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A decision support model for prototyping in-plant milk-run traffic systems

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Abstract: In the present study, a declarative model is developed which allows to formulate a constraint satisfaction problem that provides decision support for prototyping in-plant milk-run traffic systems. In particular, the model is used to determine the number of transport trips and their organization in time and space needed for timely delivery of material to specific loading/unloading points. Implemented in a constraints programming driven solver, it allows to formulate forward and reverse milk-run vehicle routing and scheduling problems subject to constraints imposed by an in-plant distribution network. In this context, our contribution can be seen as an alternative approach to DSS design, which allows one to search for solutions by alternate and iterative formulation of successive forward and reverse decision problems.

Keywords: Milk-run method, fleet routing and scheduling, decision support system.

1. INTRODUCTION

One of the basic obstacles that limit optimal use of the capacity of in-plant distribution systems is poor organization of traffic flows, which does not ensure congestion-free movement of transport vehicles. Congestion caused by heavy traffic, which exceeds the capacity of the infrastructure leads to collisions and/or deadlocks between vehicles. In general, whether or not congestion will occur depends either on the capacity (topology) of the transport infrastructure used when the volume of traffic is given, or the volume of traffic in an infrastructure of a given capacity.

The two perspectives mentioned above assume that, just as every system structure (including the infrastructure of a transport system) determines acceptable behaviors of the system (e.g. milk-run traffic routing and scheduling), so too any given system behavior (e.g. related to the distribution of goods) can be achieved (realized) in systems with different infrastructures. The solution to these problems is determined by the relationships between selected structural and functional parameters of the system. This means that the models sought should take into account both those decision variables which describe the topology of a transport network, the fleet of vehicles that use it, and the stations and loading/unloading stops across the network, as well as those which describe transport routes and delivery/pickup schedules. In particular, such models should make it possible to formulate and solve two types of problems: forward problems, hereinafter “analysis problems” (e.g. Does the arbitrarily given transport network structure of a distribution system allow to run transport processes in a way that will meet user expectations?) and reverse problems, hereinafter “synthesis problems” (e.g. Does there exist a structure of a distribution system transport network in which transport processes are executed in a way that will satisfy the given expectations of its users?).

It is easy to notice that in both classes of problems there is a constraint that preempts simultaneous access of different means of transport to the same route sections of the distribution network, a constraint which entails the necessity to resolve resource conflicts. Problems of this type, i.e. problems related to finding solutions that guarantee congestion-free (e.g. deadlock-free) traffic of concurrently executed milk-run flows belong to the class of NP-hard problems. In this context, the goal of our study is to find a computationally effective approach aimed at simultaneous routing and scheduling of flows of logistics trains as well as the design of a distribution network infrastructure. Put differently, the reference model sought, which allows to formulate a decision problem that captures the importance of striking an equilibrium between potential expectations regarding milk-run traffic and the capacity of the existing distribution network, focuses on resolving resource conflicts, i.e. conflicts that arise when different activities simultaneously request access to resources of a limited quantity.

This means that the purpose of the present study is to develop a method, derived from the reference model, oriented toward the use of decision-support-system-like software. With this in mind, we employ the declarative modeling framework, mostly because of its fast prototyping capability. It should be recalled that in declarative models, focus is on what the solution is. In other words, in contrast to imperative models of computation, which are expressed in terms of states and sequences of state-changing operations and take an “inside-out” approach, i.e. simply describe how a solution is obtained, declarative models take an “outside-in” approach. Instead of describing how a process has to work exactly, a declarative model specifies only the essential characteristics of a process.

The present study is a continuation of our previous work on methods of fast prototyping of solutions to selected problems of routing, batching and scheduling of tasks typically performed in batch flow production systems, as well as problems regarding the planning and control of production flow in departments of automotive companies (Bocewicz et al. 2019a, 2019b).

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Section 2, which presents a review of selected literature of the subject, describes the expectations related to the development of methods for interactive milk-run traffic planning. Section 3, in presenting the concept of a DSS dedicated to the prototyping of milk-run traffic systems, discusses a declarative model of a milk-run delivery problem and a supply cycles prototyping method developed on its basis. Section 4 shows how the model can be used in supply cycles prototyping tasks. The reported computer experiments, performed in the Oz Mozart constraint programming environment, illustrate the possibilities of practical application of the proposed approach. Section 5 provides the key conclusions and proposes the main directions of future research.

2. LITERATURE REVIEW

In a milk-run system, routes, time schedules, type and number of parts to be transported are assigned to different logistics trains so that they can collect orders from different suppliers (Kili et al. 2012). In other words, the trains perform several pick-ups/deliveries in a round trip to meet customer demands. The benefits of using a system of this type include improved efficiency of the overall logistics system and substantial potential savings in environmental and human resources along with remarkable cost advantages related to inventory and transportation costs (Schmidt 2016; Meyer 2015; De Moura and Botter 2016; Gola and Klosowski 2018). The Milk-run Vehicle Routing Problem (Mei et al. 2017) can be seen as a special case of the Vehicle Routing Problem (VRP) (Carić et al. 2008; Nguyen et al. 2017), which in turn is a generalization of the Traveling Salesman Problem aimed at finding the optimal set of routes for a fleet of vehicles delivering goods or services to various locations. Of course, there is a large body of (OR-) literature (e.g. on vehicle scheduling, routing, and dispatching) which addresses relevant aspects of transportation of goods, but only a few papers are devoted specifically to in-plant milk-run traffic problems. In this respect, the most relevant are areas subject to critical and often unpredictable traffic congestions which occur when logistics operators allocate too many collecting tasks to available vehicles, generating unperformed activities due to assumed just-in-time constraints and thus violating contractual obligations assumed with their clients (Novaes et al. 2015;). Most of the research in the field of distribution logistics is devoted to the analysis of the methods of organizing transport processes in ways that minimize the size of the fleet, the distance traveled (energy consumed), or the space occupied by a distribution system. In focusing on the search for optimal solutions, these studies implicitly assume that there exist admissible solutions, e.g. ones that ensure collision-free and/or deadlock-free (congestion-free) flow of concurrent transport processes. In practice, this requires either on-line updating (revision) of the routing policies used, or prior (offline) planning of congestion-free vehicle routes and schedules. Studies on generating dynamic routing policies are conducted sporadically (Carić et al. 2008); even less frequent are investigations of robust routing and scheduling of milk-run traffic, which are, by and large, limited to AGV systems.The congestion avoidance problem, which conditions the existence of admissible solutions, is an NP-hard problem (Kok 2010; Toth and Vigo 2002). Because the necessary and sufficient conditions for deadlock-free execution of concurrent processes are not known, system analysis (i.e. analysis of the states potentially leading to system deadlocks) is most frequently performed using the laborious and time-consuming computer simulation methods (Güner et al. 2017; Carić et al. 2008). In practical applications, congestion avoidance methods (e.g. deadlock prevention) are used, which implement the sufficient conditions for collision-free execution of processes. This means that the time-consuming method of analyzing distribution networks with a view to detecting situations which lead to deadlocks between concurrent transport flows can be replaced by searching for a synchronization mechanism that would guarantee cyclic execution of these flows. Methods that are most commonly used for such purposes include those that use the formalism of max-plus algebra (Polak et al. 2004) and constraint programming (Bocewicz 2019b; Sitek and Wikarek 2017). It should be noted that the possibility of fast implementation of the process-synchronization mechanism comes at the expense of omitting some of the potentially possible scenarios for deadlock-free execution of the processes.

The shortcomings of the above-described methods of generating admissible solutions restrict their implementation in DSS systems, in particular in systems supporting planning in milk-run traffic systems. Given this background, our contribution boils down to the assessment of the possibility of using declarative modeling methods (e.g. Bocewicz 2019b) in solutions that provide interactive decision support for prototyping in-plant milk-run traffic systems.

3. PROTOTYPING OF MILK-RUN TRAFFIC SYSTEMS

Consider a multi-item batch flow production system in which in-plant transport operations are organized in milk-run loops (see Fig. 1). Logistics trains traveling along fixed routes are used as in-plant transport means to deliver the required quantity of materials to work stations within given time windows. The basic problem is to find a method by which to organize timely and congestion-free movement of the logistics trains used to deliver/pick up ordered goods. There are two types of such methods which correspond to the two types of questions related to:

- the assessment of the quality of the distribution processes executed by a fleet of logistics trains moving along given transport routes,
- the prototyping of logistics train routes that allow to achieve the expected quality of distribution processes.

The investigated distribution system modeling problems can be viewed as Constraint Satisfaction Problems (CSP) (Bocewicz et al. 2019b), given by (1):

$$PS = ((\{X, B, F\}, \mathcal{D}), \mathcal{C}), \quad (1)$$

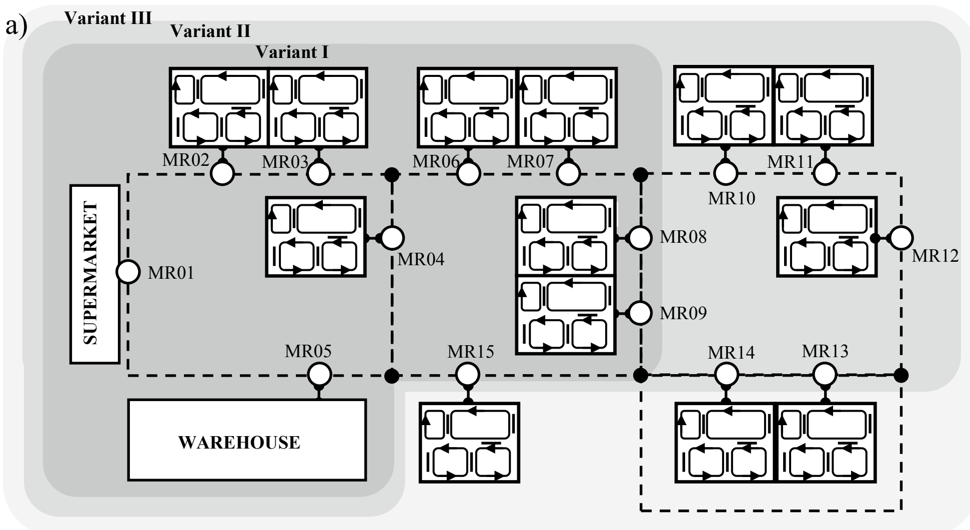
where:

$\{X, B, F\}$ – a set of decision variables including:

X – a cyclic schedule of local process operations executed in milk-run loops,

B, F – sequences specifying the order in which delivery operations o_λ are executed by successive processes in milk-run loops (processes of set P),

$\mathcal{D}$ – a finite set of decision variable domains $\{X, B, F\}$



b) Time of the transport operation from MR02 to MR04

pick and place points

	01	02	[illegible]	04	05	06	07	08	09	10	11	12	13	14	15
01	0	25	3[illegible]	42	57	41	49	58	65	63	69	76	92	99	77
02	50	0	7	18	33	17	25	34	41	38	44	52	68	75	53
03	43	67	0	11	26	11	18	27	34	32	38	46	61	68	46
04	33	57	64	0	15	12	19	28	35	33	39	47	62	69	47
05	18	42	49	59	0	59	66	75	82	80	86	94	109	116	94
06	69	93	100	54	51	0	8	17	24	22	28	35	51	58	36
07	61	85	92	47	44	58	0	9	16	14	20	28	44	51	29
08	52	76	83	38	35	49	56	0	7	13	19	27	42	49	20
09	45	70	76	31	28	42	50	7	0	20	26	34	49	56	13
10	79	103	110	65	62	76	83	54	47	0	7	14	30	37	47
11	73	97	104	59	56	70	77	47	41	60	0	8	24	31	41
12	65	90	96	51	48	62	69	40	33	52	58	0	16	23	33
13	50	74	81	35	32	46	54	24	17	36	43	50	0	7	17
14	43	67	74	28	26	39	47	17	10	30	36	43	59	0	10
15	33	57	64	19	16	30	37	46	53	51	57	65	80	87	0

Tab. Times $d_{\beta,\lambda}$ of transport operations between pick and place points

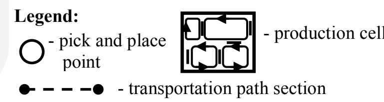


Fig. 1 Layout of the multi-item batch flow production system under study a) table of transport operations times b)

$\mathcal{C}$ – a set of constraints specifying the relationships between processes implemented in milk-run cycles and the processes executed along the technological routes of the individual products.

In general terms, to solve a constraint satisfaction problem is to determine such values of the decision variables from the adopted set of domains for which the given constraints are satisfied. Depending on the way the decision variables are declared, the reference problem CSP (1) can be used to formulate analysis or synthesis problems. Implementation of such CSPs in constraint programming environments (such as Oz Mozart) enables the construction of a computational engine implemented in an interactive DSS system. Depending on the choice of the operation mode (whether we want to state and solve the problem as a synthesis or an analysis problem), such a system allows one to quickly specify the ranges of variability of the decision variables and to introduce constraints (i.e. it allows to enter input data, such as parameters of the fleet of logistics trains, delivery times, transport operation times, etc.), thus enabling fast assessment of various variants of organization of distribution.

3.1. Declarative model of a Milk-Run Delivery Problem

For the sake of further discussion, it is assumed that the problem whose aim is to assess the quality of distribution processes, will be interpreted as an analysis problem (*what effects will we produce by choosing such and such a routing variant?*), and the problem the aim of which is to choose a variant of logistics train routes will be treated as a synthesis problem (*which routing variant will help us achieve the expected quality of distribution processes?*). In this context, the problem of analysis can be formulated as (2):

$$PS'_{ST} = \left((X, \mathcal{D}), \mathcal{C}_{ST}\right), \tag{2}$$

where:

X – decision variables, a cyclic schedule of process operations executed in milk-run cycles: $X = (X', Xs', \alpha')$, where:

$X' = (x_\lambda | \lambda = 1 \dots . \omega)$, x_λ – starting time of operation o_λ, (there is also y_λ which stands for end time). Operations o_λ are operations of delivery/loading/unloading of materials to/at work stations (resources of set Γ),

$Xs' = (xs_\lambda | \lambda = 1 \dots . \omega)$, xs_λ – time of release of a resource occupied by operation o_λ, α'– takt time of local process operations,

$\mathcal{D}$ – a finite set of decision variable domains $\{X, B, F\}$:

$x_\lambda \in \{0, \dots, T\}$, $xs_\lambda \in \{0, \dots, 2T\}$, where: T stands for a planning horizon, i.e. the "time window" in which deliveries are made,

$\mathcal{C}$ – a set of constraints specifying the relationships between operations of processes implemented in milk-run cycles and the processes executed along the technological routes of individual products.

- constraints for operations of processes executed along the technological routes of individual products

  $my_{i,j} = mx_{i,j} + mt_{i,j}$, $j = 1 \dots lm(i)$, $\forall mP_i \in mP$, (3)

  where: $mx_{i,j}$ ($my_{i,j}$) – starting (end) time of operation $mo_{i,j}$ of a process executed along route mP_i,

  $my_{i,a} + td_{a,b} \leq mx_{i,b}$, if, in conformity with route $m^l p_i$, operation $mo_{i,a}$ precedes $mo_{i,b}$ $\forall mP_i \in mP$, (4)

  where: $td_{a,b}$ – waiting time between resources on which operations $mo_{i,a}$ and $mo_{i,b}$ are executed,

  $$my_{i,j} \leq mx_{i,j} + T, \; j = 1 \dots lm(i), \; \forall mP_i \in mP, \tag{5}$$

  $$\left(my_{i,a} \leq mx_{j,b}\right) \vee \left(my_{j,b} \leq mx_{i,a}\right), \tag{6}$$

  when $mo_{i,a}, mo_{j,b} \in Q_k$, $i \neq j$, where Q_k – a set of operations of processes executed along the routes of individual products manufactured on work station R_k,

- constraints for local processes (transport operations of logistics trains):

  $$\alpha' = c \cdot T, \; c \in \mathbb{N}, \tag{7}$$

  $$y_\lambda = x_\lambda + t_\lambda, \quad \lambda = 1,2, \dots, \omega, \tag{8}$$

  $$y_\beta + d_{\beta,\lambda} \leq x_\lambda, \; \lambda, \beta = 1,2, \dots, \omega \tag{9}$$

  if, in conformity with the adopted routing, operation o_β precedes operation o_λ,where: $d_{\beta,\lambda}$ – execution time of a transport operation of a local process between resources on which operations o_β and o_λ are executed,

  $$y_\lambda + d_{\lambda,\beta} \leq x_\beta + T, \; \lambda, \beta = 1,2, \dots, \omega, \tag{10}$$

  if o_β follows operation o_λ and o_λ is the first operation,

  $$xs_\lambda \geq y_\lambda, \quad \alpha = 1,2, \dots, \omega, \tag{11}$$

$xs_\lambda = x_\beta - d_{\lambda,\beta},\ \lambda,\beta = 1,2,\dots,\omega$, (12)
if, in accordance with the adopted routing, operation o_β follows operation o_λ, if, in accordance with the adopted routing, operation o_β follows operation o_λ,

$xs_\lambda = x_\beta - d_{\lambda,\beta} + T,\ \lambda,\beta = 1,2,\dots,\omega$, (13)
if operation o_β follows operation o_λ, and o_λ is the first operation on the route,

$[(xs_\lambda < y_\beta) \wedge (xs_\beta - T < y_\lambda)] \vee [(xs_\beta < y_\lambda) \wedge \wedge (xs_\lambda - T < y_\beta)]$, (14)
$\forall o_\lambda, o_\beta \in S_k$, $k = 1,\dots,lk$, where: S_k – a set of operations of local processes executed at station R_k,

$(\mathcal{K}_{\varepsilon\beta-\lambda\gamma} = 1) \Rightarrow [(x_\beta \le xs_\lambda) \vee (x_\gamma \le xs_\varepsilon)]$ (15)
$\varepsilon,\lambda,\beta,\gamma = 1,2,\dots,\omega$. where: $\mathcal{K}_{\varepsilon\beta-\lambda\gamma} = 1$ if o_ε, o_β and o_λ, o_γ are pairs of consecutive operations, and the path connecting resources on which o_ε, o_β, are executed crosses the path that connects the resources of the operations o_λ, o_γ; $\mathcal{K}_{\varepsilon\beta-\lambda\gamma} = 0$ in the remaining cases.

- constraints for processes executed in milk-run cycles and those executed along technological routes of individual products:

$mx_{i,j} = y_\lambda + c \cdot T,\ c \in \mathbb{N}, \forall o_\lambda \in M_k$, (16)

Schedule X of problem (2) determines the timetable of logistics trains which guarantees timely delivery (in conformity with the starting times of operations of processes executed along the technological routes of individual products) of materials to work stations. This means that, assuming that the set of processes executed in milk-run cycles P (by a fleet of logistics trains), their routes (routes of logistics trains), process execution times t_λ and process flow times $d_{\lambda,\beta}$ are known, and also known are the starting times of operations of processes executed along the technological routes of individual products $mx_{i,j}$ (dates of expected deliveries), to solve problem PS'_{ST} (2) one only needs to determine such values of decision variables X (schedule of local processes), for which all constraints given in set $\mathcal{C}_{ST}$ (3)–(16) are satisfied. The synthesis problem is given by (16):

$$PS'_{RE} = ((\{X,B,F\},\mathcal{D}),\mathcal{C}_{RE}), \quad (17)$$

where: $\{X,B,F\}$ – a set of decision variables including:

X – a cyclic schedule of process operations executed in milk-run cycles, $X = (X', Xs', \alpha')$, where:

$X' = (x_\lambda | \lambda = 1 \dots .\omega)$, x_λ – starting time of operation o_λ, (there is also y_λ which stands for end time). Operations o_λ are operations of delivery/loading/unloading of materials to/at work stations (resources of set Γ),

$Xs' = (xs_\lambda | \lambda = 1 \dots .\omega)$, xs_λ – time of release of a resource occupied by operation o_λ,

α' – takt time of process operations executed,

B, F – sequences specifying the order in which operations o_λ are executed by the successive processes run in milk-run loops (i.e. processes of set P),

$B = (b_1,\dots,b_\lambda,\dots,b_\omega)$ – sequence of preceding operations, $b_\lambda \in \{0,\dots\omega\}$, b_λ is an index of the operation that precedes o_λ (operations o_{b_λ} and o_λ are executed by the same process implemented in a milk-run cycle), $b_\lambda = 0$ means that o_λ is the first operation in the system's cycle,

$F = (f_1,\dots,f_\lambda,\dots,f_\omega)$ – sequence of following operations, $f_\lambda \in \{1,\dots\omega\}$, f_λ – index of the operation that follows o_λ, (operations o_λ and o_{f_λ} are executed by the same process implemented in a milk-run cycle. Each pair (B, F) is matched with exactly one pair from the set of routes and operations of processes executed in milk-run cycles.

$\mathcal{D}$ – a finite set of decision variable domains $\{X,B,F\}$: $x_\lambda \in \{0,\dots,T\}$, $xs_\lambda \in \{0,\dots,2T\}$, $b_\lambda \in \{0,\dots\omega\}$, $f_\lambda \in \{1,\dots\omega\}$. where: ω – number of operations of processes executed in milk-run cycles,

$\mathcal{C}$ – a set of constraints specifying the relationships between the processes implemented in milk-run cycles and the processes executed along the technological routes of individual products:

- constraints for processes executed along the technological routes of individual products (3)-(6)
- constraints for processes executed in milk-run cycles (6),(7), (10), (14) and:

$b_\lambda = 0, \forall \lambda \in BS$, (18)
$BS \subseteq BI = \{1,2,\dots,\omega\}, |BS| = ln,$
$b_\lambda \ne b_\beta \quad \forall \lambda,\beta \in BI \backslash BS,\ \lambda \ne \beta$, (19)
$f_\lambda \ne f_\beta \quad \forall \lambda,\beta \in BI,\ \lambda \ne \beta$, (20)
$(b_\lambda = \beta) \Rightarrow (f_\beta = \lambda),\ \forall b_\lambda \ne 0$, (21)
$[(b_\lambda = \beta) \wedge (b_\beta \ne 0)] \Rightarrow (y_\beta + d_{\beta,\lambda} \le x_\lambda)$, (22)
$\lambda,\beta = 1,2,\dots,\omega$, where: $d_{\beta,\lambda}$ – waiting time of a local process between resources on which operations o_β and o_λ are being executed,
$[(f_\lambda = \beta) \wedge (b_\beta = 0)] \Rightarrow (y_\lambda + d_{\lambda,\beta} \le x_\beta + T)$, (23)
$[(f_\lambda = \beta) \wedge (b_\beta \ne 0)] \Rightarrow (xs_\lambda = x_\beta - d_{\lambda,\beta})$, (24)
$[(f_\lambda = \beta) \wedge (b_\beta = 0)] \Rightarrow (xs_\lambda = x_\beta - d_{\lambda,\beta} + T)$, (25)
$[(xs_\lambda < y_\beta) \wedge (xs_\beta - T < y_\lambda)] \vee [(xs_\beta < y_\lambda) \wedge \wedge (xs_\lambda - T < y_\beta)]$, (26)

- constraints for processes executed in milk-run cycles and processes executed along technological routes (16).

Decision variables B, F correspond to the parameters of structure (routes of local processes) which are to guarantee the existence of schedule X that will enable timely delivery of materials to work stations (in accordance with the starting times of operations of processes executed along the technological routes of individual products). In other words, assuming that the set of processes executed in milk-run cycles P (by a fleet of logistics trains), process execution times t_λ, process flow times $d_{\lambda,\beta}$, and the starting times of the operations of processes executed along the technological routes of individual products $mx_{i,j}$ (dates of expected deliveries) are all known, to solve problem PS'_{RE} (17), it is enough to determine such values (determined by domains $\mathcal{D}$) of decision variables B, F (routes of local processes) and X (schedule of local processes), for which all constraints given in set $\mathcal{C}_{RE}$ (17)–(34) are satisfied. A computer implementation of the reference CSP model can be used for prototyping supply cycles in a milk-run system. Trips are planned, each time, by solving a dedicated synthesis or analysis problem, as specified by access to input data characterizing the structural and functional parameters of the production system being modeled (Bocewicz et al. 2019a).

3.2. Supply cycle prototyping

The strategy of searching for a solution in the DSS under consideration resembles a situation in a game. The goal of this game is to look for such elements of a structure, e.g. decision rules, resource limits, costs, etc., which either boost the given set of criteria, or suffice to achieve the given values of the set of criteria being considered, e.g. timeliness, resource utilization rate, etc. This means that, in the former case, one seeks for such an organization of the structure of the company–order processing system, which will boost the given company-performance criteria; in the latter case, one looks for such a structure (e.g. an admissible structure) which allows to achieve the expected values of the parameters characterizing the behavior of the company. Under the action scenarios (variants) for the first strategy, one arbitrarily determines the values of selected parameters of the system's structure and evaluates the effect of the changes introduced on the values of selected company performance evaluation criteria. Under scenarios for the second strategy, one determines the values of the selected evaluation criteria and checks whether in the given ranges of variability of the parameters describing the structure of the distribution system, there exist values of these parameters which guarantee the fulfilment of the adopted company performance criteria. The purpose of the decision support process proposed above is to look for answers to one of the questions presented earlier. This search boils down, each time, to solving a suitable constraint satisfaction problem. The problems selected in this way are solved in the Oz Mozart environment. Each admissible solution should belong to this set includes:

- a planning horizon T, a sequence of delivery dates mX,
- sequences describing the order of operations B, F,
- sequence of starting/end times of operations X', (Y'),
- sequence of delivery dates mX,
- sequence of release times of resources occupied by loading/unloading operations Xs'.

An example illustrating the application of the presented approach is described in the next section.

4. CASE STUDY

In a system with the structure shown in Fig.1, a method is sought for distributing supplies of specific groups of goods in specified quantities, in the given time windows, to the given group of work stations. In this process, an answer is sought to the following question: Do there exist, in the given system, routes of logistics trains and the associated delivery schedules that guarantee timely delivery of the materials necessary for the production process to be completed? It is assumed that a fleet of two logistics trains is available in the system, whose technical parameters allow the vehicles to move along sectors of the given transport network at times ($d_{\beta,\lambda}$) given in table in Fig. 1. The system is a flow production system; as such it requires cyclic supply of parts to specific work stations (with pick and place points, hereinafter "stops", labeled MR01-MR15) in time windows with a width of $T = 2970$ t.u.. Three variants are considered, in which the required quantity of materials is transported to the individual work stations by two logistics trains moving at different velocities and visiting:

- in Variant I, 9 work stations (i.e. 9 stops labeled MR01-MR09), 1 supermarket and 1 warehouse,
- in Variant II, 14 work stations, (i.e. 12 stops labeled MR01-MR12), 1 supermarket and 1 warehouse,
- in Variant III, 15 work stations, (i.e. 15 stops labeled MR01-MR15), 1 supermarket and 1 warehouse.

The solution to the respective synthesis problem (17) are the following routes (OzMozart, Intel Core i5-3470, 8 GB RAM):

- in Variant I the route of logistics train 1 is following: MR01 → MR04 → MR02 → MR03 → MR05 → MR01 and the route of logistics train 2 is: MR01 → MR06 → MR07 → MR08 → MR09 → MR05 → MR01
- in Variant II the route of logistics train 1 is following: MR01 → MR04 → MR02 → MR03 → MR05 → MR01 and the route of logistics train 2: MR01 → MR06 → MR07 → R10→MR11→MR12→MR09→MR08→MR05→MR01
- in Variant III (see the schedule on the fig. 2a) the route of logistics train 1 is following: MR01 → MR04 → MR02 → R03→MR06→MR07→MR08→MR09→MR05→MR01 and the route of train 2: MR01 → MR10 → MR11→ MR12 → MR13 → MR14 → MR15 → MR05 → MR01

In addition to the experiments reported above, we compared the effectiveness of the procedures used in the synthesis and analysis problems. The results of the analysis are shown in Table 1. The results of the tests confirm the usefulness of the presented solution for fast online prototyping of supply schedules and transport routes of a fleet of logistics trains. In particular, depending on the adopted assessment criteria, the solver we developed enables interactive search for solutions that minimize the fleet of logistic trains used and allows to assess the possibility of timely execution of planned deliveries for arbitrarily selected logistics train routes. Synthesis problems can be solved online when the number of stops in the system does not exceed fifteen. For systems larger than this, the use of the proposed method leads to combinatorial explosion, which is a natural consequence of the NP-hard nature of the problems under consideration.

Table 1. Results of selected experiments

	Number of trains	The synthesis problem: calculation time [s]		The analysis problem: calculation time [s]	
		Train velocity		Train velocity	
		same	different	same	different
Variant I	1	10	10	<1	<1
	2	10	10	<1	<1
	3	12	12	<1	<1
Variant II	1	40	40	<1	<1
	2	45	56	<1	<1
	3	75	88	<1	<1
Variant III	1	111	111	<1	<1
	2*	120	268	<1	<1
	3	143	288	<1	<1

*the solution presented in the Fig. 2

5. CONCLUDING REMARKS

The results of the tests demonstrate that the proposed reference CSP model is a useful tool which allows one to formulate problems of analysis/synthesis of transport routes available in a given distribution system. Implemented computationally, it enables fast online prototyping of supply schedules and transport routes of a fleet of logistics trains. The constraints adopted in the model assume that the concurrent transport processes, executed in a cyclic steady resource conflicts leading to deadlocking of transport processes are resolved using a deadlock prevention method that guarantees avoidance of congestion.

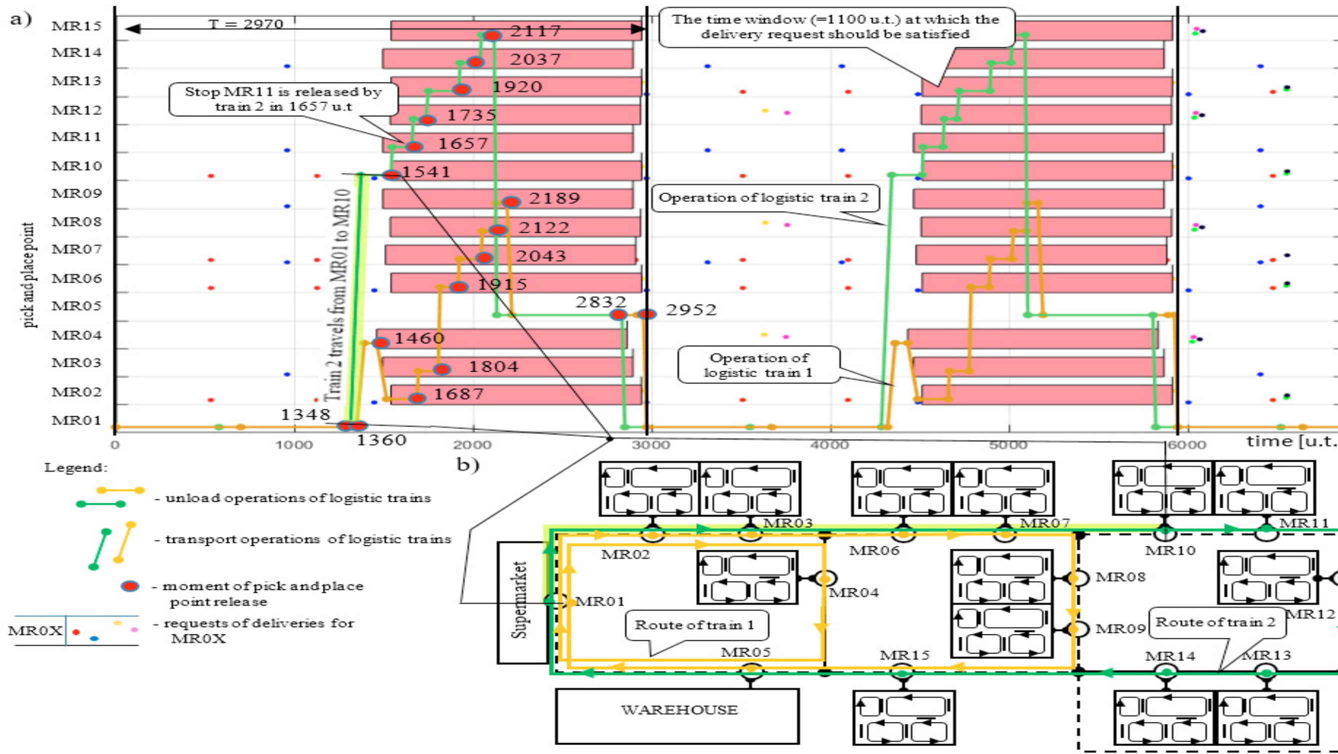


Fig. 2. Schedule a) and related milk-run routs b) following Variant III

In the future, we plan to study solutions for fuzzy, uncertain decision variables describing supply time windows and robustness of planned routings and schedules.

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