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# DISCRETE TRANSPORTATION SYSTEM – CRITICAL SETS ANALYSIS AND DISCUSSION

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The paper describes the analysis and discussion about the critical situation, which happens during ordinary work of discrete transportation systems (*DTS*). We propose the formal model of the transportation system with the approach to its modelling based on the system behaviour observation. Monte Carlo simulation is a tool for *DTS* simulation. The system availability is the global metric to find if the system is able to realise the loaded set of tasks. The critical situation sets are caused by reliability, functional and human reasons. No restriction on the system structure and on a kind of distribution describing the system functional and reliability parameters is the main advantage of the approach. The proposed solution seems to be essential for the owner and administrator of the transportation systems.

***Keywords:*** *reliability, discrete transportation system, Monte-Carlo simulation, critical sets*

## 1. Introduction

The transportation systems are characterized by a very complex structure. The performance of the system can be impaired by various types of faults related to the transportation vehicles, communication infrastructure or even by traffic congestion or human resource [1]. Each part of the system is characterised by absolutely unique set of features and can caused the critical situation of whole system if it starts to work in unusual way or the fault or error of it is noticed. It is hard for an administrator, manager or an owner to understand the system behaviour and to combine the large scale of variant states of it in single – easily observable and controlled global metric as a pointer to make the proper decision in short time period. To overcome this problem we propose a functional approach. The transportation system is analysed from the functional point of view, focusing on business service realized by a system [16]. The analysis is following a classical [4]: modelling and simulation approach. It allows calculating different system measures, which could be a base for decisions related to administration of the transportation systems. The metric are calculated using Monte Carlo techniques [7]. No restriction on the system structure and on a kind of distribution is the main advantage of the method. Such approach allows forgetting about the classical reliability analysis based on Markov or Semi-Markov processes [2] – idealised and hard for reconciliation with practice. The results of the system observation – understand as the set of data collected during the simulation process are the basis to define the critical situations and they allow providing the probably proper solution to lift-up the systems in effective way if the critical situation occurs. This is the only sensible way, because the critical situations are the real and not removable part of the system life. The discussion and analysis is based on the transportation system of the Polish Post regional centre of mail distribution (section 2). The developed discrete transportation system model is presented in section 3. The main service given by the post system is the delivery of mails. From the client point of view the quality of the system could be measured by the time of transporting the mail from the source to the destination. A driver is a new element of the system description. We pointed the set of states to characterise the actual driver position including formal – law–origin aspects: number of hours he or she can work daily for example. We offer the heuristic approach to system management (section 4). In our opinion it seems to be the most adequate to the level of detail to provide the well-established description of the critical situation. The quality of the analysed system is measured by the availability defined as an ability to realize the transportation task at a required time (described in section 5). Next (section 6), we give an example of using presented model for the analysis of the Dolny Slask Polish Post regional transportation system.

## 2. Polish Post Transportation System

The analysed transportation system is a simplified case of the Polish Post (Fig. 1). The business service provided the Polish Post is the delivery of mails. The system consists of a set of nodes placed in different geographical locations. Two kinds of nodes could be distinguished: central nodes (*CR*) and ordinary nodes (*PK*). There are bi-directional routes between nodes. Mails are distributed among ordinary nodes by trucks, whereas between central nodes by trucks, railway or by plane.

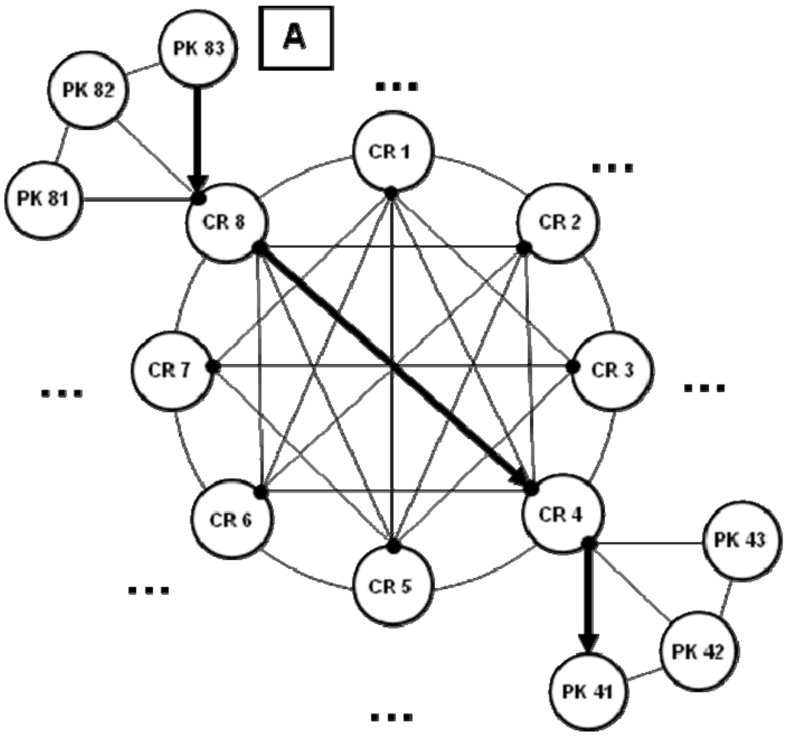



*Figure 1*. General idea of the analysed *DTS*

The mail distribution could be understood by tracing the delivery of some mail from point A to point B. At first the mail is transported to the nearest to A ordinary node. Different mails are collected in ordinary nodes, packed in larger units called containers and then transported by trucks to the nearest central node. In central node containers are repacked and delivered to appropriate (according to delivery address of each mail) central node. In the Polish Post there are 14 central nodes and more than 300 ordinary nodes. There are more than one million mails going through one central node within 24 hours. It gives a very large system to be modelled and simulated. Therefore, we have decided to model only a part of the Polish Post transportation system – one central node with a set of ordinary nodes. The income of mails to the system, or rather addressed containers of mails as it was discussed above, is modelled by a stochastic process. Each container has a source and destination address. The generation of containers is described by some random process. In case of central node, there are separate processes for each ordinary node. The containers are transported by vehicles. Each vehicle has a given capacity – maximum number of containers it can haul. Central node is a base place for all vehicles. They start from the central node; and the central node is the destination of their travel. The vehicle hauling a commodity is always fully loaded or taking the last part of the commodity if it is less than its capacity. When a vehicle approaches the ordinary node it is waiting in an input queue if there is any other vehicle being loaded/unload at the same time. There is only one handling point in each ordinary node. The time of loading/unloading vehicle is described by a random distribution. The containers addressed to given node are unloaded and empty space in the vehicle is filled by containers addressed to a central node. Further, the vehicle waits till the time of leaving the node (set in the time-table) is left and starts its journey to the next node. The operation is repeated in each node on the route and finally the vehicle is approaching the central node when it is fully unloaded and after it is available for the next route. The process of vehicle operation could be stopped at any moment due to a failure. After the failure, the vehicle waits for a maintenance crew, is being repaired (random time) and after it continues its journey [3].

## 3. *Discrete Transportation System's* Formal Model

We decided to formally model a part of the Polish Post transportation system, one regional section, which consists of one central node and a set of ordinary nodes.

A realization of the system service needs a defined set of technical resources. Moreover, the operating of vehicles transporting mails between system nodes is done according to some rules – some management system. Therefore, we can model discrete transportation system as a 4-tuple:

$$DTS = \langle Client, BS, TI, MS \rangle, \tag{1}$$

where
*Client* – client model, *BS* – business service, a finite set of service components, *TI* – technical infrastructure, *MS* – management system.

### 3.1. Technical infrastructure

The technical infrastructure of *DTS* could be described by three elements:

$$TI = \langle No, V, MM \rangle, \tag{2}$$

where
*No* – set of nodes; *V* – set of vehicles; *MM* – maintenance model.

Set of nodes (*No*) consists of single central node (*CR*), a given number of ordinary nodes ($PK_i$). The distance between each two nodes is defined by the function:

$$distance : No \times No \to R_+ . \tag{3}$$

Each node has one functional parameter the mean (normal distribution) time of loading a vehicle:

$$loading : No \to R_+ . \tag{4}$$

Moreover, the central node (*CR*) has additional functional parameter: number of service points (in each ordinary node there is only one service point):

$$servicepoints : CN \to N_+ . \tag{5}$$

Each vehicle is described by the following functional and reliability parameters:

- mean speed of a journey
  $$meanspeed : V \to R_+ , \tag{6}$$
- capacity – number of containers, which can be loaded
  $$capacity : V \to R_+ , \tag{7}$$
- mean time to failure
  $$MTTF : V \to R_+ , \tag{8}$$

a time when failure occurs is given by exponential distribution with mean equal to a value of $MTTF$ function,

- mean repair time
  $$MRT : V \to R_+ , \tag{9}$$

it is modelled by a truncated Gaussian distribution.

The traffic is modelled by a random value of vehicle speed and therefore the time of vehicle (*v*) going from one node ($n_1$) to the other ($n_2$) is given by a formula:

$$time(v, n_1, n_2) = \frac{distance(n_1, n_2)}{Normal(meanspeed(v), 0.1 \cdot meanspeed(v))}, \tag{10}$$

where *Normal* denotes a random value with the truncated Gaussian distribution [17].

Maintenance model (*MM)* consists of a set of maintenance crews which are identical and unrecognised. The crews are not combined to any node, are not combined to any route, they operate in the whole system and are described only by the number of them. The time when a vehicle is repaired is equal to the time of waiting for a free maintains crew (if all crews involved into maintenance procedures) and the time of a vehicle repair which is a random value with the truncated Gaussian distribution: *(Normal(MRT(v), 0,1·MRT(v))*.

### 3.2. Human factor

The human infrastructure is composed by the set of drivers. So the description of this part of system infrastructure requires the analysis of the drivers' state and the algorithms, which model the rules of their work. Each driver could be in one of following states ($s_d$): rest (not at work), unavailable (illness, vacation, etc.), available (at work – ready to start driving), break (during driving), driving.

The number of driver working hours is limited by the labour law. For analysed Post Transportation System the daily limit for each driver equals to 8 hours and a single driver operates with one truck. It gives a simple algorithm:

- if $w_h$ > *limit* then *state* = "rest" & $w_h$ = 0,
- where $w_h$ - working hours, *limit* = 8 hours

Drivers in Polish Post work in two shifts, morning or afternoon one. So twice a day a driver's state and shift type is analysed:

- at 6am for each driver:
  - if *shift* == morning & $s_d$ == rest then $s_d$ = available,
- at 1pm for each driver:
  - if *shift* == afternoon & $s_d$ == rest then $s_d$ = available,

The next problem ought to be modelled is the driver's illness state. We propose the following approach:

- for every driver at 4am:
  - if $s_d$ == rest and *rand()* < $d_i$ then during $x$ days (according to a given distribution) the driver is in $s_d$ = unavailable,
    where $d_i$ – driver's illness parameter.

Moreover we propose to categorise the driver's illnesses as follows: short sick: 1 to 3 days, typical illness: 7 to 10 days, long-term illness: 10 to 300 days [21]. We prepare the daily record of the driver. The algorithm to fix the driver to the vehicle is the last part of the driver model:

- if no driver – the vehicle does not start,
- driver can be chosen if: $s_d$ = available
  and $w_h$ + *estimated time of journey* < *limit* * 1.1,
- the driver is chosen randomly or by least value approach:
  *abs*(limit – $w_h$ - *estimated time of journey*).

### 3.3. Business service

Business service [19] ($BS$) is a set of services based on business logic, that can be loaded and repeatedly used for concrete business handling process. Business service can be seen as a set of service components and tasks that are used to provide service in accordance with business logic for this process. Therefore, $BS$ is modelled a set of business service components ($sc$),):

$$BS = \{sc_{1,} ..., sc_n\}, n \ = length(BS) > 0 \ , \tag{11}$$

the function $length(X)$ denotes the size of any set or any sequence $X$.

### 3.4. Client model

The service realised by the clients of the transportation system are sending mails from a source node to a destination one. Client model consist of a set of clients ($C$).

Each client is allocated in one of nodes of the transportation system:

$$allocation : C \rightarrow No \, . \tag{12}$$

A client allocated in an ordinary node is generating containers (since, we have decided to monitor containers not separate mails during simulation) according to the Poisson process with destination address set to ordinary nodes. In the central node, there is a set of clients, one for each ordinary node. Each client generates containers by a separate Poisson process and is described by intensity of container generation:

$$intensity : C \to R_+ \,. \tag{13}$$

The central node is the destination address for all containers generated in ordinary nodes.

## 4. Management Systems

### 4.1. Legacy option

The management system controls the operation of vehicle. It consists of a sequence of routes:

$$MS = \langle r_1, r_2, ..., r_{nr} \rangle \,. \tag{14}$$

Each route is a sequence of nodes starting and ending in the central node, times of leaving each node in the route ($t_i$) and the recommended size of a vehicle (*size*) :

$$r = \langle CR, t_0, n_1, t_1, ..., n_m, t_m, CR, size \rangle \quad v_i \in No - \{CR\} \quad 0 \le t_0 < t_1 < ... < t_m < 24h \tag{15}$$

The routes are defined for one day and are repeated each day. The management system selects vehicles to realise each route in random way, first of all vehicles (among vehicles available in central node) with capacity equal to recommended size are taken into consideration. If there is no such vehicle, vehicles with larger capacity are taken into consideration. If still there is no vehicle fulfilling requirements vehicle of smaller size is randomly selected. If there is no available vehicle a given route is not realised [18].

### 4.2. Heuristic option

The decisions (send a truck to a given destination node) are taken in moments when a container arrives to the central node. The truck is send to a trip if:

- the number of containers waiting in for delivery in the central node of the same destination address as that just arrived is larger than a given number,
- there is at least one available vehicle,
- the simulated time is between 6 am and 22 pm minus the average time of going to and returning from the destination node.

The truck is send to a node defined by destination address of just arrived container. If there is more than one vehicle available in the central node, the vehicle with size that a fits the best to the number of available containers is selected, i.e. the largest vehicle that could be fully loaded. If there are several trucks with the same capacity available the selection is done randomly. The restriction for the time of truck scheduling (the last point in the above algorithm) are set to model the fact that drivers are working on two 8 hours shifts.

### 4.3. Soft computing option

The system consists of a multilayer perceptron to decide if and where to send trucks. The input to the neural network consists of:

$$in = \langle pkc_1, pkc_2, ..., pkc_{npk}, crc_1, crc_2, ..., crc_{npk}, nfv \rangle \,, \tag{16}$$

*npk* – number of ordinary nodes,
$pkc_i$ – number of containers waiting for delivery in the central node with destination address set to $i$-th ordinary node,
*nfv* – number of free vehicles in the central node,

Each output of the network corresponds to each ordinary node:

$$nnout = \langle out_1, out_2, ..., out_{npk} \rangle \,. \tag{17}$$

The output of the network is interpreted as follows (for sigmoid function used in output layer):

$$j = \arg\max_{i=1...npk} \{out_i\} \,. \tag{18}$$

If $out_j$ is greater than 0.5 send a vehicle to node $j$ else do nothing. If there are more vehicles available in the central node, the largest vehicle that could be fully loaded is selected. If there are available several trucks with the same capacity selection is done randomly. The neural network decision (send a truck or not and where the truck should be sent) are taken in given moments in time. These moments are defined by following states of the system:

- the vehicle comes back to the central node and is ready for the next trip,
- if in central node there is at least one available vehicle and the number of containers of the same destination address is larger than the size of the smallest available vehicle.

The neural network used in the management system requires a learning process that will set up the values of its weights. The most typical learning in the case of multilayer perceptron is the back propagation algorithm. However, it cannot be used here since it is impossible to state what should be the proper output values of the neural network. Since it is hard to reconcile what are the results of a single decision made by the management system. Important are results of the set of decisions. Since the business service realised by transportation system is to move commodities without delays, the neural network should take such decisions that allows reducing delays as much as possible. To train neural network to perform such task we propose to use genetic algorithm [18,21]. Similar approach to training neural network is applied in case of computer games. The most important in case of genetic algorithm is a definition of the fitness function. To follow business service requirements of transportation system we propose the following definition of the fitness function calculated for a given neural network after some time ($T$) (therefore after a set of decisions taken by neural network) [17]:

$$fitness(T) = \frac{N_{ontime}(0,T) + N_{ontimeinsystem}(T)}{N_{delivered}(0,T) + N_{insystem}(T)} . \qquad (19)$$

It is a ratio of on-time containers (delivered with 24h and being in the system but not longer then 24h) to all containers (that already delivered $N_{delivered}(0,T)$ and still being presented in the system $N_{insystem}(T)$).

## 5. Critical Situation

### 5.1. Problem description

The *DTS* works correctly if there are no problems related to reliability and functional parameters. On the other hand the number and the volume of tasks loaded into the system cannot be above the system possibilities. The sentences sound very trivial, but – in general – it is not so trivial to find the global measure to check if the system is not overloaded. Of course the correctly tuned system ought to be characterised by the set of fault tolerant features. It means the system is able to realise the loaded tasks even if the different faults occur because of reliability or functional insufficiencies. The problem pointed above needs a multi-criteria solution. Other words it is possible to find a kind of pareto set (Fig. 2) to guarantee the system as functional ready for the defined tasks. The critical situation occurs if actual operating point of the system is located outside of the pareto set. The main goal if the critical situation is noticed is to drive the system to the pareto set as soon as possible. The proper management reaction is the first option to rescue the system situation. We propose the metric called the acceptance ratio to check if the operating point of the system is located at the pareto set [2].

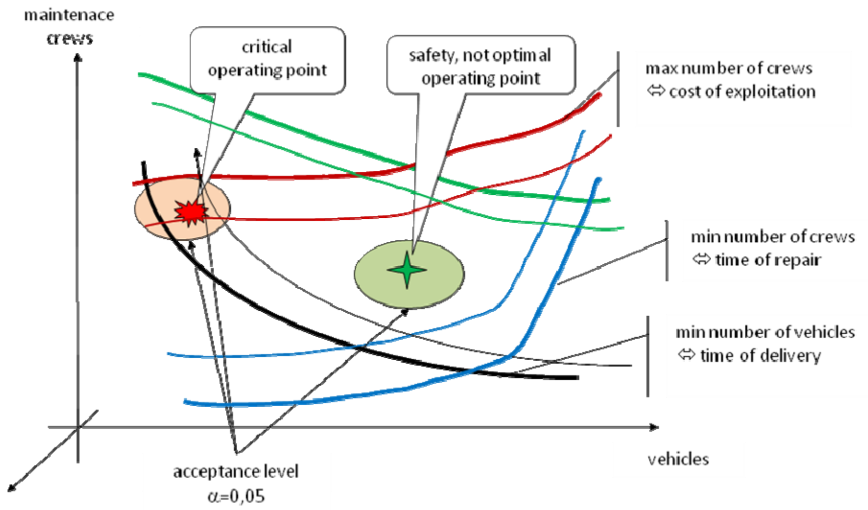



*Figure 2*. General idea of the pareto set

### 5.2. Functional availability

One can define the availability in different ways, but always the value of availability can be easy transformed into economic or functional parameters perfectly understood by owner of the system. The availability in mostly understood as a probability that a system is up and it is defined as a ratio of the expected value of the uptime of a system to the observation time. It is simple definition but requires defining what does it mean that transportation system is working.

The similar metric is the acceptance ratio defined in information since as a number of accepted requests to the total number of requests.

In paper [20] we have proposed the definition of up time as a time when the number of delayed containers does not exceed a given threshold. Let introduce the following notation:

- $T$ –a time measured from the moment when the container was introduced to the system to the moment when the container was transferred to the destination (random value),
- $T_g$ – a guaranteed time of delivery, if exceeded the container is delayed,
- $N_{deleyed}(t)$ - a stochastic process describing the number of delayed containers at time *t*, i.e. the number of containers for which T> $T_g$.

Therefore, the functional availability $A_k(t)$ can be defined as a probability that the number of delayed containers at time *t* does not exceed *k*, the value *k* is the level of acceptable delay:

$$FA_k(t) = \Pr\{N_{deleyed}(t) \le k\}. \tag{20}$$

### 5.3. Average functional availability

The defined in the previous section functional availability describes a state of an analysed system at a given point of time. In case if somebody wants to analyse a state of system in a time interval we have proposed in [7] the other metric: average functional availability $AFA_k(t)$. It is defined as an average probability that a system in the time interval from 0 to *t* is in up-time state (i.e. the number of delayed containers does not exceed threshold *k*):

$$AFA_k(t) = \frac{1}{t}\int_0^t \Pr\{N_{deleyed}(\tau) \le k\} d\tau . \tag{21}$$

### 5.4. Acceptance ratio

A very often used estimation of the availability, which uses its asymptotic property and is based on an assumption of a uniform rate of client requests is the acceptance ratio. For *DTS*, we have defined it [16] as the ratio of on-time containers (containers for which $T < T_g$) to all containers within a given time of observation (0, $\tau$). Within the time period a given number of containers are delivered ($N_{delivered}(\tau)$), a part of them or all delivered on time ($N_{ontime}(\tau)$), but at the end of analysed period time there could be some containers not yet delivered (waiting in the source node or being transported) ($N_{insystem}(\tau)$) and all or part of them being not late yet ($N_{ontimeinsystem}(\tau)$). Taking into consideration introduced symbols the availability could be calculated as the expected value (Monte-Carlo approach) of ratio of on-time containers to all containers:

$$AR_\tau = E\left(\frac{N_{ontime}(\tau) + N_{ontimeinsystem}(\tau)}{N_{delivered}(\tau) + N_{insystem}(\tau)}\right) \tag{22}$$

## 6. *DTS* Critical Situation Analysis Results

### 6.1. Exemplar *DTS*

We propose for the case study analysis an exemplar *DTS* based on Polish Post regional centre in Wroclaw. We have modelled a system consisting of one central node (Wroclaw regional centre) and twenty two other nodes - cities where there are local post distribution points in Dolny Slask Province. The length of roads was set according to real road distances between cities used in the analysed case study. The intensity of generation of containers for all destinations was set to 4.16 per hour in each direction giving in average 4400 containers to be transported each day. The vehicles speed was modelled by Gaussian distribution with 50 km/h of mean value and 5 km/h of standard deviation. The average loading time was equal to 5 minutes. There were two types of vehicles: with capacity of 10 and 15 containers. The MTF of each vehicle was set to 20000. The average repair time was set to 5h (Gaussian distribution). We also have tried to model the drivers' availability parameters. We have fulfilled this challenge by using the following probability of a given type of sickness: short sick: 0.003, typical illness: 0.001, long-term illness: 0.00025.

### 6.2. Critical situation discussion

We entered the defined above system into critical situation: first of all to observe the actual value of the acceptance ratio – to find how deep degradation we can noticed. The second goal was to compare the effectiveness of the three possible management systems in case of driving the operating point of the system to the pareto set as soon as possible (Fig. 3.). Finally we tried to find the real pareto set for the defined set of task loaded into the system, the tuned number of vehicles and the tuned number of drivers (Fig. 5.).

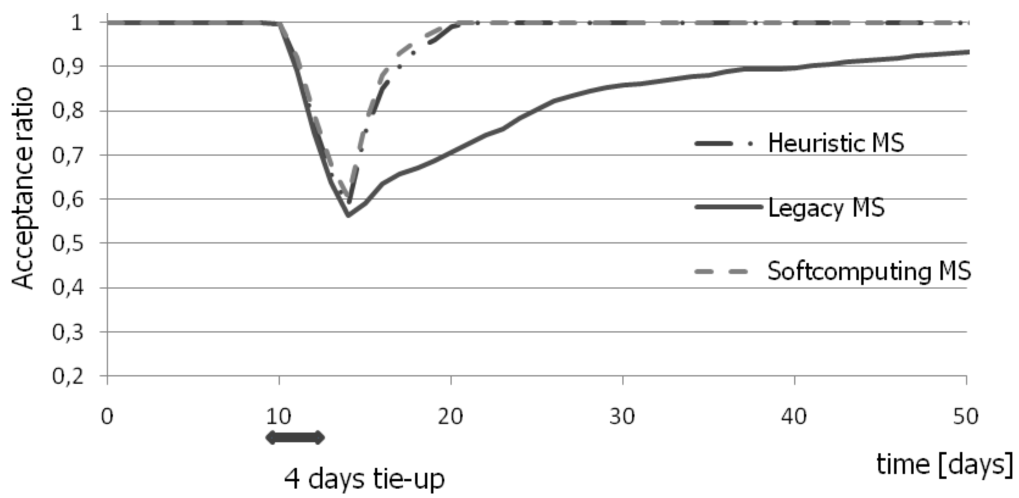
Let's assume that for some days the system is working at 50%. The tie-up of the system could be caused for example by a driver strike or some contagious diseases resulting in situation that only 50% of vehicles. After a given number of days the system is again fully working.

The achieved results (acceptance ratio calculated according to (22)) for 4 and 14 days tie-up are presented on Figure 3. As it could be expected the acceptance ratio in day 10 (when critical situation starts) is starting to drop down and when drivers come back is enlarging.

However the system with heuristic management as well as with soft computing one is coming back to normal operation much faster than legacy one. The soft computing one is slightly outperforming the heuristic one.

The Figure 4 presents how many days are needed for the transportation system to achieve a required level (0.9, 0.95 and 0.98) after a tie-up of the different length. The system is driven by the soft computing management system.

a)




b)

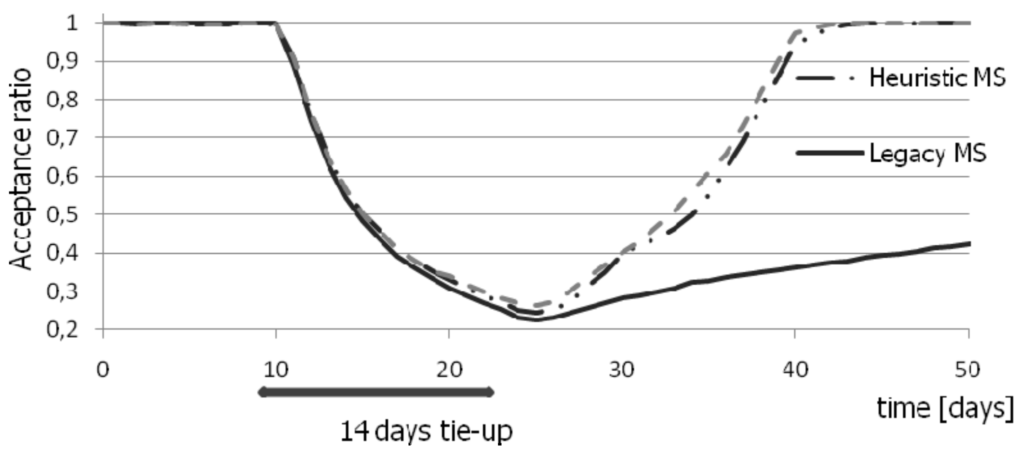



*Figure 3*. Acceptance ratio for 4 days (a) and 14 days (b) tie-up vehicles for different management system

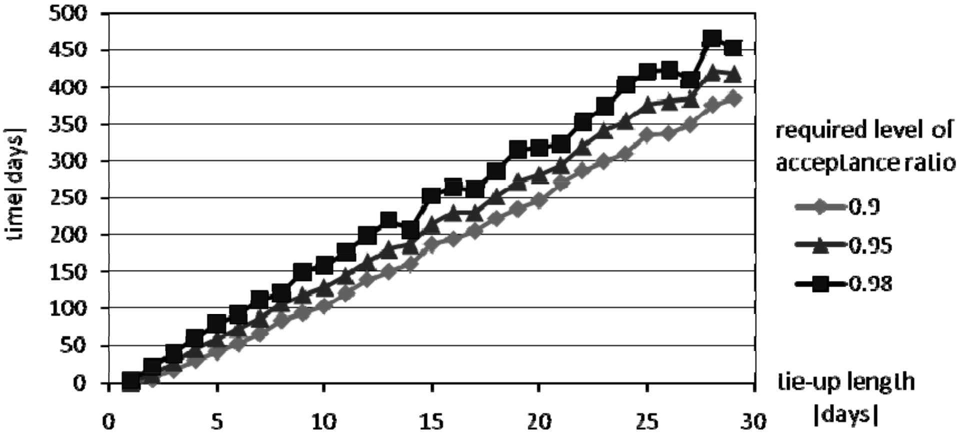



*Figure 4*. The time required to achieve a given level of acceptance ratio after a tie-up of different length for the exemplar *DTS* driven by soft computing management system

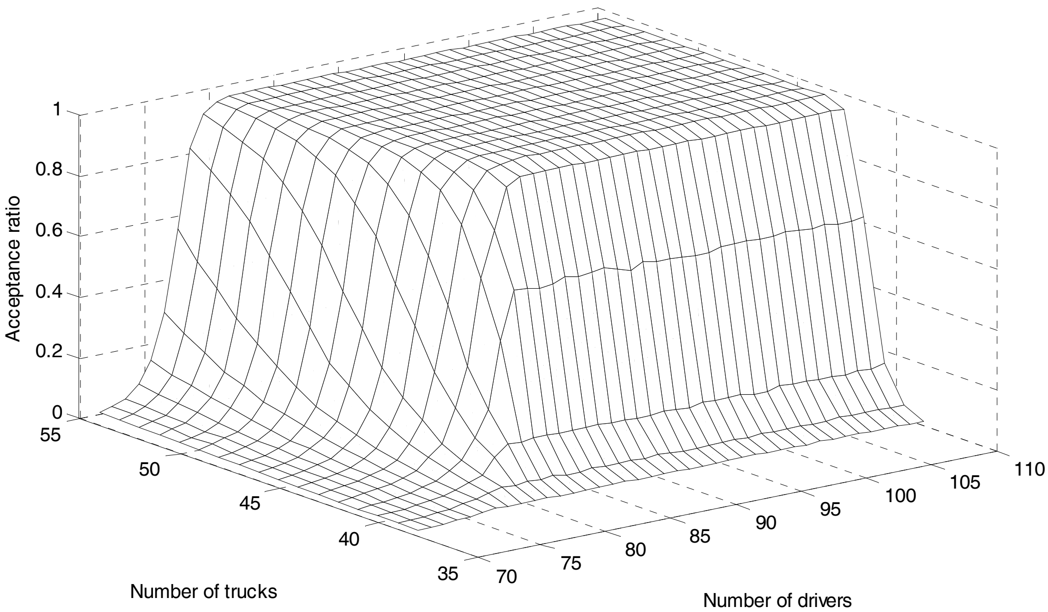



*Figure 5*. Pareto set in a function of number of trucks and number of drivers for tested *DTS*

## 7. Conclusions

We have presented a formal model of discrete transportation system (*DTS*) including reliability, functional parameters as well as the human factor component.. The *DTS* model is based on Polish Post regional transportation system. We proposed three different management approaches for the defined system. The critical situation is described and the availability metric to create the pareto set – guarantying the possible safety operating points for actual *DTS*.

The proposed approach allows performing reliability and functional analysis of the *DTS*, for example:

- determine what will cause a ”local” change in the system,
- make experiments in case of increasing number of containers per day incoming to system,
- identify weak point of the system by comparing few its configuration,
- better understand how the system behaves.

We introduced the exemplar *DTS* into critical situation to discuss how deep breakdown it caused and to test, which management approach can drive the system operating point into pareto set as soon as possible. The *DTS* described as the case study is based on real Polish Post Wroclaw area. The solution presented can be used as practical tool for defining an organization of vehicle maintenance and transportation system logistics.

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