Scheduling for Multi-modal Cyclic Transport Systems

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Abstract: This paper concerns the domain of the multimodal transportation systems composed of buses, trains, trams and subways lines and focuses on the scheduling problems encountered in these systems. Transportation Network Infrastructure (TNI) can be modeled as a network of lines providing cyclic routes for particular kinds of stream-like moving transportation means. Lines are connected by common shared change stations. Depending on TNI timetabling the time of the trip of passengers following different itineraries may dramatically differ, e.g. the same distances along the north-south, and east-west directions may require different travel time. So, the mine question regards of TNI schedulability, e.g. the guarantee the same distances in arbitrarily assumed directions will require approximate traveled time. Considered timetabling problem belongs to NP-hard ones. The declarative model of TNI enabling to formulate cyclic scheduling problem in terms of the constraint satisfaction one is our main contribution. At last, the simulated results manifest the promising properties of the proposed model.

Keywords: cyclic scheduling, multimodal transport system, multimodal processes, declarative modeling, constraints programming

1. Introduction

A cyclic schedule [2, 8] is one in which the same sequence of states is repeated over and over again. In the case of Multimodal Transportation Systems (MTS) the appropriate cyclic scheduling problem has to take into account the constraints implied by the considered Transportation Network Infrastructure (TNI), e.g. see fig. 1. Assuming the transportation lines considered are cyclic and connected by common shared change stations a network can be modeled in terms of Cyclic Concurrent Process System (SCCP) [2]. Assuming each line is serviced by a set of stream-like moving transportation means (vehicles) and operation times required for traveling between subsequent stations as well as semaphores ensuring vehicles mutual exclusion on shared stations are given, the main question regards of SCNI timetabling, for instance guaranteeing the shortest time of the trip for passengers following a given direction. In systems of that type transportation means play the role of agents [1], attempting to reach their goals while following rules being specific for a given SCCP. So, the considered MTS are treated as multi-agent ones. Depending on SCNI timetabling the time of the trip of passengers following different itineraries may dramatically differ. In that context the considered cyclic scheduling directly regards of multimodal processes encompassing passengers' itineraries, and indirectly regards of modeling them SCCPs. The TNI schedules sought have to follow vehicles (agents) collision- and deadlock-free flows as well as the passengers' itinerary optimization requirements. The problem considered belongs to NP-hard ones [3].

Literature review. So far there is no research paper on cyclic scheduling of multi-modal processes modeled in terms of above defined TNI. The existing approach to solving the SCCPs scheduling problem base upon the simulation models, e.g. the Petri nets [5], the algebraic models, e.g. upon the (max,+) algebra [4] or the artificial intelligent methods [6]. The SCCP driven models assuming a unique process execution along each cyclic route, studied in [1, 2, 4] do not allow to take in to account the stream-like flow of local cyclic processes, e.g. buses servicing a given city line. So, this work can be seen as a continuation of the investigations conducted in [1, 2, 4, 7].

New contributions. The declarative models employing the constraints programming techniques implemented in modern platforms such as OzMozart, ILOG, [1], [2] seems to be well suited to coup with SCNI scheduling problems. In that context, our contribution is a formulation of SCNI cyclic scheduling problem in terms of the constraint satisfaction one [2].

Organization. The paper is organized as follows. In Section 2, an illustrative example of TNI and its cyclic scheduling problem statement are provided. In Section 3, a cyclic processes network is modeled. In Section 4, the selected case of multimodal processes is discussed In Section 5, we draw the conclusion.

2. Problem formulation

The TNI with distinguished vehicles and stations, shown in Fig. 1, is modeled in terms of the SCCP shown in Fig. 2. Four local ***cyclic processes*** are considered: P_1, P_2, P_3, P_4. The processes follow the ***routes*** (composed of transportation sectors and separating them stations) and while providing connections in two directions i.e., the north-south and the east-west, for ***the two multimodal processes*** mP_1, mP_2 and mP_3, mP_4, respectively. P_1, P_2 contain two sub-processes $P_1 = \{P_1^1, P_1^2\}, P_2 = \{P_2^1, P_2^2\}$ representing trains (agents) moving along the same route.

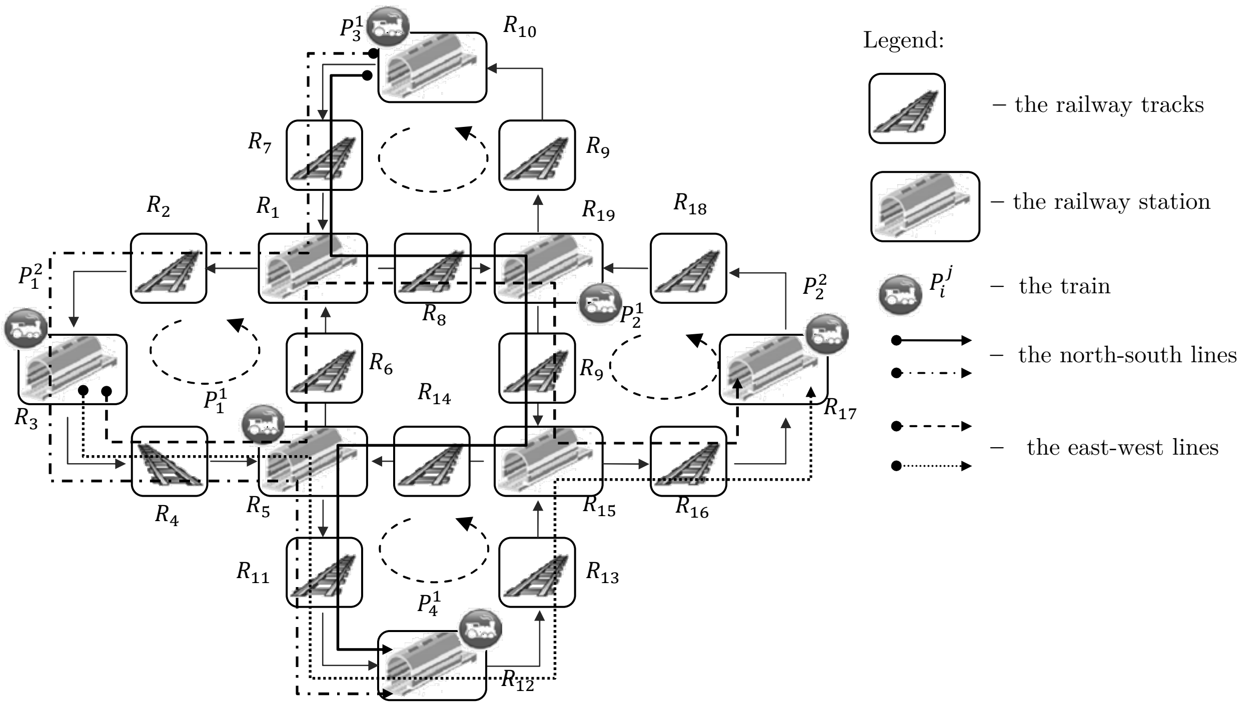

Fig. 1. An example of the TNI

Rys. 1. Przykład multimodalnego systemu komunikacji

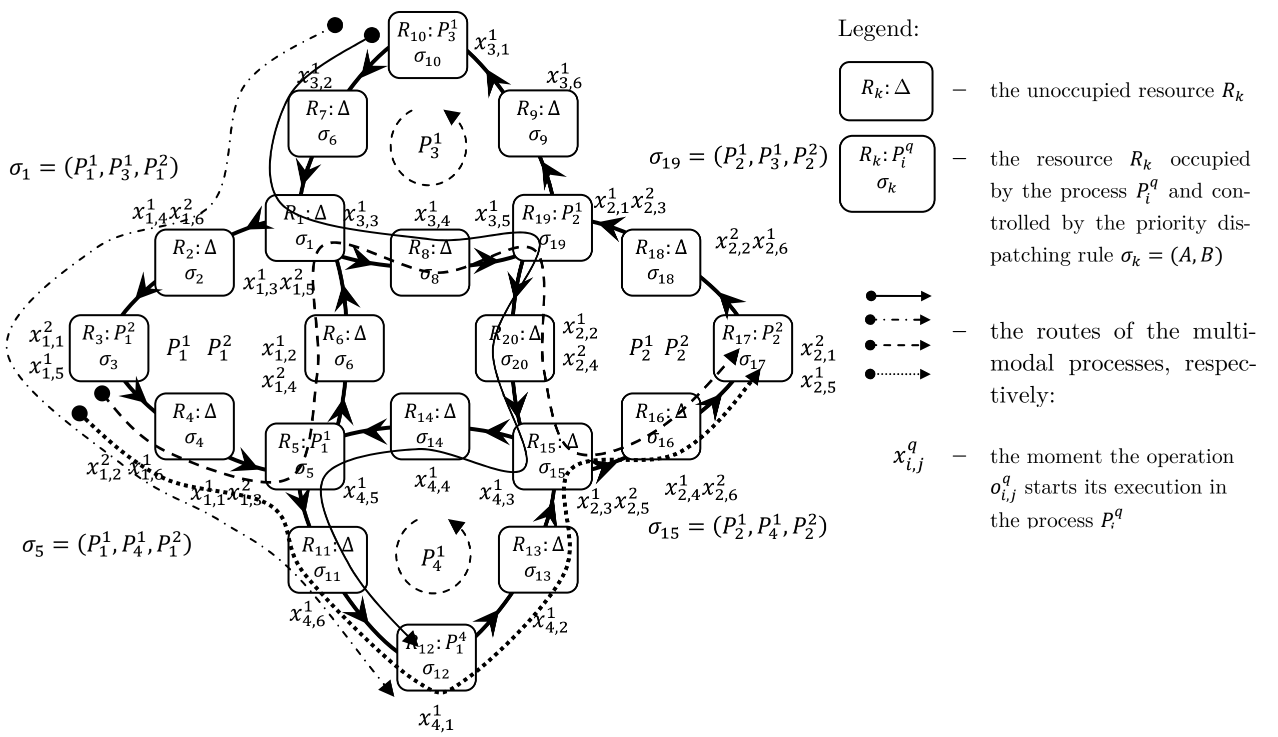

Fig. 2. SCCP of TNI from fig. 1

Fig. 2. System komunikacji z rys. 1 jako system równoległych procesów cyklicznych

The following constraints determine the processes cooperation:

- The new local process operation (the train's operation such as: passengers' transportation, boarding etc.) may begin only if the current operation has been completed and the resource designed to this operation is not occupied.
- The local processes share the common resources (the stations) in the mutual exclusion mode. The new local process operation can be suspended only if designed resource is occupied. The local processes

suspended cannot be released. Local processes are non-preempted.

- The multimodal processes follow the local transportation routes. Different multimodal processes can be executed simultaneously along a local process.
- The local and multimodal processes are executed cyclically, resources occurring in each transportation route cannot repeat. The main question concerns of SCCP cyclic steady state behavior and a way this state depends on direction of local process routes as well as on priority rules, and an initial process allocation to the system resources. Assuming the steady state there exists the next question regards of travel time along assumed multimodal process route linking distinguished destination points. Of course, the periodicity of multimodal processes depends on SCCP periodicity, i.e. characteristics of a given TNI. That means an initial state and a set of dispatching rules can be seen as control variables allowing one to "adjust" multimodal processes schedule.

Consider a SCCP model of TNI specified by the given sets of dispatching rules, operation times (see tab. 1), and initial processes allocation, the main question concerns of SCCP periodicity: Does there exist a cyclic steady state of local and multimodal processes?

3. Modeling of cyclic processes network

In the SCCP model of TNI the following notations are used [1, 2]:

- $p_i^k = (p_{i,1}^k, p_{i,2}^k, \dots, p_{i,lr(i)}^k)$ specifies the route of the local process's stream $\boldsymbol{P_i^k}$ (k-th stream of the i-th local process P_i), and its components define the resources used in course of process operations execution, where: $p_{i,j}^k \in R$ (the set of resources: $R = \{R_1, R_2, \dots, R_m\}$) – denotes the resource used by the k-th stream of i-th local process in the j-th operation; in the rest of the paper ***the j-th operation executed on resource $p_{i,j}^k$ in the stream P_i^k*** will be denoted by $o_{i,j}^k$; $lr(i)$ - denotes a length of cyclic process route. For example in the SCCP from Fig. 2 routs of streams P_1^1, P_1^2 are defined using the same resources: $p_1^1 = (R_5, R_6, R_1, R_2, R_3, R_4)$, $p_1^1 = (R_3, R_4, R_5, R_6, R_1, R_2)$.
- $t_i^k = (t_{i,1}^k, t_{i,2}^k, \dots, t_{i,lr(i)}^k)$ specifies ***the process operation times***, where $t_{i,j}^k$ denotes the time of execution of operation $o_{i,j}^k$ (see tab. 1).
- $mp_i = \left(mpr_j(a_j, b_j), mpr_l(a_l, b_l), \dots, mpr_h(a_h, b_h)\right)$ specifies ***the route of the multimodal process mP_i***, where: $mpr_j(a, b) = \left(crd_a p_j^k, crd_{a+1} p_j^k, \dots, crd_b p_j^k\right)$, $crd_i D = d_i$, for $D = (d_1, d_2, \dots, d_i, \dots, d_w)$, $\forall a \in \{1,2, \dots, lr(i)\}$, $\forall j \in \{1,2, \dots, n\}$, $crd_a p_j \in R$.
- The transportation route mp_i is a sequence of sections of local process routes. The transportation route mp_i is a sequence of sub-sequences (sections) of local cyclic process routes. For example a route of process mP_3 (Fig. 2) is following: $mp_3 = (R_3, R_4, R_5, R_6, R_1, R_8, R_{19}, R_{20}, R_{15}, R_{16}, R_{17})$. For the sake of simplicity let as assume the all operation times of multimodal processes are the same and equal to the 1 unit of time.
- $\Theta = \{\sigma_1, \sigma_2, \dots, \sigma_m\}$ is the set of **the priority dispatching rules**, where $\sigma_i = (s_{i,1}, \dots, s_{i,lp(i)})$ is the sequence components of which determine an order in which the processes can be executed on the resource R_i, $s_{i,j} \in P$ (the set of process streams: $P = \{P_1^1, \dots, P_1^a, P_2^1 \dots, P_2^b, \dots, P_n^z\}$, each process executes periodically in infinity). Dispatching rules which determine an order on the shared train stations (resources R_1, R_5, R_{15}, R_{19}) are following: $\sigma_1 = (P_1^1, P_3^1, P_1^2)$, $\sigma_5 = (P_1^1, P_4^1, P_1^2)$, $\sigma_{15} = (P_2^1, P_4^1, P_2^2)$, $\sigma_{19} = (P_2^1, P_3^1, P_2^2)$.

In that context a SCCP can be defined as a pair [2]:

$$SC = (SC_l, SC_m), \tag{1}$$

where:

$SC_l = (R, P, \Pi, T, \Theta)$ – characterizes the SCCP structure, i.e.

$R = \{R_1, R_2, \dots, R_m\}$ – the set of resources,

$P = \{P_1^1, \dots, P_1^a, \dots, P_n^1, \dots, P_n^z\}$ – the set of local processes,

$\Pi = \{p_1, p_2, \dots, p_n\}$ – the set of local process routes,

$T = \{T_1, \dots, T_n\}$ – the set of local process operations times,

$\Theta = \{\sigma_1, \sigma_2, \dots, \sigma_m\}$ – the set of dispatching priority rules.

$SC_m = (MP, M\Pi)$ – characterizes the SCCP behavior, i.e.

$MP = \{mP_1, mP_2, \dots, mP_u\}$ – the set of multimodal processes,

$M\Pi = \{mp_1, mp_2, \dots, mp_u\}$ – the set of multimodal process routes.

The main question concerns of SCCP cyclic behavior and a way this behavior depends on direction of local transportation routes Π, the priority rules Θ, and a set of initial states, i.e., an initial processes allocations to the system resources.

Tab. 1. Operation times of SCCP's (from fig. 2)

Tab. 1. Czasy pracy systemu z rys. 2

Streams	i	k	$t_{i,1}^k$	$t_{i,2}^k$	$t_{i,3}^k$	$t_{i,4}^k$	$t_{i,5}^k$	$t_{i,6}^k$
P_1^1	1	1	1	1	1	2	1	3
P_1^2	1	2	1	3	1	1	1	1
P_2^1	2	1	1	1	1	3	1	1
P_2^2	2	2	1	3	1	1	1	1
P_3^1	3	1	1	3	1	1	1	3
P_4^1	4	1	1	2	1	1	1	4

CSP-driven cyclic scheduling: Since parameters describing the SCCP model (1) are usually discrete, and linking them relations can be seen as constraints, hence related to them cyclic scheduling problems can be presented in the form of the Constraint Satisfaction Problem (CSP) [1, 2]. More formally, CSP is a framework for solving combinatorial problems specified by pairs: (a set of variables and associated domains, a set of constraints restricting the possible combinations of the variable values). The CSP relevant to the SCCP can be stated as follows [2]:

$$CS = ((\{R,P,\Pi,T,\Theta,X,Tc\},\{D_R,D_\Pi,D_T,D_\Theta,D_X,D_{Tc}\}),C) \quad (2)$$

where:

- R,P,Π,T,Θ are the decision variables describing the structure of the SCCP, i.e., (1), and X, Tc are the decision variables describing the cyclic behavior of the SCCP. $X=\{X_1^1,\dots,X_1^a,X_2^1\dots,X_2^b,\dots,X_n^z\}$ is the set of sequences $X_i^k=(x_{i,1}^k,x_{i,2}^k,\dots,x_{i,lr(i)}^k)$, where each variable $x_{i,j}^k$ determines ***the moment of*** $\boldsymbol{o_{i,j}^k}$ ***operation beginning*** in any (the l-th) cycle: $x_{i,j}^k(l)=x_{i,j}^k+l\cdot Tc$, $l\in\mathbb{Z}$, (where $x_{i,j}^k(l)\in\mathbb{Z}$ – means the moment the $o_{i,j}^k$ operation starts its execution in the l-th cycle) and Tc is the SCCP periodicity: $Tc=x_{i,j}^k(l+1)-x_{i,j}^k(l)$.
- the domains $D_R,D_P,D_\Pi,D_T,D_\Theta,D_X,D_{Tc}$ of decision variables which describe the family of: the set of resources, set of processes, sets of admissible routings, sets of admissible operation times, sets of admissible dispatching priority rules, sets of admissible coordinate values X_i^k, $x_{i,j}^k\in\mathbb{Z}$, set of admissible values of variables Tc, respectively.

  the constraints determining the relationship between the structure (specified by the quintuple (R,P,Π,T,Θ)) and the behavior following from this structure (specified by (X,Tc)) can be defined by the operator max [2]:

$$x_{i,j}^k = max\{(before(X_i^k,x_{i,j}^k)+before(T_i^k,t_{i,j}^k)+ \\ +\gamma(xi,jk),\ _{\alpha}xi,jk+1+\beta(xi,jk), \quad (3)$$

$$i=1,..,n;\ \ j=1,\dots,lr(i);$$

where:

$before(A,a_i)$ – the function provides a_{i-1} which precedes the a_i and in the case a_1 the function provides a_l which is the last element in the $A=(a_1,\dots,a_{i-1},a_i,\dots,a_l)$.

$$before(A,a_i)=\begin{cases}a_{i-1} & \text{if } a_i\neq a_1\\ a_l & \text{if } a_i=a_1\end{cases},$$

$after(A,a_i)$ – the function provides a_{i+1} which succeeds the a_i in and in the case a_1 the function provides a_l which is the first element in the $A=(a_1,\dots,a_{i-1},a_i,\dots,a_l)$:

$$after(A,a_i)=\begin{cases}a_{i+1} & \text{if } a_i\neq a_l\\ a_1 & \text{if } a_i=a_l\end{cases},$$

$$\alpha(x_{i,j}^k)=\begin{cases} before(X_i^k,x_{i,j}^k) & \text{if } o_{i,j}^k \text{ executes on unshared resource,}\\ after(X_a^k,x_{a,b}^k) & \text{if } o_{a,b}^k \text{ executes on shared resource } R_k \text{ previous to } o_{i,j}^k;\ \text{where } R_k=p_{a,b}=p_{i,j} \text{ and } P_a=before(\sigma_k,P_i),\end{cases}$$

$$\beta(x_{i,j}^k)=\begin{cases} 0 & \text{if } \alpha(x_{i,j}^k) \text{ is the moment } o_{a,b}^k \text{ starts, where } o_{a,b}^k \text{ and } o_{i,j}^k \text{ are executed in the same cycle,}\\ -Tc & \text{if } \alpha(x_{i,j}^k) \text{ is the moment of } o_{a,b}^k \text{ starts, where } o_{a,b}^k \text{ is executed in the cycle preceding of } o_{i,j}^k \text{ execution,}\\ Tc & \text{if } \alpha(x_{i,j}^k) \text{ is the moment of } o_{a,b}^k \text{ starts, where } o_{a,b}^k \text{ is executed in the cycle scuceeding of } o_{i,j}^k \text{ execution,}\end{cases}$$

$$\gamma(x_{i,j}^k)=\begin{cases} 0 & \text{if } before(X_i^k,x_{i,j}) \text{ means the moment the operation } o_{i,b}^k \text{ starts, where } o_{i,b}^k \text{ and } o_{i,j}^k \text{ are executed in the same cycle,}\\ -Tc & \text{if } before(X_i^k,x_{i,j}) \text{ means the moment the operation } o_{i,b}^k \text{ starts, where } o_{i,b}^k \text{ is executed in the cycle preceding of } o_{i,j}^k \text{ execution.}\end{cases}$$

Tab. 2. Constraints for the SCCP (from Fig. 2)

Tab. 2. Ograniczenia systemu z rys. 2

R_3:	$x_{1,1}^2=\max(x_{1,6}^1-Tc+1;x_{1,6}^2-Tc+t_{1,6}^2)$ $x_{1,5}^1=\max(x_{1,2}^2+1;\ x_{1,4}^1+t_{1,4}^1)$	R_4:	$x_{1,2}^2=\max(x_{1,1}^1+1;x_{1,1}^2+t_{1,1}^2)$ $x_{1,6}^1=\max(x_{1,3}^2+1;x_{1,5}^1+t_{1,5}^1)$
R_5:	$x_{1,1}^1=\max(x_{1,4}^2-Tc+1;\ x_{1,6}^1-Tc+t_{1,6}^1)$ $x_{4,5}^1=\max(x_{1,2}^1+1;x_{4,4}^1+t_{4,4}^1)$ $x_{1,3}^2=\max(x_{4,6}^1+1;\ x_{1,2}^2+t_{1,2}^2)$	R_6:	$x_{1,2}^1=\max(x_{1,5}^2-Tc+1;x_{1,1}^1+t_{1,1}^1)$ $x_{1,4}^2=\max(x_{1,3}^1+1;x_{1,3}^2+t_{1,3}^2)$
R_1:	$x_{1,3}^1=\max(x_{1,6}^2-Tc+1;\ x_{1,2}^1+t_{1,2}^1)$ $x_{3,3}^1=\max(x_{1,4}^1+1;\ x_{3,2}^1+t_{3,2}^1)$ $x_{1,5}^2=\max(x_{3,4}^1+1,x_{1,4}^2+t_{1,4}^2)$	R_2:	$x_{1,4}^1=\max(x_{1,1}^2+1;\ x_{1,3}^1+t_{1,3}^1)$ $x_{1,6}^2=\max(x_{1,5}^1+1;\ x_{1,5}^2+t_{1,5}^2)$

R_{17}:	$x_{2,1}^2 = \max\left(x_{2,6}^1 - Tc + 1;\ x_{2,6}^2 - Tc + t_{2,6}^2\right)$ $x_{2,5}^1 = \max\left(x_{2,2}^2 + 1; x_{2,4}^1 + t_{2,4}^1\right)$	R_{18}:	$x_{2,6}^1 = \max\left(x_{2,3}^2 + 1;\ x_{2,5}^1 + t_{2,5}^1\right)$ $x_{2,2}^2 = \max\left(x_{2,1}^1 + 1;\ x_{2,1}^2 + t_{2,1}^2\right)$
R_{19}:	$x_{2,1}^1 = \max\left(x_{2,4}^2 - Tc + 1;\ x_{2,6}^1 - Tc + t_{2,6}^1\right)$ $x_{3,5}^1 = \max\left(x_{2,2}^1 + 1; x_{3,4}^1 + t_{3,4}^1\right)$ $x_{2,3}^2 = \max\left(x_{2,6}^1 + 1;\ x_{2,2}^2 + t_{2,2}^2\right)$	R_{20}:	$x_{2,2}^1 = \max\left(x_{2,5}^2 - Tc + 1;\ x_{2,1}^1 + t_{2,1}^1\right)$ $x_{2,4}^2 = \max\left(x_{2,3}^1 + 1;\ x_{2,3}^2 + t_{2,3}^2\right)$
R_{15}:	$x_{2,3}^1 = \max\left(x_{2,6}^2 - Tc + 1;\ x_{2,2}^1 + t_{2,2}^1\right)$ $x_{4,3}^1 = \max\left(x_{2,4}^1 + 1;\ x_{4,2}^1 + t_{4,2}^1\right)$ $x_{2,5}^2 = \max\left(x_{4,4}^1 + 1, x_{2,4}^2 + t_{2,4}^2\right)$	R_{16}:	$x_{2,4}^1 = \max\left(x_{2,1}^2 + 1;\ x_{2,3}^1 + t_{2,3}^1\right)$ $x_{2,6}^2 = \max\left(x_{2,5}^1 + 1; x_{2,5}^2 + t_{2,5}^2\right)$
R_{12}:	$x_{4,1}^1 = \max\left(x_{4,6}^1 - Tc + 1; x_{4,6}^1 - Tc + t_{4,6}^1\right)$	R_{13}:	$x_{4,2}^1 = \max\left(x_{4,1}^1 + 1; x_{4,1}^1 + t_{4,1}^1\right)$
R_{14}:	$x_{4,4}^1 = \max\left(x_{4,3}^1 + 1; x_{4,3}^1 + t_{4,3}^1\right)$	R_{11}:	$x_{4,6}^1 = \max\left(x_{4,5}^1 + 1; x_{4,5}^1 + t_{4,5}^1\right)$
R_{10}:	$x_{3,1}^1 = \max\left(x_{3,6}^1 - Tc + 1; x_{3,6}^1 - Tc + t_{3,6}^1\right)$	R_7:	$x_{3,2}^1 = \max\left(x_{3,1}^1 + 1; x_{3,1}^1 + t_{3,1}^1\right)$
R_8:	$x_{3,4}^1 = \max\left(x_{3,3}^1 + 1; x_{3,3}^1 + t_{3,3}^1\right)$	R_9:	$x_{3,6}^1 = \max\left(x_{3,5}^1 + 1; x_{3,5}^1 + t_{3,5}^1;\right)$

Execution of local processes in the SCCP has to follow the constraints (3), that means the operation $o_{i,j}^k$ from the stream $\boldsymbol{P_i^k}$ may began its execution (at the moment $x_{i,j}^k$) on the resource $(p_{i,j}^k)$ only if the preceding operation has been completed (at the moment $before\left(X_i^k, x_{i,j}^k\right) + before\left(T_i^k, t_{i,j}^k\right) + \gamma(x_{i,j}^k)$) and the next operation from the process preceding $\boldsymbol{P_i^k}$ starts its execution (at the moment $\alpha\left(x_{i,j}^k\right) + 1 + \beta(x_{i,j}^k)$) on the same resource. The constraints enable concurrent execution of processes awaiting each other for the common shared resource releasing [2]. Moreover, they guarantee the deadlock-free (i.e. cyclic) processes execution.

The constraints following imposed assumptions imply for instance that an operation from the process P_1^1 can begin its execution at the moment $x_{1,3}^1$ on resource R_1 only if the previous operation executed on the resource R_6 has been already completed at $x_{1,2}^1 + t_{1,2}^1$ and the resource R_1 has been released, i.e. if the process P_1^2 occupying the resource R_1 starts its subsequent operation at $x_{1,6}^2 - Tc + 1$. Therefore $x_{1,3}^1 = \max\left(x_{1,6}^2 - Tc + 1;\ x_{1,2}^1 + t_{1,2}^1\right)$. The starting moments of the rest operations are determined in the similar way are shown in tab. 2.

The system's cyclic behavior encompasses itself through values of decision variables X, guaranteeing its periodicity Tc. The parameters determining the cyclic behavior such as X and Tc are solution to the problem (2) following the set of constraints C (Table 2.), determining the SCCP's structure (1).

4. Cyclic processes scheduling

Consider CSP stated by CS (2) and formulated for SCCP from Fig 2. The assumed set $\{\sigma_1 = (P_1^1, P_3^1, P_1^2),\ \sigma_{19} = (P_2^1, P_3^1, P_2^2),\ \sigma_5 = (P_1^1, P_4^1, P_1^2),\ \sigma_{15} = (P_2^1, P_4^1, P_2^2)\}$ of dispatching rules implies $Tc = 11$. The resultant cyclic steady state shown in Fig. 3 has be obtained in OzMozart, Dual Core 2.67, GHz, 2.0, GB RAM environment in 1 s. Obtained periodicity $(Tc = 11)$ of the SCNI behavior implies different traveling times required by different directions – the itineraries mP_4 and mP_3 following the routes mp_3, mp_4 along the east-west direction are realized in 18 and 28 time units, respectively (see the dotted and dashed lines in fig. 1÷3). In turn, the itineraries mP_1 and mP_2 following the routes mp_1, mp_2 along the north-south direction are realized in 22 and 33 time units, respectively (see the solid and dot-dashed lines in fig. 1÷3). So, the best line serving the east-west direction is faster than the best line serving the north-south direction.

However, replacing the above assumed set of dispatching rules for the following new one $\{\sigma_1 = (P_3^1, P_1^1, P_1^2),\ \sigma_{19} = (P_2^1, P_3^1, P_2^2),\ \sigma_5 = (P_1^1, P_4^1, P_1^2),\ \sigma_{15} = (P_4^1, P_2^1, P_2^2)\}$ (which imply the change of some constraints – see Table 3) provides shorter cycle time $Tc = 10$, resulting in shortening of the travel time (20 time units) following the route mp_1 (north-south line), and extension of the travel time (28 time units) following the route mp_3 (east-west line) – see fig. 4.

That means, the different sets of dispatching rules implies different traveling times in assumed directions. In the case considered the difference between the shortest traveling times along two directions changes from $4 = 22 - 18$ to $8 = 28 - 20$ time units. The open question is whether there exists such a set of dispatching rules guaranteeing the same best traveling time in both directions?

In both cases the solutions times did not exceed one second. The computational efficiency of the approach proposed is repaid however by lack of any guarantee the obtained SCCP's cyclic steady state will follow assumed frequencies of local processes executions within the cycle Tc. That means the steady state obtained for a given operation times following assumed frequencies of local processes executions may change to the new one, for instance as a consequence of operation time change, imposing however the new frequencies. For illustration observe that the increasing the operation time $t_{2,6}^2$ executed on R_{16} along the stream P_2^2 just by one unit of time (see Table 4) results in new different frequencies of local processes execution – instead the same (i.e., the process executes once within the Tc of SCCP) frequency for all local processes observed before the operation time change. That means the method considered assumed the frequencies of local processes are known in advance.

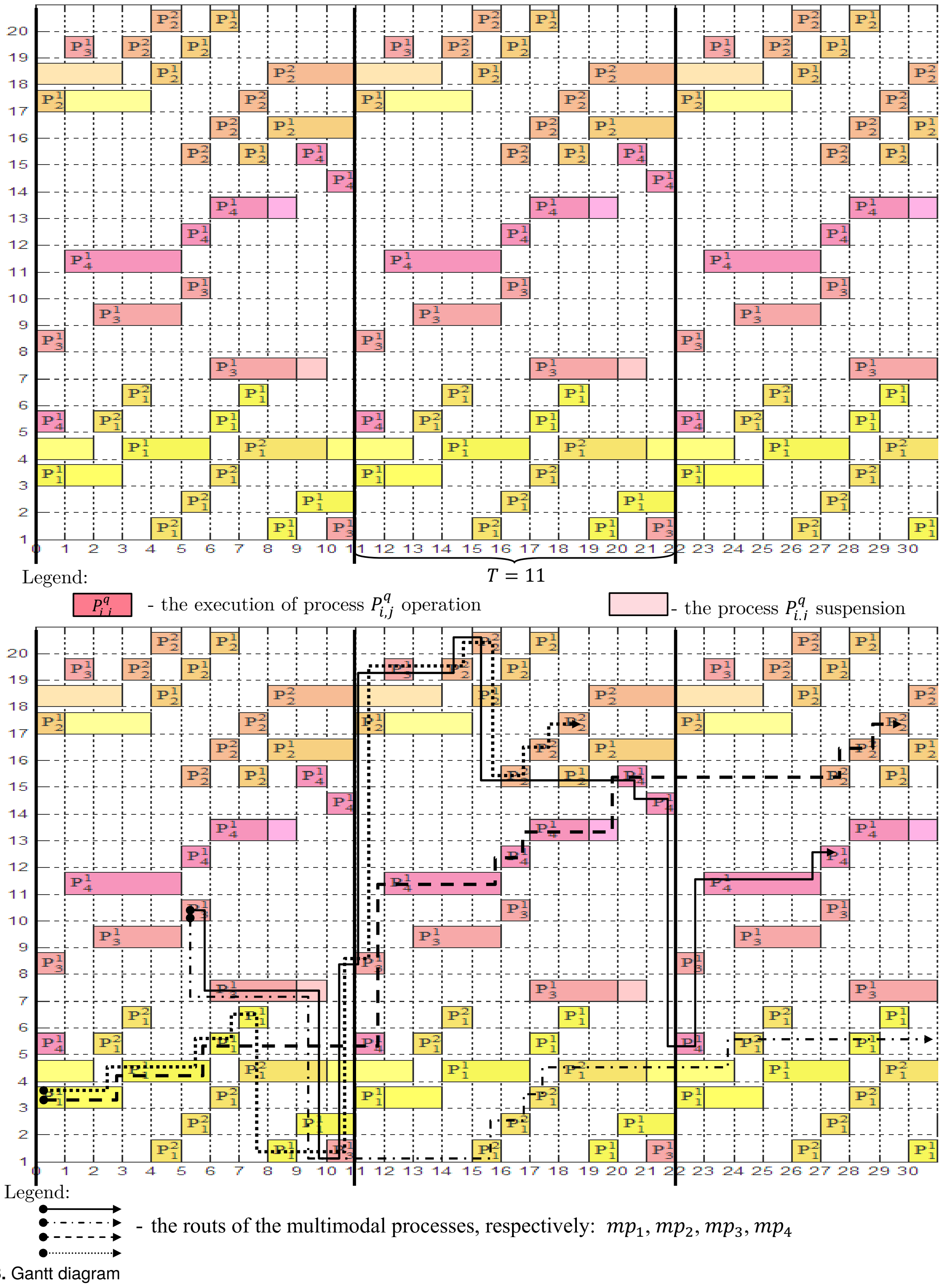

Fig. 3. Gantt diagram

Rys. 3. Diagram Gantta

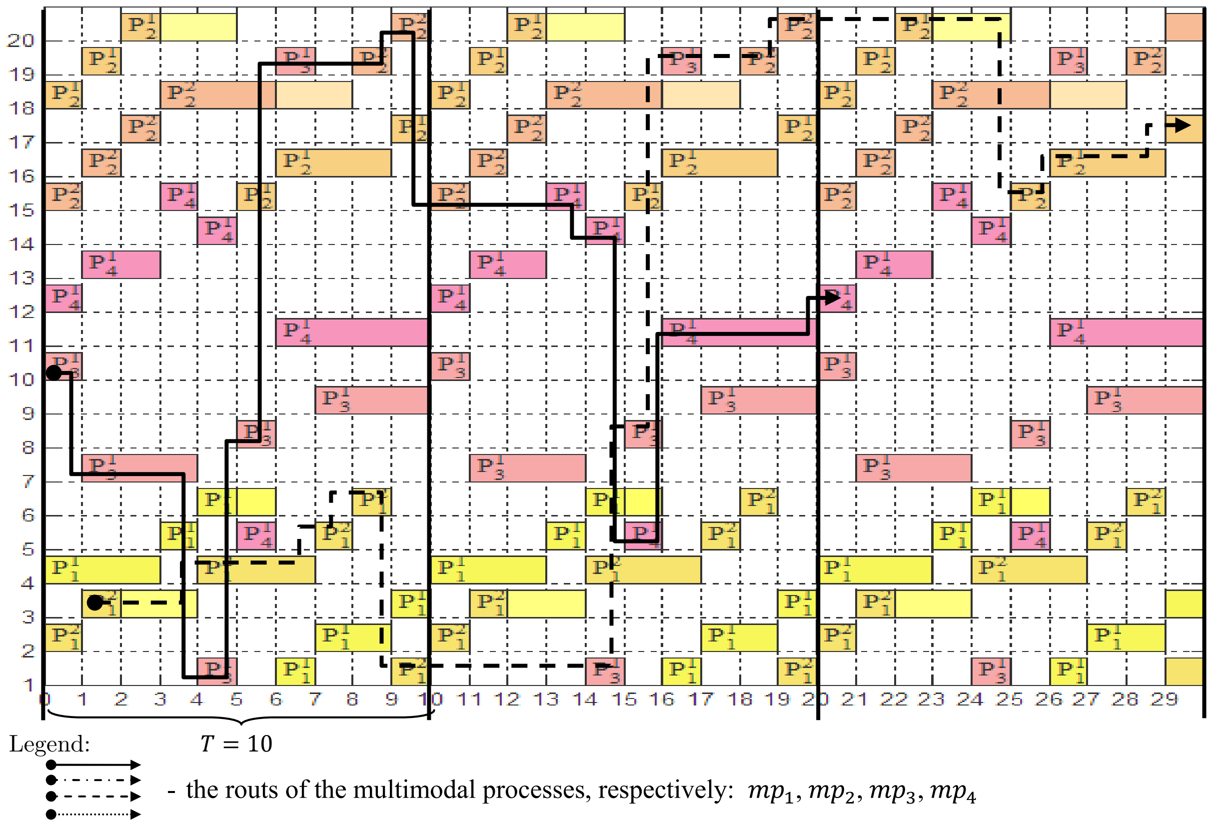

Fig. 4. Gantt diagram
Rys. 4. Diagram Gantta

Tab. 3. Constraints regarding resources R_1 and R_{15} and following the new dispatching rules: $\sigma_1, \sigma_{19}, \sigma_5, \sigma_{15}$
Tab. 3. Ograniczenia ze względu na źródła R_1 i R_{15} oraz następujące nowe reguły wysyłki: $\sigma_1, \sigma_{19}, \sigma_5, \sigma_{15}$

R_1:	$x^1_{3,3}(k) = \max\left(x^2_{1,6}(k-1)+1, (x^1_{3,2}(k)+t^1_{3,2})\right)$ $x^1_{1,3}(k) = \max\left(x^1_{3,4}(k)+1, (x^1_{1,2}(k)+t^1_{1,2})\right)$ $x^2_{1,5}(k) = \max\left(x^1_{1,4}(k)+1, (x^2_{1,4}(k)+t^2_{1,4})\right)$
R_{15}:	$x^1_{4,3}(k) = \max\left(x^2_{2,6}(k-1)+1, (x^1_{4,2}(k)+t^1_{4,2})\right)$ $x^1_{2,3}(k) = \max\left(x^1_{4,4}(k)+1, (x^1_{2,2}(k)+t^1_{2,2})\right)$ $x^2_{2,5}(k) = \max\left(x^1_{2,4}(k)+1, (x^2_{2,4}(k)+t^2_{2,4})\right)$

Tab. 4. Operation times of SCCP's (from fig. 2)
Tab. 4. Czasy pracy systemu z rys. 2

Streams	i	k	$t^k_{i,1}$	$t^k_{i,2}$	$t^k_{i,3}$	$t^k_{i,4}$	$t^k_{i,5}$	$t^k_{i,6}$
P^1_1	1	1	1	1	1	2	1	3
P^2_1	1	2	1	3	1	1	1	1
P^1_2	2	1	1	1	1	3	1	1
P^2_2	2	2	1	3	1	1	1	2
P^1_3	3	1	1	3	1	1	1	3
P^1_4	4	1	1	2	1	1	1	4

5. Concluding remarks

In contradiction to the traditionally offered solutions the approach presented allows one to take into account such behavioral features as transient periods and deadlock occurrence. So, the novelty of the modeling framework lies in the declarative approach to reachability problems enabling an evaluation of multimodal cyclic process executed within cyclic processes environments (treated as the cyclic multi-agent systems). The approach presented leads to solutions allowing the designer to compose elementary systems in such a way as to obtain the final TNI's scheduling system with required quantitative and qualitative behavioral features. So, we are looking for a method allowing one to replace the exhaustive search for the admissible control by a step-by-step structural design guaranteeing the required system behavior.

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Harmonogramowanie multimodalnych cyklicznych systemów transportowych

Streszczenie: W artykule podejmowana jest problematyka harmonogramowania marszrut pasażerskich realizowanych w multimodalnych systemach komunikacji (MSK) miejskiej obejmujących linie autobusowe, tramwajowe, pociągowe, a także linie metra i linie promowe. MSK modelowany jest jako sieć linii komunikacji miejskiej realizujących swoje cykliczne marszruty transportowe zadaną liczba odpowiednich środków transportu pasażerskiego, tzn. autobusów, tramwajów, pociągów itp. Przyjmuje się, że linie te umożliwiają przesiadanie się pasażerów na wspólnie dzielonych stacjach przesiadkowych. Rozważany problem dotyczy doboru takiej struktury i organizacji ruchu poszczególnych linii, które zapewnią podobne czasy przejazdu (na podobnych dystansach) podróżnych przemieszczających się w różnych kierunkach. Problem ten należy do problemów NP-trudnych. Proponowane w pracy rozwiązanie przyjmuje model deklaratywny MSK sprowadzając rozważany problem harmonogramowania do postaci deterministycznego problemu spełniania ograniczeń. Zamieszczone przykłady implementacji tego problemu w języku programowania z ograniczeniami potwierdzają użyteczność zaproponowanego modelu harmonogramowania MSK.

Słowa kluczowe: harmonogram cykliczny, transport multimodalny, model deklaratywny, programowanie w logice ograniczeń

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