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Multimodal processes optimization subject to fuzzy operation time constraints: declarative modeling approach#

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Abstract: We present an extension of the resource-constrained multi-product scheduling problem for an automated guided vehicle (AGV) served flow shop, where multiple material handling transport modes provide movement of work pieces between machining centers in the multimodal transportation network (MTN). The multimodal processes behind the multi-product production flow executed in an MTN can be seen as processes realized by using various local periodically functioning processes. The considered network of repetitively acting local transportation modes encompassing MTN's structure provides a framework for multimodal processes scheduling treated in terms of optimization of the AGVs fleet scheduling problem subject to fuzzy operation time constraints. In the considered case, both production takt and operation execution time are described by imprecise data. The aim of the paper is to present a constraint propagation (CP) driven approach to multi-robot task allocation providing a prompt service to a set of routine queries stated in both direct and reverse way. Illustrative examples taking into account an uncertain specification of robots and workers operation time are provided.

Key words: Automated guided vehicles (AGVs), Scheduling, Multimodal process, Fuzzy constraints, Optimization
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1 Introduction

Enterprises that produce large quantities of a variety of consumer products typically use the cyclic manufacturing strategy. It allows, at regular intervals, to provide the quantified products mixture. Cyclic manufacturing considerably simplifies the control of the flexible production system; i.e., a steady schedule is repeated for several time periods. Operational planning related to the appointment of cyclic schedules leads to difficult combinatorial problems. The vast majority of them belongs to the class of NP-hard problems, i.e., those for which there are no known solutions of polynomial computational complexity. In that context, the productivity of the flow shop served by the automated guided vehicles (AGVs), which repetitively produces a set of different products, depends on the job flow sequencing and the material handling system required, i.e., AGVs fleet sizing, assignment, and scheduling (Hall *et al*., 2001; Lu *et al*., 2013; Bocewicz *et al*., 2014).

Over several years, the majority of the research efforts in job scheduling has concentrated on the development of exact and suboptimal procedures for the generation of a baseline schedule assuming complete information and a deterministic environment. During execution, however, production flows may be the subject of considerable uncertainty, which may lead

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to numerous schedule disruptions. Therefore, in contrast to the usually studied deterministic cases, where the demand is known in advance, the problem considered in this study assumes a given transportation system encompassing the network of AGVs periodically circulating along cyclic routes while servicing load/unload operations of work pieces. The takt of production flow and its profitability depend on uncertainty constraints caused by the availability of the employed workers limited by fuzzy operation time constraints. Therefore, our contribution concerns AGVs fleet match-up scheduling subject to productivity constraints with reference to the schedule of the production flow imposed by the uncertainty implied by workers' availability for operations execution. Note that since the steady state of production flows has a cyclic character, servicing AGV-driven transportation processes also exhibit cyclic behavior. This means that, the periodicity of a flexible manufacturing system (FMS) depends on both the periodicity of the production flow cyclic schedule and, following this schedule, the AGVs periodicity. The problem of cyclic scheduling is rarely undertaken by the researchers. This is due to the lack of computational models allowing the construction of efficient algorithms. The studies concerning the cyclic systems are limited to the flow systems (Zaremba *et al.*, 1998).

Much research is concerned with the fleet assignment and maintenance planning problems (Abara, 1989; El Moudani *et al.*, 2000). Just a few works, however, have considered the integration of fleet assignment and maintenance planning and inventory policy (Polak *et al.*, 2004; Relich and Jakabova, 2013). Besides, many models and methods have been considered up to date: the mathematical programming approach (von Kampmeyer, 2006), max-plus algebra (Polak *et al.*, 2004), and constraint logic programming frameworks (Wójcik *et al.*, 2005; Bocewicz *et al.*, 2014) are the more frequently used. Most of these methods assume, however, that routing and allocation as well as batching and scheduling decisions are made independently and are oriented at finding a minimal production takt while assuming deadlock-free processes flow. In that context, our main contribution is to propose a declarative framework aimed at refinement and prototyping of the cyclic steady states for concurrently executed material handling systems composed of AGVs competing for the access to the common shared resources. In that context, our contribution can be seen as an extension of problems focusing on the question: Can the assumed AGVs fleet assignment reach its goal subject to constraints assumed on concurrent multi-product manufacturing on hand? That is, this paper is aimed at AGVs fleet match-up scheduling following itineraries of a variety of concurrently manufactured product types.

In comparison to its first extension (Wójcik *et al.*, 2015) taking into account fuzzy operation times while focusing on a direct way of scheduling problem formulation, this paper focuses on its reverse way formulation. In that context, the contribution shows the universality of the employed declarative modeling driven approach, which makes it possible to treat the above mentioned question in terms of the following two routine queries formulated in either (1) a direct way, i.e., focusing on the question 'what results from premises' (e.g., what schedule of AGVs fleet following a given set of operation times maximizes employers availability and production profitability?) or (2) a reverse way, i.e., focusing on the question 'what implies conclusion' (e.g., what set of operation times guarantees that the resultant schedule of a given AGVs fleet maximizes both employer availability and production profitability?).

2 Multimodal process prototyping

2.1 Systems of concurrent cyclic processes

An example of a multimodal transportation network (MTN) is shown in Fig. 1a. This is a transportation system of the FMS layout encompassing the network of AGVs periodically circulating along cyclic routes. This kind of system can be modeled in terms of systems of concurrently flowing cyclic processes (SCCPs) shown in Fig. 1b, where four local cyclic processes P_1, P_2, P_3, P_4 and their streams P_1^1, P_2^1, P_3^1, P_4^1, associated with the operation of four AGVs, and two multimodal processes (Bocewicz *et al.*, 2014) mP_1 and mP_2 representing two products W_1 and W_2, are considered. The processes are executed along given routes composed of six machining centers (R_1–R_6) and seven transportation sectors (R_7–R_{13}): $R=\{R_1, R_2, \ldots, R_{13}\}$.

1. $P=\{P_i|i=1, 2, \ldots, n\}$ is the set of local processes P_i specified by the set of streams: $P_i=\{P_i^1$,

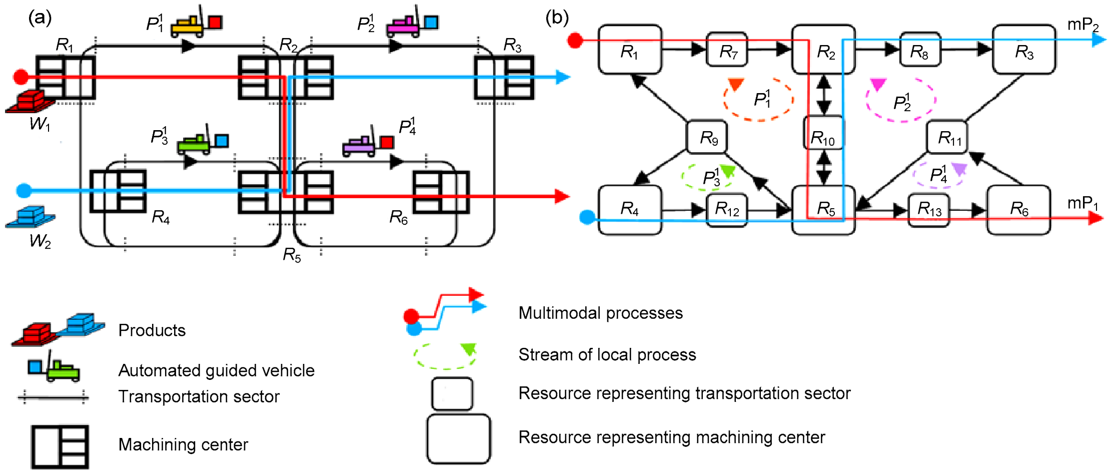


Fig. 1 Exemplary multimodal transportation network (MTN) (a) and its systems of concurrently flowing cyclic process (SCCP) representation (b)

P_i^2, …, $P_i^{\mathrm{ls}(i)}$ } (ls(i) is the number of streams of process P_i).

2. mP={mP$_i$|i=1, 2, …, w} is the set of multimodal processes described by sequences of some subsequences from local processes P, where each mP$_i$ is specified by the set of streams: $\mathrm{mP}_i=\{\mathrm{mP}_i^1$, mP_i^2, …, $\mathrm{mP}_i^{\mathrm{lms}(i)}\}$ (lms(i) is the number of streams of process mP$_i$).

The operations of multimodal processes' streams require execution of some local processes. For example, transport operations between resources in mP$_1$ (product W_1 in Fig. 1) require streams of local processes P_1, P_4, respectively. W_1 follows two streams: the first belonging to P_1 and passing along R_1, R_7, R_2, R_{10}, R_5, and the second belonging to P_4 and passing along R_5, R_{13}, R_6. 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. The resources belonging to these routes are simultaneously shared by both local and multimodal processes.

It is assumed that both kinds of processes are cyclic and act concurrently, but are synchronized by a mutual exclusion protocol, guaranteeing only one process (one product) can be executed on a common shared resource at a given time. To describe the system in Fig. 1b, let us introduce the following notations (Bocewicz *et al*., 2014):

1. $p_i^k=(p_{i,1}^k, p_{i,2}^k,\dots,p_{i,\mathrm{lr}(i)}^k)$ specifies the route of the kth stream of a local process P_i^k (the kth stream of the ith local process P_i), and its components define the resources used in the course of process operation execution, where $p_{i,j}^k\in R$ (R={R_1, …, R_c, …, R_m}) denotes the set of resources used for the jth operation in the kth stream of the ith local process; the jth operation executed on resource $p_{i,j}^k$ in stream P_i^k is denoted by $o_{i,j}^k$; lr(i) is the length of the process route.

2. $t_i^k=(t_{i,1}^k, t_{i,2}^k,\dots,t_{i,\mathrm{lr}(i)}^k)$ specifies the ith process operation times, where $t_{i,j}^k$ denotes the time of execution of the jth operation $o_{i,j}^k$ in stream P_i^k.

3. $x_{i,j}^k(l)\in\mathbb{N}$ is the moment of operation $o_{i,j}^k$ beginning in the lth cycle.

4. $\mathrm{mp}_i^k=(\mathrm{mpr}_{i_1}^{a_1}(a_{i_1}, b_{i_1})\cap \mathrm{mpr}_{i_2}^{a_2}(a_{i_2}, b_{i_2})\cap\dots$ $\cap\mathrm{mpr}_{i_y}^{a_y}(a_{i_y}, b_{i_y}))$ specifies the route of the stream mP_i^k from the multimodal process mP$_i$ (the kth stream of the ith multimodal process mP$_i$), where

$$\mathrm{mpr}_i^q(a,b)=\begin{cases}(p_{i,a}^q, p_{i,a+1}^q,\dots,p_{i,b}^q), & a\le b,\\ (p_{i,a}^q, p_{i,a+1}^q,\dots,p_{i,\mathrm{lr}(i)}^q, p_{i,1}^q,\dots,p_{i,b}^q), & a>b,\end{cases}$$

a, $b\in${1, 2, …, lr(i)}, and $u\cap v$ is the concatenation of sequences u and v. If u=(u_1, u_2, …, u_a), v=(v_1, v_2, …, v_b), and u_a=v_1, then $u\cap v$=(u_1, u_2, …, u_a, v_2, …, v_b).

The route mp_i^k is a sequence of sections of local streams p_i^q and determines the production routes taking into account transportation means (e.g., AGVs). In the rest of the paper, the jth operation of the stream mP_i^k will be denoted by $\mathrm{mo}_{i,j}^k$. The operation times $\mathrm{mt}_{i,j}^k$ of multimodal processes are the operation times of AGV moving between the machining centers (i.e., assigned to AGVs moving along sectors R_7–R_{13}) and the working times assigned to machining centers R_1–R_6. Transportation times are the same as those of relevant operations in local processes. However, the working time $\mathrm{mt}_{i,j}^k$ assigned to machining centers R_g is equal to $\mathrm{mt}_{i,j}^k = x_{a,b}^c(l) - x_{d,e}^f(l)$, where $x_{a,b}^c(l)$ is the moment the process mP_i^k leaves R_g (taken by local stream P_c^a) and $x_{d,e}^f(l)$ is the moment the process mP_i^k enters R_g.

5. $\mathrm{mx}_{i,j}^k(l) \in \mathbb{N}$ are moments of operation $\mathrm{mo}_{i,j}^k$ beginning in the lth cycle.

6. $\Theta^l=\{\sigma_1^l, \sigma_2^l, \ldots, \sigma_c^l, \ldots, \sigma_m^l\}$ is the set of the priority dispatching rules of local (l=0) and multimodal processes (l=1), where σ_c^l is the sequence whose components determine an order in which the streams of processes can be executed on resource R_c. Therefore, the SCCP can be defined as the pair

$$\mathrm{SC}=((R,\mathrm{SL}),\mathrm{SM}), \tag{1}$$

where $R=\{R_1, R_2, \ldots, R_m\}$ is the set of resources, $\mathrm{SL}=(P, U, T, \Theta^0)$ characterizes the structure of local processes of SCCP (P is the set of local processes, U the set of local process routes, T the set of local process operations times, Θ^0 the set of dispatching priority rules), and $\mathrm{SM}=(\mathrm{mP}, M, \mathrm{mT}, \Theta^1)$ characterizes the structure of multimodal processes of SCCP (mP is the set of multimodal processes, M the set of multimodal process routes, mT the set of operation times, Θ^1 the set of dispatching rules).

The considered SC model (1) of the SCCP (Bocewicz *et al*., 2014) enables one to state a search problem aimed at determining the structural parameters (U, M, T, mT, Θ, etc.) guaranteeing cyclic execution of processes. Since parameters guaranteeing a cyclic behavior of an SCCP under uncertain operation time constraints are sought, the following uncertainty assumptions have to be taken into account:

1. Working time $\mathrm{mt}_{i,j}$ assigned to a machining center belongs to a so-called availability zone specified by fuzzy set $s_{i,j}=\mu(\mathrm{mt}_{i,j})$, $s_{i,j}\in[0, 1]$. The membership function $\mu(\mathrm{mt}_{i,j})$ determines the worker's availability for operations handling. $s_{i,j}$=0 means that the corresponding value $\mathrm{mt}_{i,j}$ is out of the worker's availability, while $s_{i,j}$=1 means available, with acceptable working time value $\mathrm{mt}_{i,j}$.

2. The accepted production takt mTc_i of the ith multimodal process has to follow the assigned production profitability sT_i measured along mP_i. The takt time of the process mP_i is the time between two consecutive moments of its subsequent streams completion: $\mathrm{mTc}_i=\mathrm{mx}_{i,j}^k(l)-\mathrm{mx}_{i,j}^{k-1}(l)$ (for one pipeline process: $\mathrm{mTc}_i=\mathrm{mx}_{i,j}^k(l)-\mathrm{mx}_{i,j}^k(l-1)$). Similar to the availability zone $s_{i,j}$, the assigned production profitability zone sT_i is specified by fuzzy set $\mathrm{sT}_i=\mu(\mathrm{mTc}_i)$, $\mathrm{sT}_i\in[0, 1]$. The membership function $\mu(\mathrm{mTc}_i)$ determines production profitability following mTc_i. sT_i=0 means that production performed with takt mTc_i is not profitable, while sT_i=1 means that takt mTc_i ensures profitability.

Tables 1 and 2 show the representative workers' availability for operations handling and production profitability zones (specified by the membership functions $\mu(\mathrm{mt}_{i,j})$ and $\mu(\mathrm{mTc}_i)$) for the system in Fig. 1. That means, for instance, the expected worker's availability for product W_1 (process mP_1) on resource R_5 should be about 6 (e.g., between 3 and 8) and production takt mTc_1 be less than 19 (e.g., no higher than 31). The uncertainty constraints as well as constraints guaranteeing deadlock-free processes execution contribute to a declarative model of SCCP behavior.

2.2 Constraint programming model

The behavioral characteristics guaranteeing deadlock-free execution of processes while following above-mentioned uncertainty requirements can be specified by the following cyclic schedule:

$$X_{\mathrm{SC}}=((X, \alpha), (\mathrm{mX}, \mathrm{m}\alpha)). \tag{2}$$

This kind of schedule X_{SC} is defined as a sequence of ordered pairs describing the behavior of local (X, α) and multimodal $(\mathrm{mX}, \mathrm{m}\alpha)$ processes, where $X=\{x_{1,1}^1, \ldots, x_{i,j}^k, \ldots, x_{n,\mathrm{lr}(n)}^{\mathrm{ls}(n)}\}$ is a set of moments

Table 1 Awaiting working times of operations for multimodal processes mP_1 and mP_2

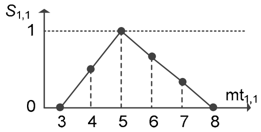
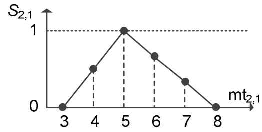
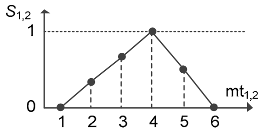
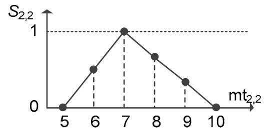
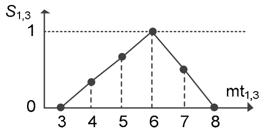
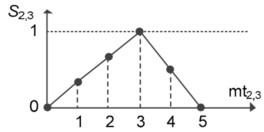
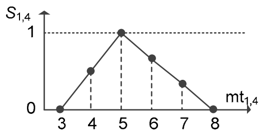
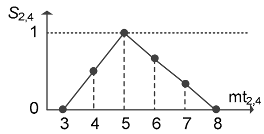
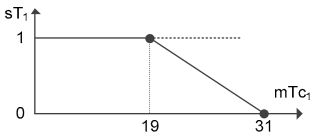
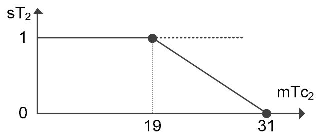
Awaiting working times for mP_1	Awaiting working times for mP_2
 Working time $mt_{1,1}$ of operation assigned to R_1 is 'about 5'	 Working time $mt_{2,1}$ of operation assigned to R_4 is 'about 5'
 $mt_{1,2}$ is 'about 4' (on R_2)	 $mt_{2,2}$ is 'about 7' (on R_5)
 $mt_{1,3}$ is 'about 6' (on R_5)	 $mt_{2,3}$ is 'about 3' (on R_2)
 $mt_{1,4}$ is 'about 5' (on R_6)	 $mt_{2,4}$ is 'about 5' (on R_3)

Table 2 Expected profitability measured by production takt of processes mP_1 and mP_2

Production profitability measured along mP_1	Production profitability measured along mP_2
 Production takt mTc_1 less than 19	 Production takt mTc_2 less than 19

$x_{i,j}^k$ for the first cycle of operations $o_{i,j}^k$ beginning from stream P_i^k. By analogy, the set mX= $\{mx_{1,1}^1, ..., mx_{i,j}^k, ..., mx_{w,lm(w)}^{lms(w)}\}$ consists of moments of multimodal processes operations beginning, where w is the number of multimodal processes and lm(i) the number of operations of the ith multimodal process. Variables $x_{i,j}^k / mx_{i,j}^k \in \mathbb{Z}$ determine moments of operations beginning in the lth cycle of the SCCP cyclic steady state: $x_{i,j}^k / mx_{i,j}^k = (x_{i,j}^k + l \cdot \alpha)/(mx_{i,j}^k + l \cdot m\alpha)$. Since values of $x_{i,j}^k / mx_{i,j}^k$ follow the system structure parameters, the cyclic behavior X_{SC} is determined by SC. Moreover, the multimodal processes behavior (mX, mα) depends on the local cyclic processes behavior (X, α). The constraints determining the admissible cyclic schedule (2) are the following:

1. Uncertainty constraints (Tables 1 and 2): level of workers' availability for operations handling S and level of production profitability E (caused by X_{SC}) for the whole SCCP, are determined as a minimal value $s_{i,j}$ among all of the workers' availabilities, and a minimal production profitability sT_i among all the multimodal processes, respectively:

$$S = \min_{i=1,2;\ j=1,2,3,4} \{s_{i,j}\},\ E = \min_{i=1,2} \{sT_i\}. \tag{3}$$

2. Constraints describing the local processes execution: the moment of operation $o_{i,j}^k$ beginning states for a maximum of both: the completion time of the operation $o_{i,j-1}^k$ preceding $o_{i,j}^k$, and the release time of the resource $p_{i,j}^k$ awaiting $o_{i,j}^k$ execution:

moment of $o^k_{i,j}$ beginning=

$$\max\{(\text{moment of } p^k_{i,j} \text{ release} + \text{lag time } \Delta t), (\text{moment of } o^k_{i,j-1} \text{ completion})\}. \quad (4)$$

3. Constraints describing multimodal processes execution: the moment of operation $\text{mo}^k_{i,j}$ commencement is equal to the nearest admissible value (determined by the set $\chi^k_{i,j}$ of values $\text{mx}^k_{i,j}$) being a maximum of both: the completion time of operation $\text{mo}^k_{i,j-1}$ preceding $\text{mo}_{i,j}$, and the release time (lag time Δtm) of the resource $\text{mp}^k_{i,j}$ awaiting $\text{mo}^k_{i,j}$ execution:

moment of $\text{mo}^k_{i,j}$ beginning=

$$\lceil \max\{(\text{moment of } \text{mp}^k_{i,j} \text{ release} + \text{lag time } \Delta\text{tm}), (\text{moment of operation } \text{mo}^k_{i,j-1} \text{ completion})\} \rceil_{\chi^k_{i,j}}, \quad (5)$$

where $\chi^k_{i,j} = \{x^c_{a,b}(l) \mid x^c_{a,b}(l) = x^c_{a,b} + l\cdot\alpha; l \in \mathbb{Z}\}$ is the set of admissible values of $\text{mx}^k_{i,j}$ determined by $x^c_{a,b}$, where $x^c_{a,b}$ is the moment of operation $o_{a,b}$ beginning enabling execution of the operation $\text{mo}^k_{i,j}$, $\lceil a \rceil_B=\min\{k\in B: k\geq a\}$.

Constraints (3)–(5) describe the conditions guaranteeing cyclic execution of SCCP processes subject to arbitrarily given uncertainty constraints assuming employers availability S and production profitability E.

A number of admissible schedules X_{SC} (2), denoted by L, depend on SC (1) and especially on the assumed operations times of local processes T (including transportation and layover times of AGVs). In that context, different values of transportation and layover times $t^k_{i,j}$, determining different values of working time $\text{mt}^k_{i,j}$ and takts mTc_i, lead to schedules with different levels of workers' availability S and, following these, levels of production profitability E (according to Tables 1 and 2). Relevant illustration of that fact can be seen in Fig. 2 showing a number L of admissible schedules X_{SC} following constraints (4) and (5) for SCCP from Fig. 1, while taking into account uncertainty constraints (3) for S and E. The observed results are obtained for operation times $t^k_{i,j} \in\{1, 2, \ldots, 6\}$. Space $\mathbb{L}$ from Fig. 2 consists of 362 880 cyclic schedules X_{SC} following constraints E, S>0.

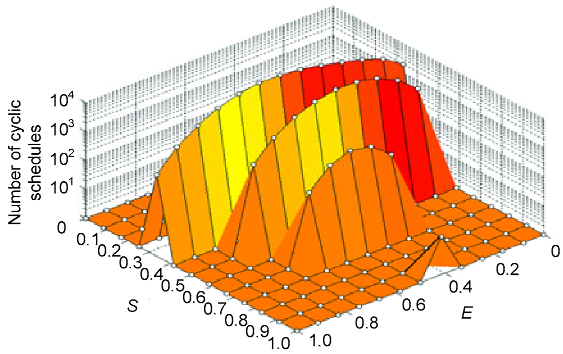


Fig. 2 Space of admissible schedules $\mathbb{L}$ including L solutions for the system from Fig. 1 parameterized by S and E

2.3 Problem statement

Considering the SCCP (1) specified by the given sets of resources R, dispatching rules Θ^0 and Θ^1, as well as local U and multimodal M process routes, we seek answers to the following two questions:

1. What cyclic schedule X_{SC} following a given set of dispatching rules Θ and operation times T and mT, maximizes the employers' availability S and production profitability E?

2. What operation times T and mT guarantee the cyclic schedule X_{SC} following a given set of dispatching rules, while maximizing the employers' availability S and production profitability E?

The considered questions correspond to two kinds of SCCP optimization problems, analysis and synthesis, i.e., standing for a direct way and a reverse way problem formulation respectively:

Problem of the SCCP analysis: Given the model (1) specified by the set of resources R, sets of routes U and M, sets of operation times T and mT, sets of priority dispatching rules Θ^0 and Θ^1, as well as constraints (3)–(5), implying the cyclic schedule X_{SC} encompassing the behavior of the modeled SCCP, we seek the answer to the question whether there exists a cyclic schedule X_{SC} guaranteeing maximum values of S and E: S→max and E→max.

This kind of problem boils down to the following optimization constraint satisfaction problem:

$$\mathrm{CS}_X = ((X_{\mathrm{SC}}, D_X), C), \quad (6)$$

where X_{SC} represents the decision variables (cyclic schedule), D_X the domains determining the admissible values of decision variables (D_X: $\mathrm{mx}_{i,j}^k, x_{i,j}^k \in \mathbb{N}$), and C the set of constraints describing the execution of local and multimodal processes (3)–(5), and requirements: $S\rightarrow$max and $E\rightarrow$max.

Problem of SCCP synthesis: Given the model (1) specified by the set of resources R, sets of routes U and M, sets of priority dispatching rules Θ^0 and Θ^1, as well as constraints (3)–(5), we seek the answer to the question which operation times T and mT guarantee there exists a cyclic schedule X_{SC} maximizing S and E: $S\rightarrow$max and $E\rightarrow$max.

This kind of problem boils down to the following optimization constraint satisfaction problem:

$$\mathrm{CS}_{\mathrm{XT}}=((\{X_{\mathrm{SC}}, T_{\mathrm{SC}}\}, \{D_X, D_T\}), C), \quad (7)$$

where X_{SC} is the cyclic schedule (2), T_{SC} the sequence of operation times, $T_{\mathrm{SC}}=(T, \mathrm{mT})$, D_X and D_T the domains determining the admissible values of decision variables (D_X: $\mathrm{mx}_{i,j}^k, x_{i,j}^k \in \mathbb{N}$; D_T: $\mathrm{mt}_{i,j}^k, t_{i,j}^k \in \{1, 2, \ldots, 6\}$), and C the set of constraints describing the execution of local and multimodal processes (3)–(5), as well as requirements: $S\rightarrow$max and $E\rightarrow$max.

Note that variables X_{SC} and T_{SC}, following constraints C, provide a solution to problems (6) and (7) for CS_X and $\mathrm{CS}_{\mathrm{XT}}$, respectively, i.e., guarantee cyclic behavior of local and multimodal processes while following $S\rightarrow$max and $E\rightarrow$max. Moreover, since S and E have to be optimized simultaneously, the solution following a trade-off between those conflicting objectives has to belong to Pareto-optimal ones. Well-known constraint programming driven software platforms such as ILOG, OzMozart, and ECL^{i}PSE (Sitek and Wikarek, 2015) can be used for solving problems (6) and (7).

3 Computational experiments

Consider the AGV system in Fig. 1. Given the expected profitability value measured by production takts mTc_1 and mTc_2 of multimodal processes mP_1 and mP_2, respectively (Table 2), as well as awaiting working times of operations (Table 1), for this kind of system the following two problems are considered:

Problem of SCCP analysis: Given the set of operation times $T=\{t_1^1, t_2^1, t_3^1, t_4^1\}$ specifying local processes (i.e., times required for AGVs movement along transportation sectors and machining times the work pieces spent on machining centers), where $t_1^1=(5, 2, 4, 2, 1, 2)$ represents execution times of P_1^1 operations performed on the resources R_1, R_7, R_2, R_{10}, R_5, R_9, respectively, $t_2^1=(5, 2, 1, 2, 3, 2)$, $t_3^1=(5, 2, 5, 2)$, $t_4^1=(5, 2, 4, 2)$, in case of the so-called no-wait schedule (where operations do not await their execution), the considered operation times guarantee the maximum level of workers' availability S while taking into account constraints from Table 1.

Request 1 Does a cyclic schedule X_{SC} maximizing the values of S and E, $E\rightarrow$max and $E\rightarrow$max, exist?

The solution was obtained in 1 s. The corresponding schedule X_{SC} is shown in Fig. 3, where operation times of multimodal processes (mP_1 and mP_2) are distinguished by membership functions. In both cases, for operation times the constraints collected in Table 1 are considered with the same level S=1. However, the value of takt (mTc_1=mTc_2=26) following from the schedule exceeds the requirement ('about 19', see Table 2) with level E=0.416. It means that a high value of workers' availability S=1 results in a low level of production profitability E=0.416.

Problem of SCCP synthesis: The arising question regards the SCCP synthesis problem, i.e., whether there exists any value of SCCP parameters (e.g., operations times of local processes) resulting in a higher value of E.

Request 2 What operation times T (where $t_{i,j}^k \in \{1, 2, \ldots, 6\}$) guarantee that a cyclic schedule X_{SC} maximizing S and E ($S\rightarrow$max and $E\rightarrow$max) exists?

Problems for CS_X and $\mathrm{CS}_{\mathrm{XT}}$ formulated due to problems (6) and (7), respectively, have been implemented and solved in the constraint programming environment OzMozart (Intel Core 2 Duo 3 GHz CPU and 4 GB RAM). Due to Fig. 2, the search process took into account the space $\mathbb{L}$ of admissible solutions containing over 3.6×10^5 items. The set of Pareto-optimal solutions (Fig. 4a) was obtained in less than 30 s. Four kinds of alternative solutions (S, E) can be considered: (1, 0.416), (0.66, 0.66), (0.5, 0.75), (0.33, 1) (denoted by circle/dot points in Fig. 4b).

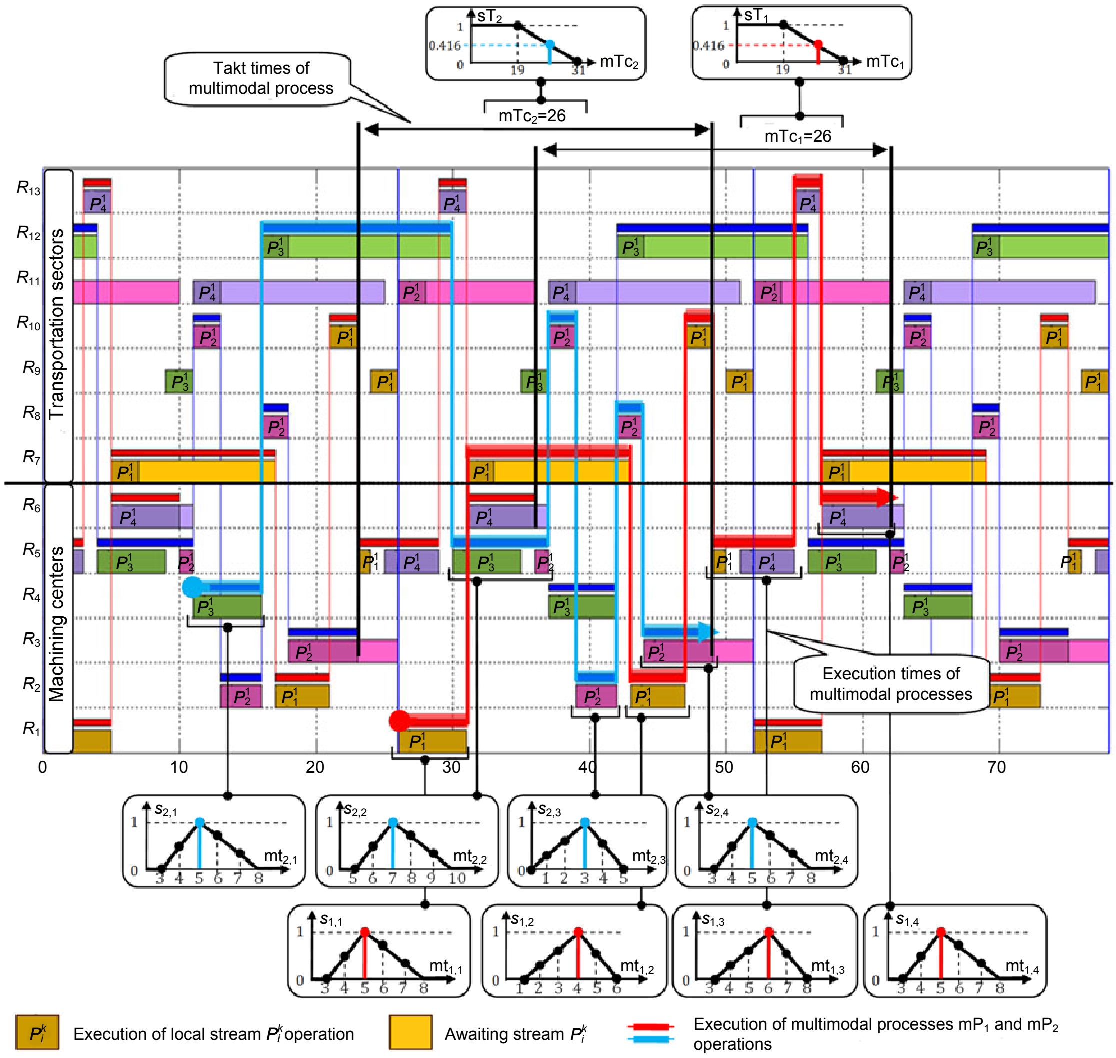


Fig. 3 The cyclic schedule for the automated guided vehicle system from Fig. 1 which guarantees *S*=1 and *E*=0.416

Fig. 5 shows the exemplary schedule X_{SC}, following $T=\{t_1^1, t_2^1, t_3^1, t_4^1\}$, where t_1^1=(5, 2, 4, 2, 1, 2), t_2^1=(5, 2, 1, 2, 3, 2), t_3^1=(5, 2, 5, 2), t_4^1=(5, 2, 4, 2), while leading to (0.33, 1).

In the studied case (*E*=1) it means that the shorter takt ($mTc_1=mTc_2=19$) implies a higher value of production profitability. However, this is achieved at the cost of multimodal processes deceleration caused by the decreasing workers availability *S*=0.33. Besides the case (1, 0.416) being the solution to the earlier discussed problem of SCCP analysis, other feasible solutions (0.66, 0.66) and (0.5, 0.75) can be treated as middle way ones, i.e., providing high but not maximal values of *E* and *S*.

Table 3 summarizes the results of the experiments conducted for different scale cases belonging to the classes of analysis and synthesis problems. In all the considered cases, the number of operations in each local cyclic process does not exceed six. So, the presented approach seems to be quite effective in case of analysis problems—the calculation time is less than 10 s. In case of synthesis problems, however, the practical implementation of the approach is limited to networks composed of up to 10 locally acting cyclic processes. So, the low efficacy follows from a rapid growth in the search space caused by the introduction of extra decision variables *T*. The reason is that in case of *T* the phenomenon of the so-called weak constraints propagation occurs (Sitek and Wikarek, 2015).

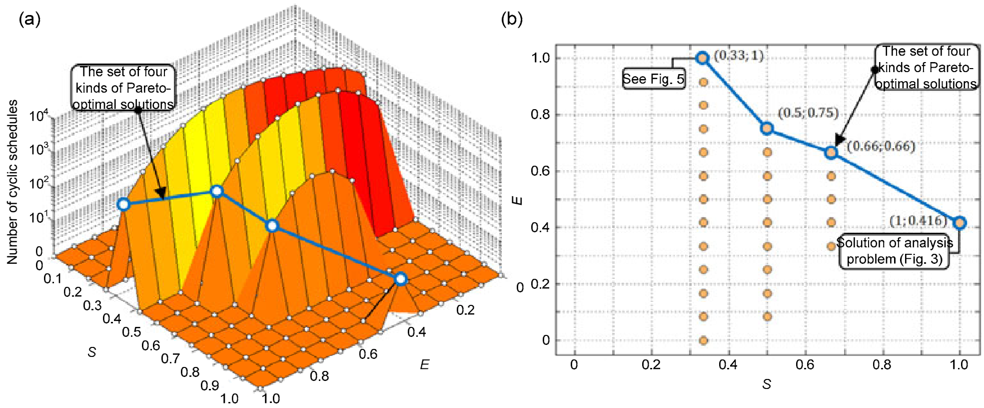


Fig. 4 Space of admissible schedules 𝕃 including *L* solutions for the system from Fig. 1 parameterized by *S* and *E* (a), and 'top-down view'—elevation of 𝕃 onto the *S*-*E* plane (b)

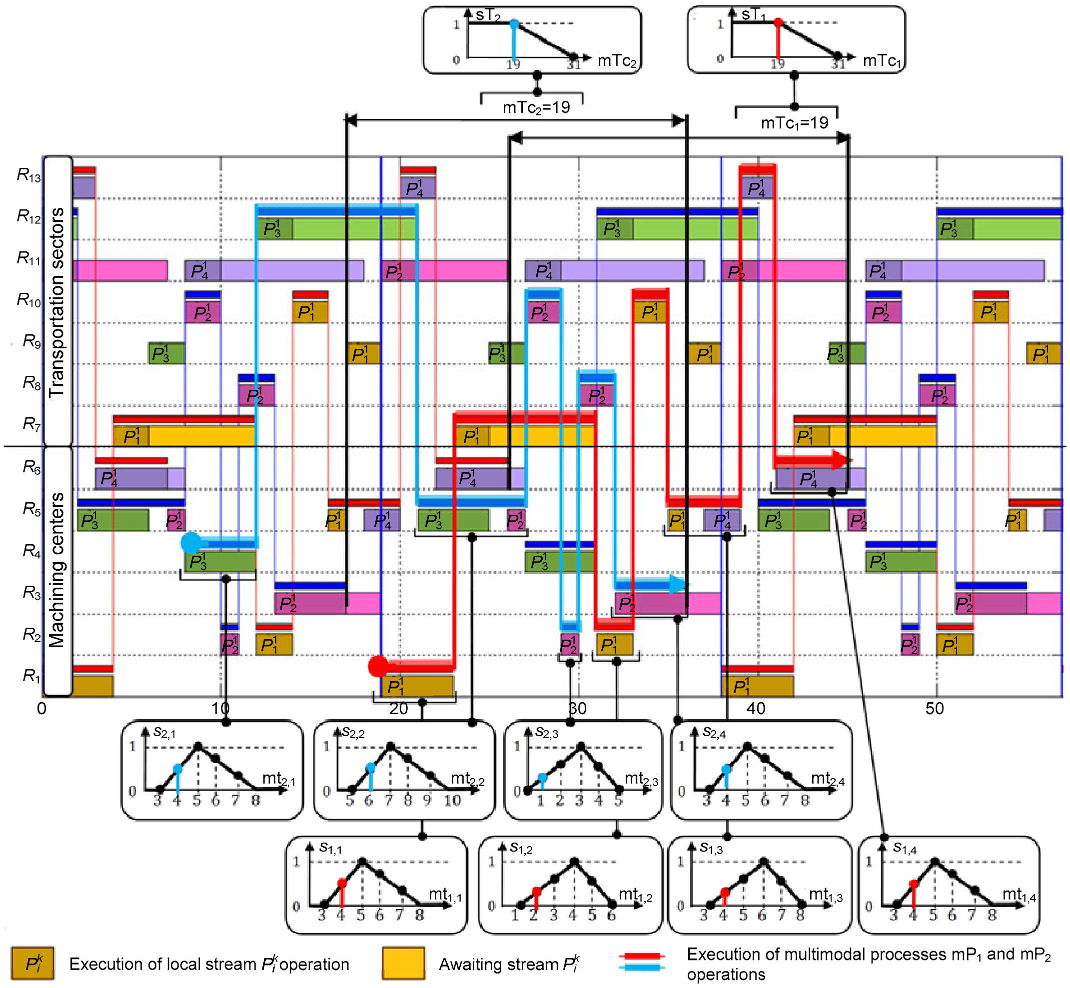


Fig. 5 The cyclic schedule for the automated guided vehicle system from Fig. 1 which guarantees *S*=0.33 and *E*=1

4 Conclusions

The considered declarative modeling driven approach offers a unified method for performance evaluation of local and multimodal processes supported by them. Particularly, the AGVs fleet scheduling problem stated in terms of the constraint satisfaction problem provides a constraint programming

Table 3 Calculation times required for solutions of analyzing and synthesizing different scale problems

Size of SCCP (number of local processes)	Computation time (s)*	
	SCCP analysis (variables: X_{SC})	SCCP synthesis (variables: $T(t_{i,j}^k \in \{1,2,\ldots,6\})$ and X_{SC})
3	<1	5
4**	<1	30
5	<1	111
10	3	4213
15	5	>7200***
20	7	>7200***
30	10	>7200***

* Computational environment: OzMozart with Intel Core 2 Duo 3 GHz CPU and 4 GB RAM; ** considered example (Figs. 1–5); *** after 7200 s computations have been stopped

driven platform enabling to consider frequently occurring questions corresponding to two kinds of SCCP optimization problems, namely analysis and synthesis, which represent a direct way and a 'reverse' way of problem formulations. Subsequently, to solve these problems, a set of constraints was developed based on the particular nature of the model, which could be implemented in a constraint programming driven DSS, which makes it possible to deal with the selection of modes to operations, and with the scheduling of all operations. The results and analyses were illustrated through examples presenting introduced assumptions and resulting from their sufficient conditions.

The provided sufficient conditions make it possible to design an AGV transportation network in such a way as to obtain the final AGVs fleet schedule guaranteeing the required quantitative and qualitative features. This leads to a method allowing one to replace the exhaustive search for the admissible control by a step-by-step design (Bocewicz *et al*., 2014) of the transportation system encompassing the required behavior. The most important challenge for further work deals with rescheduling problems subject to fuzzy operation time constraints (Relich and Jakabova, 2013). Special attention will be devoted to conditions guaranteeing the assumed robustness level of the AGVs fleet schedule.

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