective of possible re-scheduling the multimodal flows of jobs assigned to certain technological routes passing through common shared workstations. The considered reference model of a Material Transportation Network (MTN), where several heterogeneous means of material handling, e.g. AGVs, hoists, lifts, etc., interact with each other via common shared workstations, enables the formulation of scheduling and re-scheduling tasks in the context of a Periodic Vehicle Routing Problem. The main problem is in essence to identify conditions guaranteeing transient period free re-scheduling of cyclic steady state flows of multimodal processes and local transportation processes supporting their execution. Such sufficient conditions allows one to replace the exhaustive search for the admissible flows control by design of regular structure material handling system, i.e. to solve the considered class of re-scheduling problems online. The proposed methodology behind re-scheduling cyclic steady state production flows executed in regular-structure MTNs is clarified through multiple illustrative examples.

Keywords: Periodic Vehicle Routing Problem, re-scheduling, fleet of AGVs, multimodal process, declarative modelling, cyclic scheduling.

1. INTRODUCTION

The productivity of an Automated Guided Vehicle AGV-served flow shop repetitively producing a set of different products, depends on both the job flow sequencing and the material handling system's ability to achieve a pre-specified throughput, i.e. sizing the AGVs fleet, assignment and scheduling (Bocewicz et al. 2014; Hall et al. 2001). The approach considered in this paper assumes a given transportation system encompassing the network of AGVs periodically circulating along cyclic routes while servicing work-pieces load/unload operations. In that context, the problem considered is related to the well-known *Vehicle Routing Problem* (VRP) where production routes are specified by sequences of subsequently executed operations performed on AGVs and machine tools, respectively. Transport operations are executed by AGVs arranged in a streaming closed-loop network where each vehicle from a given AGV's stream travels along an arbitrary assumed cyclic route. Machining operations taking into account setup times must be done within the given time windows.

The approach proposed in this paper assumes that routes together with the local transport processes executed along those routes have a regular mesh-like topology. Such an assumption facilitates the design of distribution structures composed of repeating fragments (grids). It also provides the possibility of predicting certain behavioral characteristics of the system (e.g., cyclic, collision-free, interference-free behaviors, etc.) on the basis of an analysis of the behavior of a repeating part of its structure. The paradigm of regularity of a material handling system's structure meets the expectations associated with the simplification of design procedures as it entails that it is better to design regular structures (which ensure appropriate repetitive behavior) than to look for this kind of behavior in arbitrarily given structures, running the risk of failing to find a feasible solution.

Since most real-life available manufacturing processes manifest cyclic steady state production flows, AGV-served material handling/transportation processes also exhibit cyclic behavior. Many models and methods aimed at cyclic scheduling of concurrently flowing jobs have been considered to date. Among those, the mathematical programming approach (Kampmeyer 2006), max-plus algebra (Polak et al. 2004), Petri nets (Baruwa and Piera 2015), tabu search (Zheng et al. 2015) constraint logic programming (Bocewicz et al. 2014) frameworks are the more frequently used. Most of these methods aim at finding a minimal cycle or maximal throughput while assuming deadlock-free processes flow. However, very rarely do they concern production systems consisting of an AGV fleet arranged to transport work-pieces between workstations (i.e. following a given production route) while moving in a carousel mode along cyclic path topologies.

The aim of this work is to develop a methodology for the synthesis and control of regularly structured material handling networks which would ensure fixed cyclic execution of local transport processes. The proposed methodology, which implements sufficient conditions for the

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synchronization of local cyclic processes, allows one to develop a method for rapid prototyping of cyclic steady state flows encompassing processes of multiple products distribution. The main motivating research question is: What are sufficient conditions guaranteeing transient period free re-scheduling of cyclic steady state production flows?

The remainder of the paper is organized as follows: Section 2 provides a brief review of related work. Section 3 introduces the System of Concurrently Cyclic Processes (SCCP) driven framework aimed at modeling AGVs fleet flow. Section 4 provides the problem formulation as concerning AGVs' fleet steady state flow re-scheduling. Section 5 elaborates on the sufficient conditions enabling transient-state-free re-scheduling of AGVs flow. A discussion of the approach is presented using an illustrative example in Section 6. Concluding remarks and further work are submitted in Section 7.

2. LITERATURE REVIEW

Numerous papers have been published to address vehicle routing problems (Carić and Gold 2008), integrated machine scheduling and vehicle routing with time windows (Ullrich 2013), as well as multimodal network flow models. In that context, the Vehicle Routing Problem (VRP) can be defined as the problem of designing least cost delivery routes from a depot to a set of geographically dispersed locations subject to a set of constraints (Kovacs et al. 2014; Kumar et al. 2012). VRPs are solved using exact algorithms (e.g. direct tree search methods, dynamic programming, integer linear programming) or approximated algorithms (i.e. those employing artificial intelligence heuristics) (Laporte 1992). Among approximated methods, which are used more frequently due to the NP-hard character of the problem, worth mentioning are metaheuristics such as tabu search, simulation annealing, and evolutionary algorithms (e.g. ant colony and particle swarm) (Lan et al. 2007). Among a variety of possible extensions of VRP, the most popular are the Heterogeneous Fleet VRP (or Mixed Fleet VRP) which assumes that goods are delivered by a fleet of vehicles with dissimilar capacities as well as the Heterogeneous Fleet VRP with Time Windows (HFVRPTW), assuming that deliveries to a given customer must occur in a certain time interval (varying from customer to customer), and the Multi Depot VRP assuming that multiple depots are geographically spread among customers (Kovacs et al. 2014). The goal of the HFVRPTW is to find transportation times (i.e. intervals required to pass a distance between two subsequent machine tools in a closed-loop followed by an AGV) for each AGV stream such that hard time window constrains on both kind of windows hold for a cyclic steady state of AGV flow. A special role among VRPs is played by the Periodic VRP (PVRP), in which delivery routes are constructed over a period of time (Francis and Smilowitz 2006; Angelelli and Speranza 2002; Coene and Arnout 2010). Besides the assumptions traditionally accepted by the VRP, the PVRP has to take into account a time horizon, usually subdivided into regular periods, as well as a customer visit frequency stating how often within a particular period a customer must be visited. A solution to the PVRP consists of sets of routes which jointly satisfy demand constraints and frequency constraints. The objective is to minimize the sum of the costs of all routes over the planning horizon (Coene and Arnout 2010).

The so-called vehicle flow models are used much more often than cargo flow models (Caric et al. 2004). As a consequence most research concentrates basically either on synchronizing (scheduling) available transport modes so that they can service customers in given time windows, or on designing distribution networks taking into account the size and capacity of the planned fleet and the topology and traffic capacity of routes.

3. MESH-LIKE TRANSPORTATION NETWORK MODELLING

In a mixed floor and overhead material handling transport system equipped with many unidirectional AGV and overhead hoist transport modes a guarantee of congestion and deadlocks-free plays a pivotal role in achieving a well-organized material flow. A specific network topology of the considered Mesh-like Material Transportation Network (MMTN) assumes that it can be seen as composed of multiple Elementary Transport Networks (ETNs).The assumption behind this postulate is that a regular composition of ETNs encompassing local transportation modes cyclic steady state implies the cyclic steady state of whole MMTN. An example of such a MMTN structure with a highlighted repeating pattern is shown in Fig. 1 a). The realistic examples supporting the adopted topological assumption follow from numerous reports concerning mesh-like or grid-like and fractal-like structures of transportation networks and are considered for over twenty years, see (Qiu et al. 2002). It is worth noting that the topology of the structure of local processes may, but are not required to coincide with the layout of routes which allow actual implementation of local processes. In the general case the graph of execution of local transport processes can be a subgraph of an ETN or MMTN structure. For the sake of simplicity, in the discussion to follow we however focus, on processes structure which map a regular-structure MMTN.

3.1. Mesh-like material handling processes

The considered material handling processes can be seen as the cyclically circulating pipeline-like processes typical for a serial production supported by a steady stream of AGVs. By treating an AGV stream as a convoy of vehicles driving over the same path in the same direction, all its vehicles can be instanced by subsequently numbered entities called sub-processes. In terms of Systems of Concurrently flowing Cyclic processes (SCCPs) representation, such models will be called the SCCP-driven model of MMTN (in short SMTN) and SCCP-driven model of ETN (in short SETN).

Fig. 1b) shows the SMTN composed of eight SETNs, where each SETN consists of two *local cyclic processes*: P_1, P_2 and their *streams*: P_1^1, P_2^1 (distinguished in Fig. 2 by ${}^{(i)}P_1^1$, ${}^{(i)}P_2^1$, respectively – superscript i indicates the number of SETNs), associated to four AGVs following their routes in the ETN.

Apart from local processes, two *multimodal processes*: mP_1, mP_2 representing parts of manufacturing routes of two products W_1 and W_2 executed in the SETN, are considered.

The processes follow given routes composed of workstations: $R_1 - R_4$ (resources ${}^{(i)}R_c$ denoted by a superscript i refer to a number of SETN) and resources representing transportation sectors ($R_5 - R_{13}$). Formally, local P and multimodal mP processes are defined in the following way:

- $P = \{P_i \mid i = 1, \dots, n\}$ – the set of local processes described by sequences of operations executed on resources R, where each P_i is specified by the set of streams: $P_i = \left\{P_i^1, P_i^2, \dots, P_i^k, \dots, P_i^{ls(i)}\right\}$,
- $mP = \{mP_i \mid i = 1, \dots, w\}$ – the set of multimodal processes described by sequences of some sub-sequences from local processes P, where each mP_i is specified by the set of streams: $mP_i = \left\{mP_i^1, mP_i^2, \dots, mP_i^k, \dots, mP_i^{lms(i)}\right\}$.

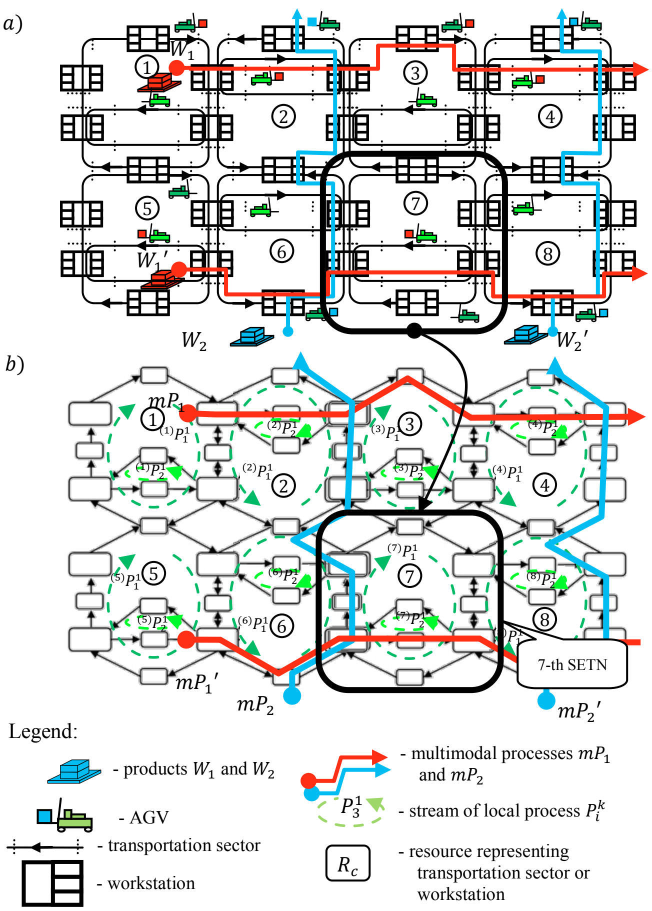

Fig. 1. An example of MMTN a) and its SMTN model b)

The operations of multimodal processes' streams require the execution of some local processes. For example, transport operations between resources in mP_1 (product W_1) - see Fig. 1b) - require streams ${}^{(i)}P_1^1, {}^{(i)}P_2^1$ of local processes P_1, P_2, respectively. This means the routes of multimodal processes are also determined by the subsequences of routes of the local processes through which they have to be processed. It is assumed that processes are synchronized by a mutual exclusion protocol, i.e. guaranteeing that only one process can be executed on a shared resource at a given time. In other words, the SMTN can be treated as a set of pipeline cyclic processes P, and mP interacting via the commonly shared resources R. Potential process conflicts are resolved in advance by assigned priority dispatching rules from the set Θ^0 determining local and the set Θ^1 determining multimodal processes interactions.

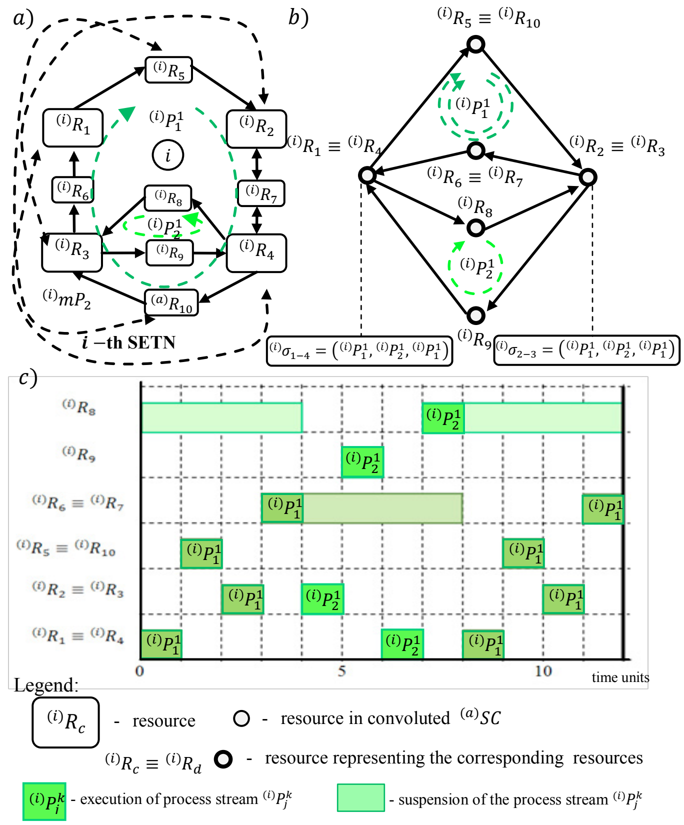

Fig. 2. The i-th SETN belonging to the SMTN from Fig. 1b) a), its covered form b), and Gantt's chart following the dispatching rules ${}^{(i)}\sigma_{1-4} = \left({}^{(i)}P_1^1, {}^{(i)}P_2^1, {}^{(i)}P_1^1\right)$, ${}^{(i)}\sigma_{2-3} = \left({}^{(i)}P_1^1, {}^{(i)}P_2^1, {}^{(i)}P_1^1\right)$ assigned to covered form of SETN c)

Dispatching rules for synchronization of access of local transport processes to shared network resources are marked with labels ${}^{(i)}\sigma_r$, e.g. ${}^{(i)}\sigma_3 = \left({}^{(i)}P_1^1, {}^{(i)}P_2^1\right)$ describing the order of access of means of transport, e.g. ${}^{(i)}P_1^1, {}^{(i)}P_2^1$ to a shared resource ${}^{(i)}R_r$, e.g. ${}^{(i)}R_3$.

3.2. AGVs flow prototyping

Travel and/or dwelling times of means of transport for various network resources are designated with the symbol $t_{i,j}$ which denotes the time of execution of the j-th operation of the i-th transport process. A graphic model which can be used to represent both travel/dwelling times and the wait times of the means of transport used and the goods moved using those means is a Gantt chart (Fig. 2 c). Its graphical representation allows one to assess waiting times associated with the fact that AGVs have to wait for access to a requested but currently occupied resources, as well as waiting times of work-pieces transported in MMTN resulting from unavailability of the scheduled AGVs.

Due to our assumption, a SMTN can be seen as composed of a finite set of identical repeating substructures, i.e. SETNs, comprised of elementary substructures modelling local transportation processes. Each SETN has a corresponding covered-form (see Fig. 2b) which is formed by gluing together the vertices of the SETN which in the regular structure of the SMTN are joined with the corresponding fragments of the elementary structures of an adjacent SETN. Note, that the selection of dispatching rules guaranteeing a cyclic execution of a SETN's elementary processes belongs to NP-hard problems. The behavior of a given SMTN can be predicted on the basis of the behavior of its SETNs. It is easy to observe that an initial allocation of local processes in a regular network will be followed in each individual SETN by subsequent allocation of local processes in compliance with the same priority dispatching rules. That is because if one replicates the same initial process allocation in all the remaining SETNs, the structure will be free of collisions between processes which use the same resources.

The new allocation in the regular structure concerns the processes and resources which are "copies" of the processes and resources of the contemplated SETN. This means that the successive process allocations which occur in cycles after each initial allocation in the SETN will have their counterparts in the overall regular structure – allocations of all the local processes of the structure. Thus, period α of the processes executed in the regular structure is equal to the period of processes executed in the SETN. This means that cyclic behavior of the SETN implies a cyclic behavior of the regular-structure SMTN.

Therefore, a cyclic behavior of the covered form of the SETN entails a cyclic behavior of the SMTN. This means that by solving a small-scale computationally hard problem (associated with an SETN), one can in online mode solve a large scale problem associated with a corresponding regular-structure supply network.

Since different conflict resolutions of processes executed in a SETN results in different periods α of its cyclic behavior, different behaviors of the whole SMTN can also be prototyped. Moreover, viewing SMTNs as time-driven discrete event systems provides the possibility of quantitative analysis of their behavior oriented toward estimating AGVs fleet scheduling as well as production flow.

4. PROBLEM STATEMENT

Since the SETN can be modeled in a declarative framework, i.e. in terms of a Constraint Satisfaction Problem (CSP), the dispatching rules guaranteeing its processes execute in a cyclic manner can be obtained with help of commercially available software packages, e.g. ILOG, ECL^{i}PS^e, Oz Mozart, (Sitek and Wikarek 2015, Bocewicz et al. 2015). A CSP is defined as a triple $SC = (X, D, C)$ where $X = \{x_1, x_2, \ldots, x_n\}$ – is a finite set of decision variables, $D = \{D_i | D_i = \{d_{i,1}, \ldots, d_{i,j}, \ldots, d_{i,m}\}, \quad i = 1..n\}$ – is a finite family of finite domains of discrete decision variables, and $C = \{C_i | i = 1..L\}$ – is a finite set of constraints limiting the values. What is sought is an admissible solution, i.e. a solution in which the values of all decision variables X satisfy all constraints C. In that context the following formulation, of the CSP aimed at selecting a set of dispatching rules guaranteeing a cyclic steady state execution of SETN's processes, can be considered. In other words, assuming that the behavior of each i-th SETN is represented by a cyclic schedule ${}^{(i)}X' = ({}^{(i)}X_k | \, k = 1,2 \ldots, L_i)$, where: ${}^{(i)}X_k$ is a set of beginning moments of operation of the k-th local process of the i-th SETN, the CSP in question has the following form:

$$PS_i = ((\{{}^{(i)}X', {}^{(i)}\Theta, {}^{(i)}\alpha\}, \{D_X, D_\Theta, D_\alpha\}), \{C_L, C_M, C_D\}) \qquad (1)$$

where: ${}^{(i)}X'$, ${}^{(i)}\Theta$, ${}^{(i)}\alpha$ – decision variables,

- ${}^{(i)}X'$ – cyclic schedule of the i-th SETN,
- ${}^{(i)}\Theta$ – set of dispatching rules determining the order of operations competing for access to the common resources of the i-th SETN,
- ${}^{(i)}\alpha$ – set of values of periods of local processes occurring in the i-th SETN,

D_X, D_Θ, D_α – domains of admissible values of discrete decision variables

C_L, C_M, C_D – finite sets of constraints limiting the values of decision variables

- C_L, C_M – sets of conditions constraining the set of potential behaviors of the i-th SETN (Bocewicz and Banaszak 2015),
- C_D – a set of sufficient conditions the satisfaction of which guarantees congestion-free (i.e. deadlock-free and collision-free) flow of traffic in a transport network modeled by the i-th SETN and, execution of transport operations and loading/unloading operations (i.e. operations competing for access to common resources).

The sought solution to problem (1) is schedule ${}^{(i)}X'$ which satisfies all the constraints of the family of sets $\{C_L, C_M, C_D\}$. Constraints C_L, C_M ensure that local processes in the "uncovered" form of an ECS are executed in a cyclic manner, i.e. the execution of operations is specified by an appropriate cyclic schedule. However, they do not guarantee the same for the "covered" form of this structure. The additional constraints C_D given below, which follow from the match-up rule (Bocewicz et al. 2014) that conditions the fit between cyclic schedules, guarantee that the local processes occurring in the structures which satisfy them are executed in a cyclic manner.

In order to state our main problem let us consider two steady states following different sets of dispatching rules obtained for the same SETN. The problem boils down to the following question: What are the sufficient conditions guaranteeing transition-state-free passing among given cyclic steady states? The problem belongs to a class of reachability problems and is also computationally hard. Its solution enables to switch directly from one state of the given cyclic steady state flow of AGVs to another belonging to other cyclic steady state flows of the same fleet.

5. STEADY STATE FLOW RE-SCHEDULING

Since, in the general case, a solution to the problem (1) can be seen as a non-empty family of sets of dispatching rules, the set of corresponding different cyclic steady states of SETN local processes can be also considered. Consequently, the problem of steady state flow re-scheduling is reduced to the question: Do there exist direct or indirect transitions enabling switching among assumed cyclic steady states? An illustrative example of re-scheduling of a given cyclic steady state Sc_1 is shown in Fig. 3. Two possible transitions leading to an assumed cyclic steady state Sc_1 are distinguished. The Gantt's chart illustrating the way of indirect transition among steady states is shown in Fig. 3 b). The states S_j^i occurring within the cyclic steady states describe local processes' allocation to resources of the SETN.

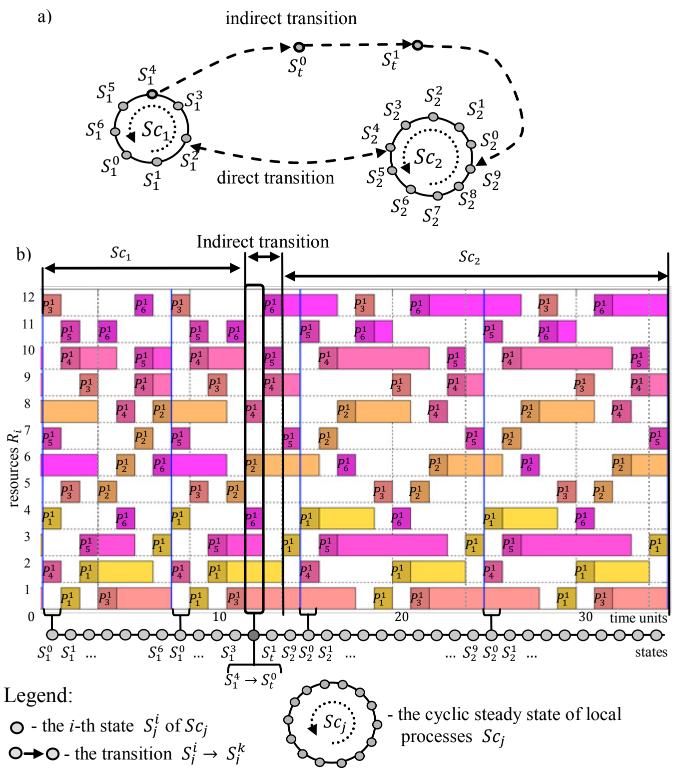

Fig. 3. State space a), Gantt chart illustrating the way the cyclic steady state Sc_2 can be reachable from Sc_1 b)

The sufficient conditions which can be deduced from the example shown in Fig. 3 b) can be reduced to the following conclusions:

- The cyclic steady state Sc_2 composed of the set of states SS_2 is directly reachable from the cyclic steady state Sc_1 composed of the set of states SS_1 if $SS_2 \cap SS_1 \neq \emptyset$.
- The cyclic steady state Sc_2 composed of the set of states SSc_2 is indirectly reachable from the cyclic steady state Sc_1 composed of the set of states SS_1 if there exists a non-empty set of transition states ST_{2-1} composed of states occurring in a transient state linking cyclic steady states Sc_1 and Sc_2 and such that $SS_2 \cap ST_{2-1} \neq \emptyset$ and $SS_1 \cap ST_{2-1} \neq \emptyset$. In case from Fig. 3 b) $ST_{2-1} = \{S_1^4, S_t^0, S_t^1, S_2^9\}$.

The illustration of the first of the above conditions is discussed in the following section.

6. ILLUSTRATIVE EXAMPLE

Consider MMTN Fig. 1 a) and two multimodal processes mP_1, mP_2 following manufacturing routes of two different products W_1 and W_2 respectively. Let us assume the two following solutions of the problem (1) stated for the SETN of the SMTN model Fig. 1b): $SW_1 = \{{}^{(i)}\sigma_{1-4} = ({}^{(i)}P_1^1, {}^{(i)}P_2^1, {}^{(i)}P_1^1)$, ${}^{(i)}\sigma_{2-3} = ({}^{(i)}P_1^1, {}^{(i)}P_2^1, {}^{(i)}P_1^1)\}$ and $SW_2 = \{{}^{(i)}\sigma_{1-4} = ({}^{(i)}P_1^1, {}^{(i)}P_1^1, {}^{(i)}P_2^1)$, ${}^{(i)}\sigma_{2-3} = ({}^{(i)}P_2^1, {}^{(i)}P_1^1, {}^{(i)}P_1^1)\}$. The solutions result in cyclic steady state of both AGVs fleet and production flows.

The parameters characterizing the flows considered are collected in Table 1 while the corresponding Gantt charts are shown in Figs. 4 and 5.

Table 1 The lengths of cyclic steady states and production cycles following solutions SW_1 and SW_2

solutions	Period of steady state	Production cycle time	
	α [u.t.] (units time)	T_{W1} [u.t.]	T_{W2} [u.t.]
SW_1	12	19	45
SW_2	8	31	29

Due to the solution SW_1 the production process responsible for the product W_1 executes without any suspensions (see multimodal processes depicted by red color in Fig. 4) while in the case of product W_2 its suspension on resource ${}^{(i)}R_7$ can be observed (see multimodal processes depicted by blue color in Fig. 4).

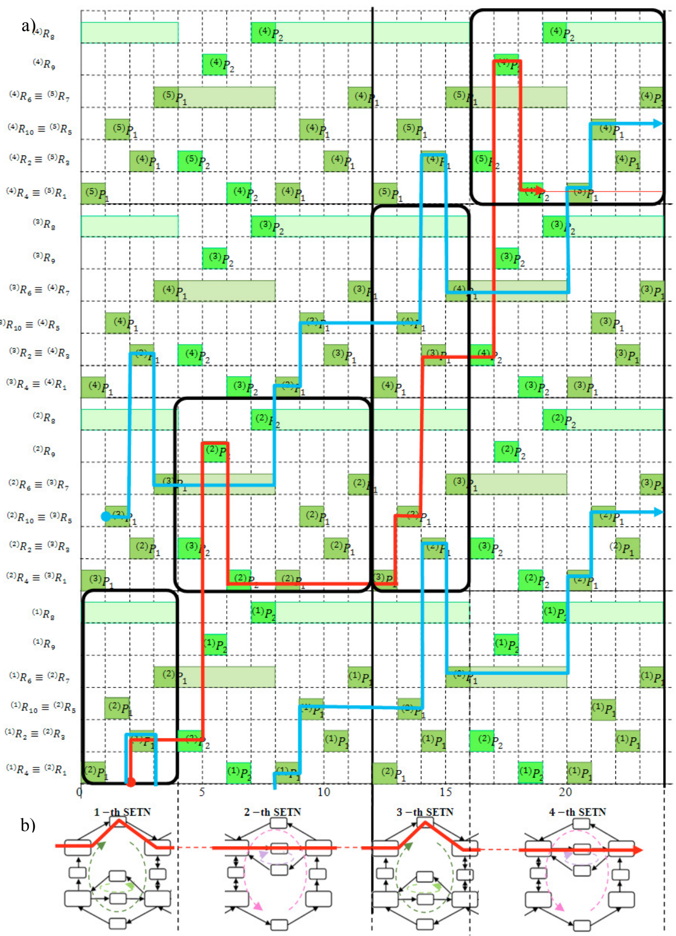

Fig. 4. Gantt chart of production flow following SW_1.

In turn, due to the solution SW_2 the production process responsible for the product W_2 executes without any suspensions (see multimodal processes depicted by blue color in Fig. 5) while in the case of product W_1 its suspension on resource ${}^{(2)}R_9$ can be observed (see multimodal processes depicted by red color in Fig. 5). The icons placed at the bottom of the Gantt charts display SETNs passed along by product W_1, see Fig. 4 b) and Fig. 5 b). If someone would like to re-schedule the production flow following SW_1 into one following SW_2 it is enough to find the states following earlier mentioned sufficient conditions. The appropriate states can be found as shown in Fig. 6 (see the states distinguished in black frames). It should be noted that such re-scheduling assuming direct transition among two steady states requires transition to a relevant set of dispatching rules. Moreover, direct transition enables bidirectional re-scheduling, i.e. from the cyclic steady flow following SW_1 to SW_2, and vice versa.

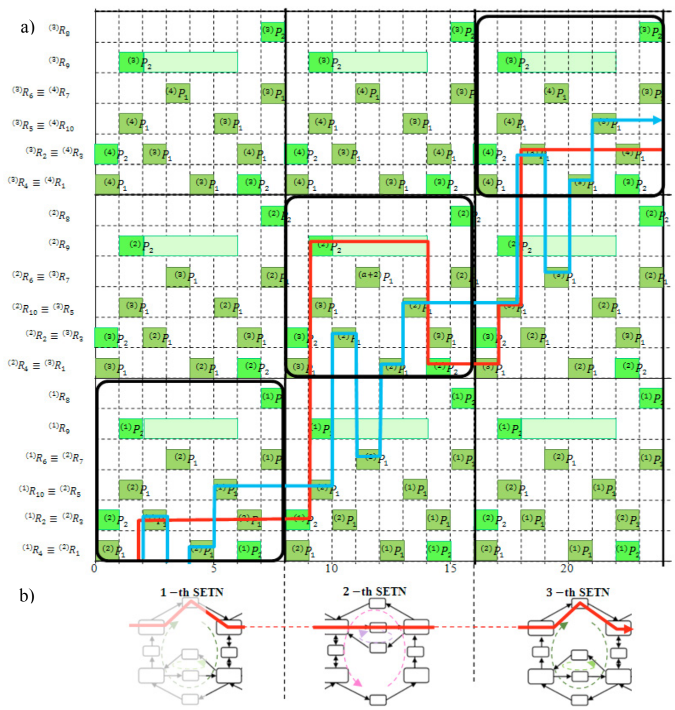

Fig. 5. Gantt chart of production flow following SW_2

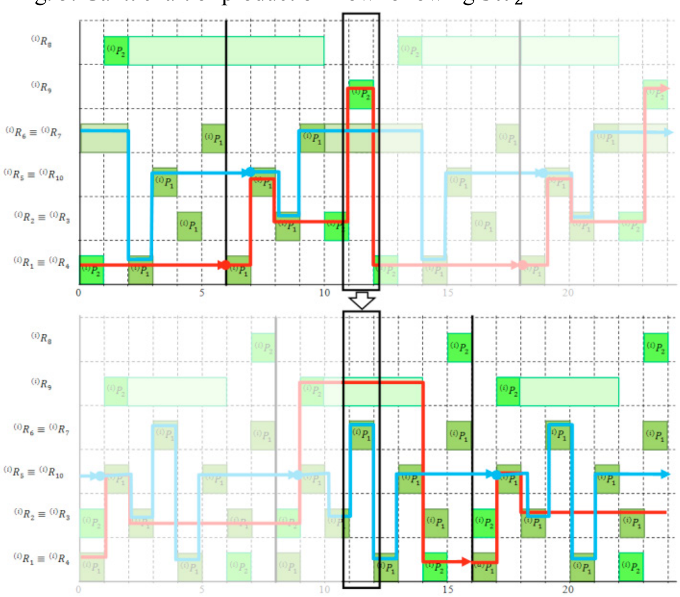

Fig. 6. Gantt chart of production flow re-scheduling from production flow following SW_1 and production flow following SW_2

7. CONCLUSIONS

The sufficient conditions driven approach to AGVs fleet re-scheduling provides a step towards a method allowing one to replace the exhaustive search for the admissible control by design of regular structure material handling system guaranteeing its presumed required behaviors.

The problem of sufficient conditions guaranteeing existence of a limited length transient period enabling passing between cyclic steady states of AGV's fleet flows remains open.

In the future, we plan to broaden the scope of our research to include the problems of robust scheduling including introduction of the new production orders as well changes to the AGV fleet.

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