Dependability Model of a Discrete Transport System

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***Abstract* — The paper presents reliability and functional model of discrete transport system (*DTS*). The approach includes hardware and software resources features as well as task description and dispatcher of vehicles. The failure types and necessary procedures to minimise the consequences of faults are categorised. The set of functional and reliability measures is defined.**

***Keywords* — theory of system dependability, discrete transport system reliability, functional and reliability models**

I. Introduction

The most often discussed methods of transport are focused on commodity movement according to declared routes, using autonomous equipment (vehicles) characterised by the capacity and based on prepared schedule. The presented class of transport systems is called discrete transport system (*DTS*). We can find an example of *DTS* as a commodity transportation realised by trucks. The schedule of such *DTS* can be not very precise against to coaches, passenger airplanes or trains. Of course there are situations where the schedule ought to be very precise – productive systems working without storehouses – for example – with remote co-operating parties [20], [10].

It is not trivial to model the transportation system properly for quality and efficiency estimation.

The discrete transport system definition presented below includes all elements which have effect on service quality served by a supplier according to fixed strategy, real functional and reliability parameters of equipment. Such defined model combines both dependability and functional features. It allows to model discrete transport systems and to analyse the efficiency of the system if the number as well as quality of vehicles changes. We can also test how the system works if the number and location of recipients vary or different types of service strategy are available, or we notice failures [8], [11].

If we think about the transportation system as combination of equipment, infrastructure and human dispatcher we need to substitute the ordinary reliability models by functional and dependability models to check the system reaction for failures as well as to find the system efficiency changes after the dispatcher decisions [23], [5].

It is necessary for functional and dependability models to expand the definition of proper (reliable) state of system. The transportation system works correctly if tasks are realised according to the agreement – it means the commodity is transported on schedule, with declared volume. Failures of vehicles and infrastructure deteriorate the efficiency of the system, but if transportation tasks are realised according to the agreement we can say that the system works correctly.

In the real transportation systems it is possible to substitute some functions by similar functions operating by various configurations, using different infrastructure features and redefined schedule [6], [12].

This way the system realises the task based on set of resources called functional configurations.

The resources allocation is realised in dynamic way – modifications are driven by the stream of tasks, failures and dispatcher decisions [4], [7].

II. Discrete Transport System

The **discrete transport system** (*DTS*) is understood as a system of **transport resources** (e.g. vehicles), **transport infrastructure** (e.g. roads) and a **management system** (e.g. a dispatcher supported by a computer system). In this way dependability (functional – reliable) properties of the *DTS* depend not only on technical infrastructure of the system but also on dispatcher decisions [21], [17].

Dispatcher decisions may be reaction on traffic situations (e.g. a traffic jam, a temporary limitation of vehicle speed on the fixed segment of a road), on infrastructure faults (e.g. a truck with cargo is failed and it has to be repaired), on functional system faults (e.g. a point storehouse is overfilled or already sent parcels are not collected yet) [9], [20], [16].

The dispatcher decisions are taken on the base of such different criteria as financial costs, system performance parameters, availability of renewal teams (the conservator problem!), possibility to access other routes, acceptability of parcel delaying, etc.

The **Discrete Transport System** *DTS* is defined as [24]:

$$DTS = \langle TI, RES, TT, MS \rangle \tag{1}$$

where:

TI – technical infrastructure of the system,
RES – system resources,
TT – transport tasks,
MS – management system which is called dispatcher.

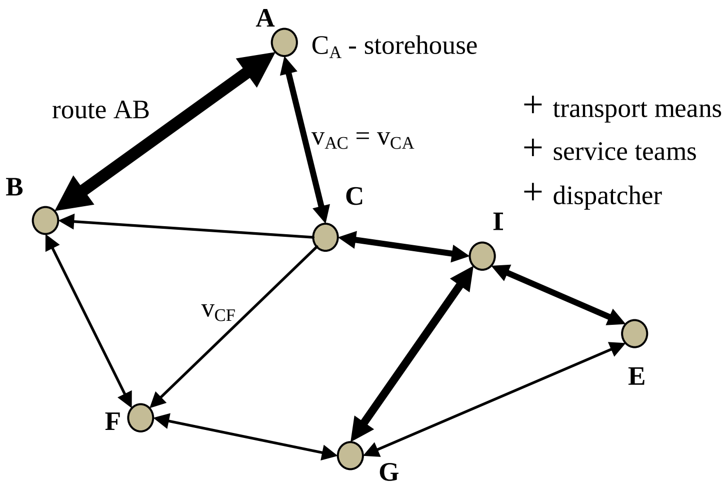

Fig. 1. Discrete Transport System (*DTS*)

The **technical infrastructure** *TI* of the discrete transport system is modelled as a directed graph [22], [15]:

$$TI = \langle reloading\ \ places, roads \rangle = \langle RP, R \rangle \qquad (2)$$

where:

$RP = \langle A, B, C, \ldots \rangle$ - set of reloading places (Fig. 1),

$R = \langle AB, AC, BC, \ldots \rangle$ - set of roads connecting reloading places.

A **reloading place** is a node of the discrete transport system (a node in the *TI* graph) in which such functions as parcels collecting in storehouses, reloading parcels from one transport resources to other one or to a storehouse may be realised. The reloading place may be equipped with a storehouse (with limited capacity; e.g. C_A, C_B, etc.) and needs such "mechanical tools" as cranes or fork-lift track.

Roads are modelled as directed arcs connected to nodes of the *TI* graph. Engineering parameters of the road are integrated into one representative measure called *average speed* of transport resource on this road segment (e.g. v_{AB}). Of course the average speed depends of cargo, transport means type, direction of traffic, day time or month time etc. Sometimes it is possible that $v_{AB} \neq v_{BA}$, but we can also assume the speed values are equal ($v_{AB} = v_{BA}$).

System resources of the *DTS* are understood as collections of transport means, drivers and service teams which the dispatcher may use for transport tasks realisation and for removing some disturbances in the system work.

A system resource is described by its functional (e.g. load capacity of a truck), technical (e.g. fuels expendable per kilometre) and reliability parameters (e.g. mean time between failures or mean time renewal) which may have deterministic or probabilistic nature. Drivers create a specific class of the system resource [19], [10], [24].

A **transport task** *TT* is understood as a pickup of a fixed cargo from the start node and a delivery of it to final node according to assumed time-table. Of course the transport task may be defined in more complicated way, e.g. a cargo may be collected in a few nodes and reloaded in several ones. Transport schedule can be defined in different ways, for example a cargo ought to be delivered to the node before the end of fixed time-period, because a train cannot wait for a truck with the cargo.

Faults and renewals of a discrete transport system. There are considered many disruptions in execution of the discrete transport systems. The failures of the *DTS* resources *RES*, e.g. physical failures of trucks or technical infrastructure *TI* (e.g. roads or reloading devices) need to use adequate such the *DTS* system means as service teams, garages, spare elements or substituted routes. Generally, in these situations **"technical" system renewal** processes are started on with assumption of the limited resources [22], [19].

Other sources of the *DTS* system disruptions we can find in organisation and management matters:

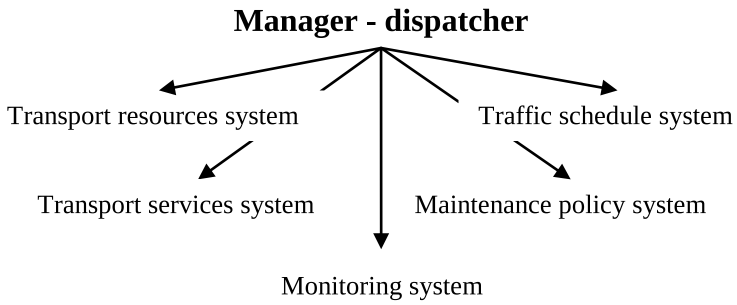

Fig. 2. A dispatcher work is supported by computer systems

1) overloading of the technical infrastructure (roads, reloading machines, etc.),
2) traffic accidents or jams (faults of people!),
3) dispatcher faults – he or she is not able to keep up the dynamic changes of the situation in the working *DTS* system. In these cases exploitation system renewal processes are initiated by the system dispatcher. The processes very often consume more time and money than a renewal of a "simple (physical)" broken technical resource, e.g. a repair of a failed truck or a lift.

The **dispatcher** organises a work of the *DTS* system - available system resources are assigned to realised tasks.

The dispatcher administers logistics of a transport firm based on the signed agreements specifying conditions of correct realisation of a task or sets of tasks [17], [21].

Dispatcher decisions are taken based on needs of assumed transport tasks and according (if it is possible) to assumed proper time-tables. When some disruptions (failures, faults) occur the dispatcher chooses adequate system reactions.

The dispatcher is supported by the computer aided tools (Fig. 2) to improve an assignment of system resources to transport tasks, to compose system traffic time-tables (planned and reserved for emergency conditions), to provide maintenance policies ready to use both for normal and disrupted situation in the system work. Because there are a lot of people involved into the system work the dispatcher should take his/her decisions taking into account not only computer system support results, but also based on his/her experience and his/her intelligence [13], [8], [5].

It is possible to define many classes of dispatchers, who are working in harmony with agreement between an transport employer and an owner of the discrete transport system. A **passive dispatcher** realises transport tasks agree to previously defined conditions and schedules. He or she uses earlier prepared lists of assumed *DTS* disruptions and lists of planned adequate system reactions in case of disruptions. A **task oriented dispatcher** is focused on execution of selected task or its sets. He or she may works agree with such strategy as FIFO, LIFO, FILO etc. A **dynamic dispatcher** is monitoring on-line a system and takes decisions adequate to system situation; of course the dynamic dispatcher cannot work as a fantastic virtuoso manager. If more detailed supporting data (collected from different components of the system – see Fig. 2) are prepared a priori, the real dependability properties (performance and reliability parameters) of the considered *DTS* system are closer to expected.

The Fig. 3 presents a part of a very simplified UML model of supervising of a transport task realisation in a discrete transport system (see the definitions given by the formulas (1) and (2)). The dispatcher takes decisions about allocation of system resources ("vertical lines" *REAL* based on information received from computer systems ("lines" *COMP* in Fig. 3). Two possible situations are presented: the task is realised without failures (a) and the failures are present (b). The dispatcher when the failure occurs ought to start necessary maintenance procedure. When the maintenance is finished the task is continued [22], [10].

The task expresses the ready state for execution. In the first step the dispatcher checks (using the computer transport resources system) if an adequate task resources (*TASK RESOURCES*) are available. If the necessary resources are not in use and are not reserved in time-period of the task execution the dispatcher allocates them. Next the technical infrastructure (reloading places and roads) is checked and allocated to the task; that means a route is created for the task, etc.

III. Dependability of the Discrete Transport System

Dependability measures of discrete transport systems are defined as global values (e.g. system efficiency, financial profit or loss) or as more detail measures such as a probability of isolated task execution or a set of tasks realised in a determined time interval [22], [19].

Functional and reliable properties of a discrete transport system have an effect on dependability measures at two fundamental levels:

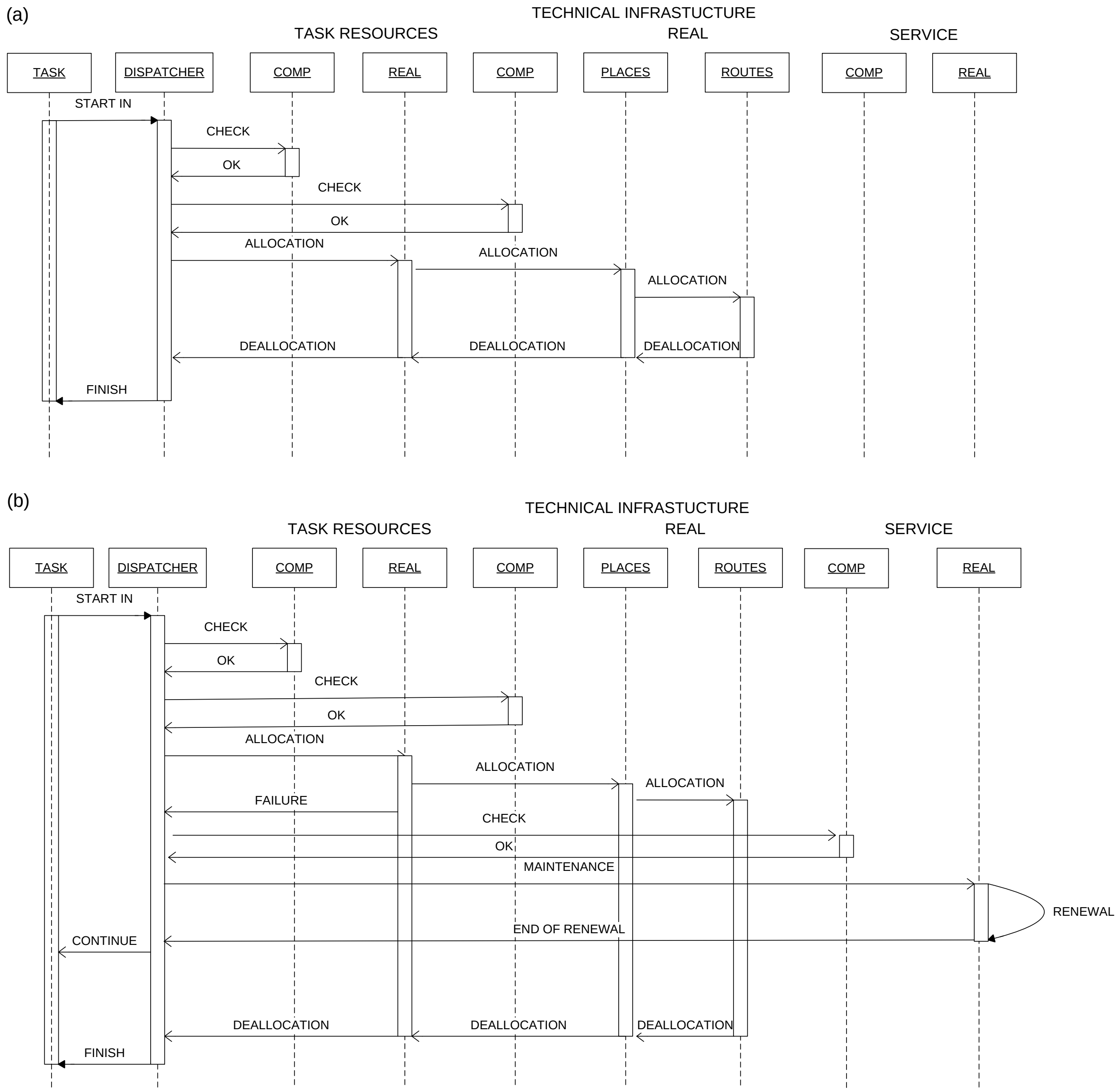

Fig. 3. A dispatcher model in UML representation: (a) task realisation without failures, (b) task realisation with failures

1. it is possibility to create a functional configuration of the task or the set of tasks, that means it is possibility to allocate needed system resources for the transport task (or tasks) execution,

2. it is possibility that the transport task is correctly realised, that means allocated resources correctly work during assumed time and the assumed cargo is delivered according to assumed time-table.

The resources of all real systems are limited, so the system dispatcher has a significant impact on solving above given problems.

His/her decisions concerning allocation technical infrastructure, transport means, service teams or reconfiguration of the system have to be taken up quickly and adequate to the situation [7], [11], [4].

IV. DEPENDABILITY MEASURES EVALUATION OF DISCRETE TRANSPORT SYSTEM

It is considered a discrete transport system (Fig. 4). A supplier of medium located at the node Z should deliver adequate quantity of medium to consumer (nodes $N_1, \dots, N_N$) in time period $(0, t)$. The supplier possess K identical trucks with u capacity of each. It is assumed that routes and distances ($l^{(n)}$, $n=1 \dots N$) are constant during time realisation of the contract [16], [20].

The correct agreement realisation means we guarantee for n-th recipient the medium in time-period $[0, T^{(n)}]$. The commodity is used by the recipient and we cannot agree for the shortage of it to the end of time when the agreement is valid. So the dispatcher ought to set such chronicle of deliveries to fix the commodity at the recipient at $t = 0$ and to minimise the commodity overload at the end of agreement period. It means the deliveries should start and stop properly.

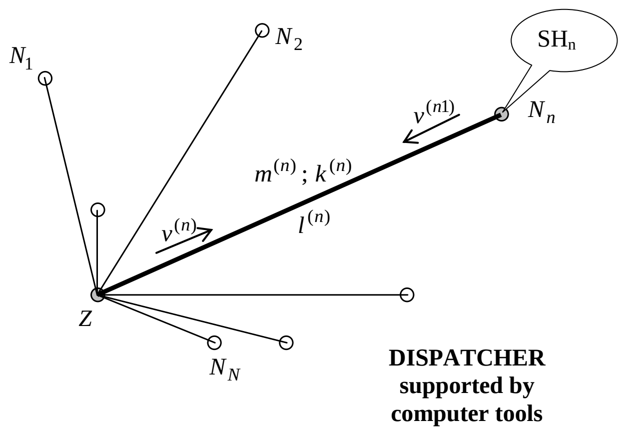

Fig. 4. The considered *DTS*

Tasks – *J*. The commodity is delivered to recipient storehouse by vehicles with capacity u operating circular between the supplier and recipient. The vehicle failure elongates the time necessary for task realisation by time-period of maintenance. The delivered commodity is used by linear model $w^{(n)}t$ where $w^{(n)}$ is the parameter of commodity consumption in time unit. The agreement guarantees that deliveries satisfy the average commodity consumption with fixed overload – we introduce the parameter of protected level of reserves α [%]. We do not care about the limited capacity of the recipient storehouse [22], [10].

The transportation task is divided into three stages based on actual state of recipient storehouse: introducing deliveries, normal deliveries and reserves consumption (Fig. 5).

Vehicles – *H*. The system includes K vehicles with capacity u of each. The vehicle with load for n-th recipient moves with constant average speed $v^{(n)}$ and returns in empty state with speed $v^{(n1)}$. The average speed covers a time period of additional operations as: loading, unloading, breaks for driver, etc.

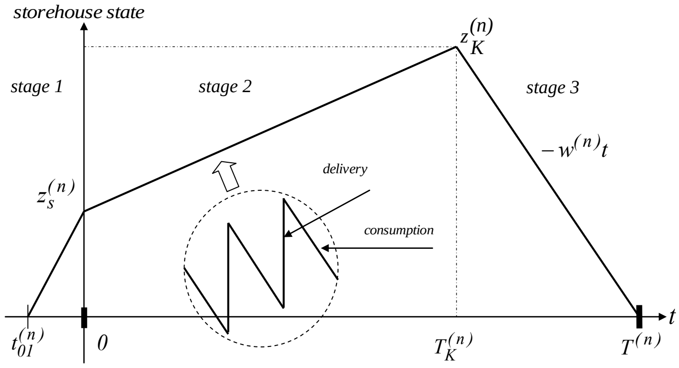

Fig. 5. Storehouse state of n-th recipient

The vehicles can fail and are repairable. The time to failure and time of repair are described by exponential distribution with parameters: λ_F and μ_F.

Infrastructure – I_{TR} = $\{i_{TR}^{(j)};\ j = 1, 2, \dots\}$. Routes and storehouses create the system infrastructure with fixed paths of delivery and distances ($l^{(n)}$, $n = 1 \dots N$). There are no alternative paths, the route parameters allow to travel with maximum average speed for each vehicle. The routes not fail, there are no traffic problems. We also relax the problem of limited capacity of the recipient storehouse [23], [19], [15].

Dispatcher – *D*. The system is driven by static dispatcher working according to ready to use plan for time-period of agreement. The plan considers already defined hazards and proper solutions. The dispatcher decisions are taken by following rules:

- single agreement needs $k^{(n)}$ vehicles for n-th recipient, $$K = \sum_{n=1}^{N} k^{(n)}$$
- the commodity is transported from supplier to recipient, return journey vehicle realises in empty space,
- vehicles started in unified time-periods called cycles and they realised transport tasks: commodity delivering, return in empty state to a base,
- each route is equipped by single maintenance group, the repair time combines the real repair time and necessary time to reach the failed vehicle, maintenance is realised according to FIFO approach,
- commodity consumption starts at the begin of agreement time-period – so it is necessary to store the volume of commodity and it is necessary to start vehicle fleet little bit before the agreement starting point.

The main goal is to estimate the number of necessary vehicles, the state of recipient storehouse and the proper moment to start the vehicles with the commodity - taking into account guaranteed average level of reserves in the recipient storehouse [12], [9], [10].

Number of vehicles. The average number of vehicles with capacity u working for n-th recipient – based on model assumptions and logistic - we can estimate as follow:

$$k^{(n)} \cong \frac{w^{(n)}\left(1+\alpha^{(n)}\right)}{u}\left(\frac{l^{(n)}}{v^{(n)}}+\frac{l^{(n)}}{v^{(n1)}}\right) \tag{3}$$

Based on agreement conditions - penalty if the level of resources is lower than $(1 + \alpha^{(n)})\ w^{(n)}$) – the number of trucks we should round to the closer integer value. The final number of necessary vehicles to operate with all N recipients equals to:

$$K \cong \sum_{n=1}^{N} \frac{w^{(n)}\left(1+\alpha^{(n)}\right)}{u}\left(\frac{l^{(n)}}{v^{(n)}}+\frac{l^{(n)}}{v^{(n1)}}\right) \tag{4}$$

The equations above are true if there are no barriers related to vehicles. If we add this kind of limitations the problem how to allocate the system resources among the recipients is more sophisticated. The most typical solution is based on the supplier profits, operating costs and penalties if the agreement cannot be fulfilled. The equations (3) and (4) are absolutely correct if the vehicle fleet is perfectly reliable. If the time-period of agreement is significant the fleet can lost very good dependability parameters. This way it is possible that the system owner's profits are less than expected, he or she has to cover additional costs of vehicle maintenance and he or she has some problems to fulfil the agreement conditions. If we use the overflow number of vehicles the costs grow up, we can meet the problem of storehouse overload, or the queues of vehicles waiting for unloading procedure [14], [21].

Storehouses. The actual state of n-th recipient storehouse depends on the volume of delivery, commodity consumption in time unit ($w^{(n)}$) and time-period of the agreement. The volume of delivery is driven by: the number of used vehicles ($k^{(n)}$), vehicle capacity (u), distance from supplier ($l^{(n)}$), routes quality, average speed of vehicle ($v^{(n)}$, $v^{(n1)}$), reliability of vehicles ($\lambda_F^{(n)}$) and strategy of maintenance.

The state of storehouse is estimated based on balance equation of average level of resources for n-th recipient:

$$E_t\left[m^{(n)}(t)\right] = u\,\frac{E_t\left[k^{(n)}\right]}{\frac{l^{(n)}}{v^{(n)}}+\frac{l^{(n)}}{v^{(n1)}}}\,t - \left(1+\alpha^{(n)}\right)w^{(n)}\,t \tag{5}$$

where:

$E_t\left[m^{(n)}(t)\right]$ - expected value of resources for n-th recipient calculated for time-period agreement $[0, t]$,

$E_t\left[k^{(n)}\right]$ - expected value of active vehicles for n-th recipient calculated for time-period agreement $[0, t]$.

Task – Stage 1. Before $t = 0$ – begin of agreement time-period – we have to collect in the storehouse the proper volume of commodity $m_S^{(n)}$ – equal to the consumption process in time-period $[0,\ t_S^{(n)}]$. The starting moment of the introducing deliveries can be estimated as follow:

$$t_{01}^{(n)} = ceil\left(\frac{l^{(n)}}{v^{(n)}}\right), \tag{6}$$

Number of necessary vehicles to realise Stage 1:

$$k_1^{(n)} = ceil\left(\frac{\left(1+a^{(n)}\right)w^{(n)}t_S^{(n)}}{u}\right) \tag{7}$$

where:

ceil – the smallest integer value greater or equal to argument

Task – Stage 2. The state of commodity in the storehouse is analysed. The commodity is taken to provide the production process – for example – and the storehouse is refilled by cyclic deliveries. Number of deliveries can be estimated as follow [23]:

$$d^{(n)} = ceil\left(\frac{\left(1+\alpha^{(n)}\right)w^{(n)}T^{(n)}}{u}\right) \tag{8}$$

Number of deliveries meets the number of realised transportation tasks by vehicles characterised by capacity u. The key problem is to fix time-period of single cycle – it means the interval between starting points of the following deliveries [21]:

$$t_C^{(n)} = floor\left(\frac{u}{\left(1+a^{(n)}\right)w^{(n)}}\right) \tag{9}$$

where:

floor – the greatest integer value lower or equal to argument

Task – Stage 3. According to the agreement the volume of commodity in the storehouse should meets the consumption to the time-moment $T^{(n)}$. The dispatcher sometimes is not able to fit the delivery cycles precise enough to start the last delivery process properly earlier. The time overload (Fig. 6) can be the time redundancy of *DTS*:

$$\tau_R^{(n)} = T^{(n)} + t_{01}^{(n)} - T_K^{(n)} \tag{10}$$

The value of time redundancy can be tuned based on reliability parameters of the system elements [19], [15], [5].

V. Conclusions

The proposed model combines functional and reliability parameters of discrete transport system (*DTS*). The most interesting seems to be using the model for further works about the influence of the system logistic for the system efficiency: agreement realisation in case of limited resources or when the system is in critical situation.

The analysis realised based on analytic approach set a lot of very serious assumptions. The computer simulation approach allows to relax most of the limitations and opens the real possibility to make very detailed analysis of dependability features of actual transportation systems.

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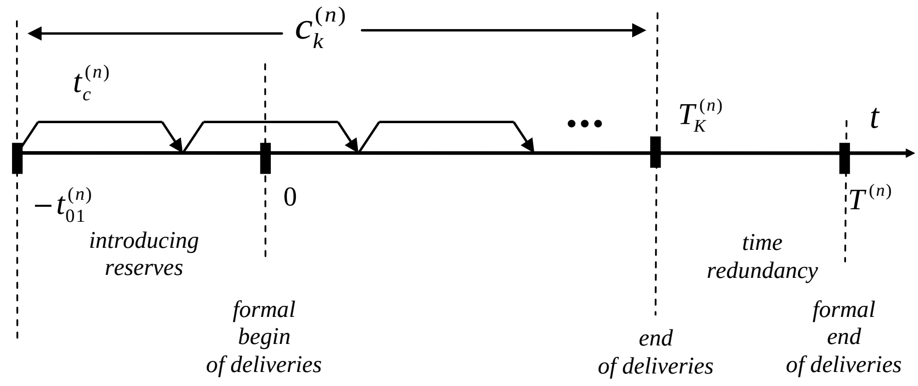

Fig. 6. Time redundancy of *k*-th recipient

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