RIGA TECHNICAL UNIVERSITY

Jeļena Pečerska

A COMBINED APPROACH TO THE SIMULATION OF MATERIAL FLOW HANDLING SYSTEMS

Summary of Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Computer Science and Information Technology
Institute of Information Technology

Jeļena Pečerska
Student of the Doctoral study programme
“Management Information Technology”

Summary of Doctoral Thesis

Scientific supervisor
Dr. habil.sc., prof.
G. MERKURJEVA

Scientific consultant
Dr. habil.sc.ing. J. TOLUJEVS

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DOCTORAL THESIS
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The defence of the thesis submitted for the doctoral degree in engineering science (Management Information Technology) will take place at an open session at the Faculty of Computer Science and Information Technology of Riga Technical University, in 1/3 Meza Street, auditorium 202, at 14^{30}, on December 3, 2012.

OFFICIAL REVIEWERS

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DECLARATION

I hereby confirm that I have developed this thesis submitted for the doctoral degree at Riga Technical University. This thesis has not been submitted for the doctoral degree at any other university.

Jeļena Pečerska…………………………….(Signature)

Date: October 24, 2012

The doctoral thesis is written in Latvian. It consists of introduction, 4 sections, conclusions, bibliography and 8 appendixes. It includes 44 figures and 13 tables. The thesis is printed on 160 pages. The full bibliography comprises 107 entries.

GENERAL DESCRIPTION OF THE THESIS

The thesis is elaborated in the area of modelling and simulation and deals with the development of a new combined approach to the simulation. The purpose of the approach is to improve the efficiency of material flow handling systems analysis. The combined simulation approach is important for the studies of logistic and manufacturing systems that are interpreted and analysed as *discrete-event systems* (*DES*).

Research motivation

The analysis of statistical performance measures that describe the volume and the growth rate of business activities for industrial sectors closely relating to material flow handling and processing, such as manufacturing, construction, transportation and others, corroborates the topicality of the choice of researched subject.

The national economies of the industrialized countries have shown the trend over the recent years to include simulations as integral parts of projects, both in design and reengineering of manufacturing, service, logistics and transport systems [17, 24]. This trend is the result of managers increasing reliability in modelling and simulation and stochastic systems simulation in particular as one of the methods of information technology [6, 13 etc.].

The advance of *material flow handling systems* (MFHS) simulation methods is considered as an important and perspective area. The *material flow* (MF) in general is defined as a dynamic phenomenon that occupies considerable place in common three-dimensional space. MF, being the widely-spread elements of complex systems of various types, ensures both the interaction of system elements and system links with the environment thereby most of complex systems may be considered and analyzed as MFHS. Therefore almost all up-to-date simulation software provides tools and components for MF analysis, description, incorporation into simulations, obtaining and visualization of appropriate simulation results [23].

Nowadays MFs usually are simulated using traditional simulation approaches, i.e. continuous or discrete-event ones [23]. The flows, including material ones, within the continuous simulation approach are simulated as variables. Within the discrete-event simulation paradigm material flows are simulated as flows of different individual material objects or entity flows.

In recent years, several authors have suggested alternative approaches to the applied research that have been implemented as combined ones [5, 35 etc.]. At present, as it may be issued from the overview of publications; almost no any theoretical studies are conducted in the area of combined simulation approaches. However the necessity of the relevant theoretical justification became indirectly apparent in the specific functions of simulation software systems [7, 10].

The combined simulation approach is able to expand the application possibilities of the discrete-event systems simulation in the area of MFHS simulation and analysis and to improve both the effectiveness of model creation process and the practical significance of simulation [7]. The research motivation actuality is associated with the necessity to improve the approaches to MFHS simulation.

The goal and the tasks of the thesis

In the framework of the discrete event system simulation (further – DESS) approach the event and objects flows and operations detailing level are not coordinated at the modelling process separate stages. For example, simulated system data are available as aggregated ones at the stage of model conceptualisation. Input flow separate objects data are obtained from the mentioned above and described in detail at the stage of model programming; accumulated simulation results are available as aggregated event flow data [1, 10, 11, 23, 29, 36, 42 etc].

The goal of the present thesis is to develop such MFHS simulation approach in the frame of the DESS approach, which provides opportunity:

- to describe the elements of MFHS in aggregated form;
- to decrease the events quantity and associated calculations volume accordingly;
- to obtain the reliable estimates which correspond to DESS ones as the result of the present approach application.

Modelling approach should be systematic, simple enough, taking into account the existing theory of DESS, effective and applicable practically.

The following tasks are defined to reach the goals of the present thesis:

1. To review and classify the types of the material flows and formalisation forms.
2. To execute the analysis of the MFHS importance in manufacturing and logistics.
3. To make the MFHS modelling paradigm comparative study.
4. To develop the combined approach to the simulation of MFHS.
5. To develop basic components and models for realisation of combined simulation approach.

The research object and subject

The research objects are MFHS, which could be formalised as the discrete event systems.

The research subject is a set of MFHS traditional and combined modelling methods, which are based on the discrete events.

The research methods

The theoretical studies in the present thesis apply the system theory, discrete mathematics, system dynamics and DESS.

For the application of the developed approach the simulation and mathematical statistics method are applied.

The scientific novelty

The scientific novelty comprises as follows:

1. The traditional simulation approach imperfections in MFHS modelling sphere are revealed.
2. The requirements for the development of the combined approach to the simulation are stated.
3. The mathematic scheme of the combined models is proved.
4. A combined approach to the simulation of MFHS is developed.
5. The combined model to test MFHS simulation approach is realised.

Theses to be defended

1. The basis of a new mathematical scheme of MFHS simulation.
2. The development of MFHS simulation approach based on the DESS.
3. The analysis of the advantages of MFHS combined model to the traditional discrete event simulation model.

Publications

The results of the research are published in 10 international scientific editions approved by Latvian Council of Science, namely [1 – 7, 9, 11, 12] in the author's publication list. The publications could be grouped as follows: methodical ones [3, 6, 7, 9, 10, and 14], the presentation of the applied studies results [4, 8, and 13] and theoretical ones dealt with the development of a new simulation approach [1, 2, 7, 11, and 12].

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Scientific conferences and workshops

The author has reported the main results of the scientific studies at 8 International Scientific Conferences and Workshops: RTU 42nd International Scientific Conference (Riga, 2001); RTU 43rd International Scientific Conference (Riga, 2002); RTU 45th International Scientific Conference (Riga, 2004); International conference "European Conference of Modelling and Simulation", ECMS 2005 (Riga, 2005. g.); 11th International conference Maritime Transport and Infrastructure (Riga, 2009); 12th Conference of Young Scientists of Lithuania, „Science – Lithuania's Future. TRANSPORT". (Vilnius, Lithuania, 2009); UKSim 12th International Conference on Computer Modelling and Simulation (Cambridge, Great Britain, 2010); 3rd International Doctoral Student Workshop on Logistics (Magdeburg, Germany, 2010).

The structure of the thesis

The thesis consists of introduction, 4 chapters, conclusions, and list of references, 9 appendixes, 44 figures and 13 tables, total 148 pages (appendixes included). The list of references comprises 107 sources. The structure of the thesis is as follows:

Introduction motivates the research, formulates the research aim and tasks, defines the research object and subject, describes research methods used in the thesis, and explains scientific novelty, practical use and approbation of the thesis.

In ***Chapter 1 "Material flows and material flow handling systems"*** the types of material flows and the ways of flow formalisation are examined and classified, the importance of MFHS in manufacturing and logistics is analysed.

In ***Chapter 2 "Material flow modelling paradigms"*** the comparative analysis of MFHS traditional modelling paradigms is carried out, the mathematical formulation of the problem as well as the necessary assumptions are defined.

In ***Chapter 3 "The development of material flow combined simulation approach"*** a combined approach to the simulation of the MFHS is developed. The new approach unites the DESS time tracking principle with the state variables that are characterized by the piecewise-linear changes. The operation algorithms of the components, the corresponding state variable conversions and performance measure evaluation formulas are developed making it possible to create combined models and to apply these models for the analysis of the simulated systems.

In ***Chapter 4 "The application of the developed approach for material flow handling system simulation"*** basic components and models for the realization of the combined approach are worked out. The chapter describes the developed combined approach approval based on the MFHS example - the realization of the tactical plan for the applied research of a coal terminal.

Results and conclusions of the thesis

List of references

Appendixes

THE SUMMARY OF THESIS CHAPTERS

Material flows and material flows handling systems

The Chapter 1 presents the study of the material flow concept to identify its special features for simulation studies as well as unresolved problems and tasks. This study also is aimed to define general requirements of material flow formalisation and description in frame of MFHS simulation studies that should fit the simulation methodology. The importance of MFHS in manufacturing and logistics is analysed there.

In modelling the specialists have noted such material flows, which most frequently are investigated in the simulation projects. Originally the concept of material flow was used by philosophers and physics; however, the field of the present thesis applies the interpretation of concept from the point of view of the management science as most suitable.

The majority of the authors include the following main signs in the definition of material flow: the generality of material resources, their displacement or circulation, the specific period of time, susceptibility to different operations and functions [42]. Although the authors – economists and logistics specialists – include time in definitions, nevertheless it is should be refined that during the investigated time interval it is possible to mark the special time moments - events, when flow state changes. Information about state changes of material flow has vital importance for determining the dynamic behaviour of the material flow.

Both the range of material flows and their definitions are very wide. By **material flow** in general the majority of the authors understands **the certain dynamic phenomenon, which could occupy significant place in the three-dimensional space of the surrounding world.** This definition is of a very general nature and it should be scaled down in the context of simulation studies.

Material flow in the artificial material systems is frequently interpreted as **a flow of** the actually observed **material objects**. Both means of the transportation-technological operations (resources) and the moving entities (loads, passengers and vehicles) are implied as "material objects". With this interpretation special attention is paid to material nature of the flow objects and their discernability and discontinuity.

Material flows, as a class of the simulation objects, are subjected to the analysis within the framework of various simulation projects therefore the development of approaches to material flow simulation is an important task. It is possible not only to describe the general properties of material flow but also to use one of the existing material flow classifications for details.

In systems, which are analysed as DES, the operation of a system is interpreted as a chronological sequence of state change events. These events comprise the events corresponding with material flows, such as starting, finishing, intensity changing events and others. In the framework of DESS the following material flow definition could be provided: **Material flow is the chronological sequence of events, each event is the appearance of one or several objects in this space region.**

The objects of a flow form its naturally substantial composition and determine the special features of a flow and natural units of measurement. The flow parameters are characterized by a quantity of objects (component parts) of a flow per specified time interval. Thus, the units of the measurement of flow are absolute units (e.g. items, kilograms, cubic meters or other units) per time interval (second, minute, year or other time unit).

The flow objects within the framework of the system specification could be interpreted by different approaches: discrete, continuous or combined, and are presented as state variable trajectories. Four main flow types are marked out [29]:

- continuous time flow with continuous rate changes;
- continuous time flow with discrete rate changes;
- continuous time flow with discrete-continuous rate changes;
- discrete flow.

The examples of flow trajectories are shown in Fig.1. All examples show the time along the horizontal axis. In a), b) and c) the flow rate or intensity $\lambda(t)$ is represented along the vertical axes. Flow rate $\lambda(t)$ can be expressed in the absolute units per time unit. In d) the quantity of the substrate in one discrete flow „portion" $q(t)$ is shown along the vertical axis. T designates the time of flow observation. This figure for the clear vision provides the flow in the c) example as a sum of flows in a) and b) examples. $\lambda(t)$ can be named also the state of a continuous flow, since this value characterizes flow at any arbitrary moment of time.

Material flows are inherent components of diverse systems. The publications of the last years apply such terms as "flow system", „material flow system", „material handling" or „material flow handling system" [2, 5 - 9, 26, 27 and others]. Some authors separate the material flow system from investigated or projected one. They state that the guarantee of effective interaction between the flow and production systems is an important task and evaluate the volume of the costs, related to control of the material flows between the elements of production system, from 13 to 30 percent of total production costs [13]. The concept of flow system is wider than the concept of material flow system or MFHS, and it can be used to describe the systems of different nature. With the account of above mentioned, we could formulate the definition of material flow handling system: **the material flow handling systems are the technical controlled systems, created to process the objects of material flows.**

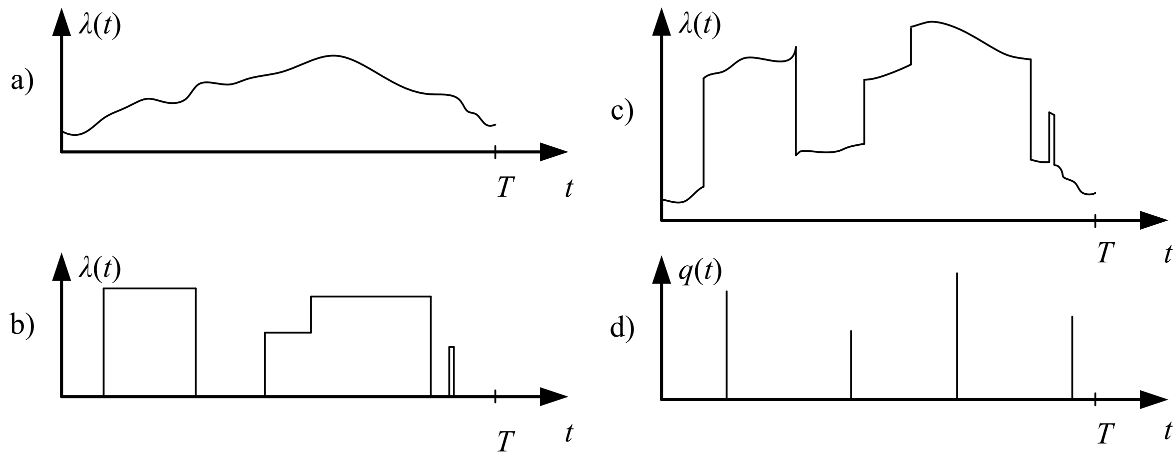


Figure 1. Examples of flow trajectories

Here the „processing” implies the operations of all types, which are carried out with the objects of material flows. For simulation analysis of MFHS or the MFHS networks the system specification including material flow specifications should be created.

The specification of material flow could be made in the form of informal description, table, formalism, graphic scheme, description according to the standard or combining any or all forms mentioned before [13, 23]. Material flow specification as a table is elementary flow model. Table 1 shows example of material flow specification.

This tabular model can be also named the protocol of material flow events [29]. The designation Ob_{ji} relates to the j-type objects of flow, which are observed at time moment t_i. Here j is a number of object class type, i is an ordinal number of the flow event. In this example variable v_i designates the type of a train with ordinal number i, variable n_{ji} – the number of Ob_j-type wagons in a train with ordinal number i.

Table 1

The protocol of the train flow events in the marshalling yard

The ordinal number of a train arrival event in a flow (i)	The event time (t_i)	The type of a train (v_i)	The number of wagons (Ob_j)					
			Ob_1	Ob_2	...	Ob_j	...	Ob_K
1	t_1	v_1	n_{11}	n_{21}		n_{j1}		n_{K1}
2	t_2	v_2	n_{12}	n_{22}		n_{j2}		n_{K2}
...								
i	t_i	v_i	n_{1i}	n_{2i}		n_{ji}		n_{Ki}
...								
M	t_M	v_M	n_{1M}	n_{2M}		n_{jM}		n_{KM}

The material object (train) flow, described in the table, is a structure

$$P = \langle T, V, Ob \rangle, \tag{1}$$

where T is a continuous distribution function of train interarrival time,
V is a discrete distribution function of train type and
Ob is a discrete distribution function of wagon quantity.

Material flow graph examples with the appropriate time functions are shown in Fig. 2 and 3. Fig. 2 depicts the time diagram of the wagon flow or „quantity-time" process diagram in differential form, where t_i are arrival event time moments, τ_i are interarrival times, n_{ij} is a number of wagons of type j in train i and v_i is a type of the i-th train. The same flow is shown in Fig. 3. using another approach: the graph shows the rate of wagon flow $\lambda(t)$. The rate is interpreted as a quantity of wagons in this place of space over the specific period of time, for example, wagons per hour.

Creating material flow specifications, the best results can be achieved with combination of different types of description. A universal material flow description method or type could hardly be defined, but certain types of description, such as formal and graphic, are more applicable in the area of simulation.

The main conclusions are as follows:

- the concept of material flow is of a general nature, and has universal, practically unlimited area of application;
- the material flow theory and its components ensure systematic basis of the material flows investigation in artificial physical systems;
- the objects of material flow determine the type of a flow and form discrete and continuous material flows;
- it is appropriate to analyse systems that provide the "processing" of material flows as a material flow handling systems and/or as MFHS networks;
- material flows, as artificial material system elements, should be described by one of description types in the framework of material flow theory.

Chapter sets out the general requirements to material flow description, which should fit the simulation methodology, and develops the universal approach to the analysis and formalization of material flows at a conceptualization stage of simulation model.

Material flows simulation paradigms

The thesis second chapter carries out a comparative study of the different modelling approaches to dynamic object flow simulation for the purpose of identification of the outstanding issues and tasks, as well as of definition general requirements to combined approach to the simulation discreet object flow in MFHS framework.

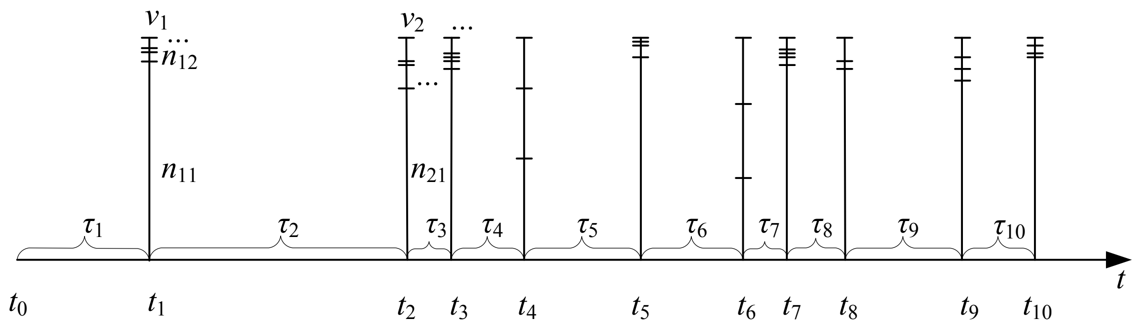


Figure 2. An example of wagon flow time diagram

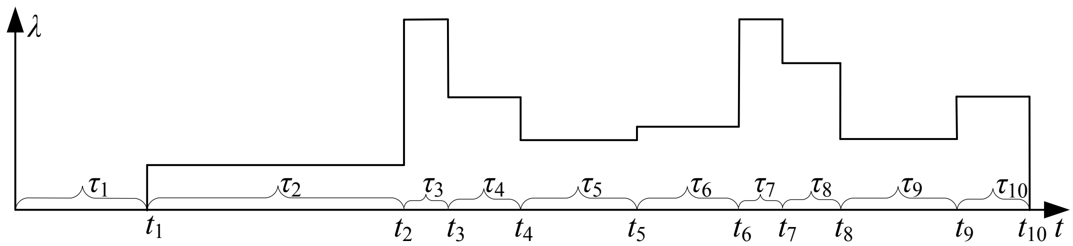


Figure 3. An example of the rate graph of wagon flow

Modelling of flows of discrete objects is an integral part of the approaches considered in this chapter. The chapter focuses on the material flow simulation in system dynamics, discrete event simulation approach and combined approach. In system dynamics the variable flows or process flows are described, in DESS the separate entities are tracked down. The combined approach combines some aspects of both traditional approaches.

In system dynamics continuous models the time steps are constant, time advance is regular and the variable changes are directly linked to time changes and simulated system state variable values display the state of a system at any single time moment. In system dynamics models the flows may be interpreted as flows of liquids in pipes, at any time moment the liquid volume could vary but flows in general are continuous. Flow intensities are constant during a single fixed time step.

In discrete event models system state changes only when an event occurs. As opposed to continuous models the simulation time advances in discrete steps (typically of unequal size). The separate flow objects, entities, are detected at event moments and the pipe analogy looks different: at any time moment the pipe may be empty or if there are separate buckets full of liquid. Another essential difference applies to the outgoing flow: buckets with liquid depart from the pipe at random time intervals.

It is possible to unite the invariability of flow rate in time interval with the variable duration of this interval or in other words to unite the system dynamics constant flow rate during the time step with the unequal, random length of the time step as it is used in DESS. In addition, the possible events list may be supplemented with the "flow events". The flow consists of a substance as it is in continuous models rather than from separate discrete objects or entities as in DESS. If flow intensities are constant between discrete events, then the system state changes are observed and simulated only at discrete events time moments. Between discrete events the levels in the model change linearly and here is the main difference from discrete event models. However, the constant flow rate between events gives a possibility to advance the simulation time and to perform no calculations between events in the same way as it is provided in discrete event models. To continue the pipe analogy: the flow is continuous but flow rate could change immediately, for example when the valve state changes.

The formulation of the problem is the following: to develop the simulation approach, where the system model can be realized as the mathematical structure:

$$M = \langle X, Z, Y, H, G, t \rangle, \tag{2}$$

where X is the set of input signals,
Z is the set of state values;
Y is the set of output signals,
H is internal transition operator,
G is output operator,
t is simulation time.

In this chapter:

- The main modelling approaches are analysed in terms of discrete object flow simulation.
- The basic concepts behind the combined approach and implementation options are described.
- The necessity of the theoretical justification of combined approach is grounded for accurate and reliable simulation of object flows based on discrete-events.

The main conclusions are as follows:

- Traditional simulation approaches provide object flow simulation with different levels of detail.
- There is a practical opportunity to formulate fundamentals for different implementation options of a combined simulation approach that is based on traditional approaches.
- The combined simulation approach to the simulation of object flow provides the possibilities of model creation for the more efficient studies of MFHS, compared with a traditional simulation approaches.

The chapter states that for the creation of effective and reliable combined models the whole and correct theoretical justification is required, which is currently not yet developed.

The development of a combined approach to the simulation of material flow handling systems

The third chapter considers the theoretical justification of the developed approach in accordance to the problem formulation.

To eliminate the classical approach shortages, connected with multiple data processing actions and to retain acknowledged positive properties of discrete-event approach, the following actions should be provided:

- to determine the representation of discrete objects flows;
- to describe characteristics and special features of other model components, required for the realization of the combined approach to the simulation of material flows;
- to simulate the usage of resources as a partial usage of the total resource capacity and
- to summarize and interpret the data accumulated during the simulation run in the form of simulation report.

The realization of new approach is ensured by discrete event simulation, which includes the simulation of the events, associated with changes of flow state. For the implementation of the above-mentioned functions it is sufficient to provide the four model components:

1) The flow source, which ensures flow object arrivals to the model in form of continuous flow on in separate portions.
2) The departure point of the flow or the sink, which is the boundary of the model and simulates the flow run out.
3) The universal element, which simulates the delay of flow objects for some actions (storage, handling, packaging and others), or the bunker.
4) The transport element, which performs the transportation of the flow objects between model base elements over a specified time period.

If necessary, one can define additional components made in accordance with the requirements to the components of the combined models, as well as in additional control elements.

In discrete event models the object flows are simulated as the chronological sequence of events. The discrete event and combined models apply the same method for time advancing. The flow description for combined models should meet the requirements of the combined approach: the flow intensities are constant between event time moments. Such flows may be referred also as mesoscopic ones [29]. From now on flows in combined models are interpreted in this way. Simulated flow is established as a superposition of separate substance or object „portions". Three random variable distribution functions should be determined to define the flow: the portion interarrival time, the duration and the volume.

The processes that are event-driven usually should not be simulated using continuous approach, but in some cases the combined simulation approach better fits the features of the simulated system. The systems with no identified separate objects or with the quantities of that objects that makes the discernability meaningless, can be simulated more naturally with the combined approach application.

Within the framework of combined approach the flow processes are defined by the rates $\lambda(t)$(the number of flow objects per time segment) and the cumulative rate functions (the accumulated amount of flow objects).

Each flow includes the products of the same type; a number of parallel flows can be simulated in one model. Model flows are displayed as "portions" that move from one model node to the next one as one object. The model node balance or contents is formed as the difference of incoming and outgoing flow.

Combined models in general process fewer events, compared to the discrete event models, and allow discussing in terms of flows, reservoirs and rates or intensities.

In case a combined model represents the open system, the system boundary elements are designed as a source and a sink. The component "source" (hereinafter referred to as source) should perform the flow simulation resulting in time series that are accessible at the output point of the component. In general, the source may generate several flows (multichannel source). It is sufficient to describe the source with a single channel, because the channels are independent and only differ with the parameter values.

To describe a source three random variable distribution functions should be determined: the portion interarrival time, the duration and the volume. The simple source can be created similarly as a source of discrete entities in DESS, which generates the separate entities after random time intervals, using distribution density function $f(\Delta t)$ of interarrival time Δt. In this case the flow rate changes at specific time moments t_1, t_2, ...t_i, ... ($t_0 \le t_1$, t_2, ...t_i, ... $t_{i\max} \le T$, t_0=0 is the simulation run start time, $i_{\max}$ is the number of the last change of flow rate and T is a simulation run end time). The flow rate is constant during the time period $\Delta t_i = t_i - t_{i-1}$, and is equal to $\lambda_i = 1/\Delta t_i$, $i = 1, i_{\max}$. The finite number of flow rate changes occurs during any finite time period.

As it follows from the description of a component: the set $Z = \{\lambda, z_1\}$ is a set of component's states, the state of a component is determined by the rate of output flow $\lambda(t)$ and by the elapsed time since the last transition $z_1(t)$. At any time moment $t \in (0, T)$ the source is in one of possible states belonging to Z. The rate of the outgoing flow λ is a value of a function $\lambda(t)$ and is a real number $0 \le \lambda(t) \le \lambda_{\max}$. The elapsed time since the last transition $z_1(t)$ is a real number $z_1(t) \ge 0$. The state of the source at any time moment $t > t_0$ is defined by the operator H and is calculated from the previous state:

$$z(t) = H[z(t_0), t]. \tag{3}$$

The type of operator H depends on whether during the time interval the source state changes are observed. The state changes instantly. In general, not only one state $z(t)$ corresponds with a single state $z(t_0)$, but a number of states with some distribution function, which depends on the type of operator H.

At the beginning of the simulation, at time $t=t_0$ the rate of an outgoing flow is $\lambda_0=0$.

At time moments τ_i a control signal g affects the source. The signal g belongs to a set Γ. The time moments τ_i are defined by the distribution density function $f(\Delta\tau)$ of a random variable $\Delta\tau$.

The state of the source changes, when a control signal affects the source. Suppose that the finite number of control signals affect the source during any finite time period. From now on the pooled set of event time moments is under consideration including both flow rate changes and control signal affect time moments.

As the output of the source the signal y is produced, which coincides with the rate of the output flow, i.e. the output signal is the value of the status variable λ at any arbitrary moment of time. Output signal is defined from the source status z (t) with the help of operator G, which may be described as follows:

$$y(t_i) = G[z(t)] = \frac{1}{\Delta t_i},\ i = 1,\ i_{\max} \tag{4}$$

Not only should the state z (t) be taken into account, but also the state $z(t+0)$. Let us assume that for any $t_i > t$ time moment $t+0$ belongs to the interval $(t,t_i]$. The source changes the state from $z(t)$ to $z(t+0)$ in a moment when control signal is obtained. The simplified image of a source is represented in Fig.4. a) and an example of an output signal – in Fig. 4. b).

From the description of the component it follows that a source can be formally described as a piecewise-linear aggregate with no incoming signal and with a simple transition operator H and output operator G.

The source features determine the type of source simulation results. The total flow volume, which is observed on the component output during the simulation run, is:

$$A = \int_0^T \lambda(t)dt = \sum_1^{i\max} \lambda_i \Delta t_i\ , \tag{5}$$

where $i = \overline{1, i_{\max}}$, $i_{\max}$ is the last flow portion number during simulation run time T, and $\Delta t_{i\max} = T - t_{i\max-1}$ is the last interval in a run.

Average outgoing flow rate during simulation run time T:

$$\bar{\lambda} = \int_0^T \lambda(t)dt \Big/ T = \sum_1^{i\max} \lambda_i \Delta t_i \Big/ \sum_1^{i\max} \Delta t_i = \sum_1^{i\max} \lambda_i \Delta t_i \Big/ T\ . \tag{6}$$

From the source a flow must be directed to one of the other components of the combined model.

The base component of a combined model is a “bunker” (hereinafter referred to as bunker). This component simulates the processing, converting and storing processes of a single flow portion. It means that a bunker in a model

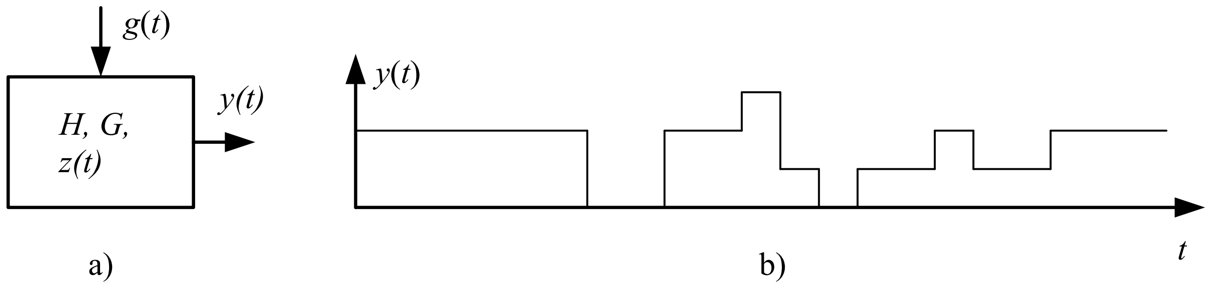


Figure 4. The single-channel source: a) simple image, b) an example of an outgoing signal

could represent a single working place, a processing point, a workshop or a logistic enterprise. Bunker may be a single- or a multichannel component. Let us consider a simple single-channel bunker.

Incoming flow enters the bunker. For the description of a bunker its main parameters should be defined. They are the capacity $B_{\max}$ and the maximum value of an outgoing flow rate $\mu_{\max}$. The outgoing flow is formed on the exit of a bunker. The state of a bunker at any simulation time moment is determined by the rate of incoming and outgoing flows $\lambda^{\text{ien}}(t)$ and $\lambda^{\text{iz}}(t)$, and the level of flow substance at the beginning of a simulation run b_0 and a current level $b(t)$:

$$b(t) = b_0 + \int_0^t \lambda^{\text{ien}}(t)dt - \int_0^t \lambda^{\text{iz}}(t)dt. \qquad (7)$$

It should be taken into account that a bunker itself can cause events. These events affect the event scheduling of a combined model: the rate of an outgoing flow can change at a moment when bunker becomes empty or full; such time moments may be calculated and added to the scheduled event list. Suppose that at time moments t_1, $t_2 \dots t_i \dots$ $t_0 \le t_i \le t_{i\max} \le T$ the incoming or outgoing flow rate changes instantly. $t_0 = 0$ is a starting time of a simulation run, $i_{\max}$ is a current number of a last change of the incoming or outgoing flow and T is simulation run duration. Then the equations that describe the dynamic behaviour of the bunker are:

$$\lambda^{\text{iz}}(t) = \begin{cases} 0, \text{ja } \lambda^{\text{ien}}(t) = 0 \text{ and } b(t) = 0; \\ \lambda^{\text{ien}}(t), \text{ja } \lambda^{\text{ien}}(t) > 0 \text{ and } b(t) = 0; \\ \mu_{\max}, \text{ if } b(t) > 0, \end{cases} \qquad (8)$$

and

$$b(t_i) = b(t_{i-1}) + (\lambda_i^{\text{ien}} - \lambda_i^{\text{iz}})\Delta t_i, \qquad (9)$$

where $\Delta t_i = t_i - t_{i-1}, \lambda_i = \lambda(\Delta t_i) = \lambda(t_i)$, i=1,$i_{\max}$, subject to the constraints

$$\lambda^{\text{iz}}(t) \le \mu_{\max}, \; b(t) \le B_{\max}. \qquad (10)$$

At any time moment $t \in (0,T)$ the bunker state is one of the possible ones that belongs to the set Z. Equations and limitations (8), (9) and (10) define the set of possible states of the bunker $Z = \{\lambda^{ien}, \lambda^{iz}, b, \tau\}$. The bunker state changes are determined by the intensities of the incoming $\lambda^{ien}(t)$ and outgoing flows $\lambda^{iz}(t)$, the bunker content $b(t)$ and the time until the next state transition (or elapsed since the previous state transition) $\tau(t)$.

At the beginning of a simulation run $t_0 = 0$ the bunker state is

$$z_0 = \{\lambda_0^{ien}, \lambda_0^{iz}, b_0, \tau_0\},$$

where τ_0 is time to nearest bunker state change, which is equal to

$$\tau_0 = \begin{cases} t_1 & \text{if } b_0 = 0, \lambda_1^{iz} = \lambda_1^{ien}, \text{or} \\ \dfrac{b_0}{\mu_{max} - \lambda_1^{ien}} & \text{if } b_0 > 0, \lambda_1^{iz} = \mu_{max} \end{cases}, \tag{11}$$

where λ_1^{ien} is the incoming flow rate and λ_1^{iz} is the outgoing flow rate during the time interval $\Delta t_1 = t_1 - t_0$.

The state of the bunker at the arbitrary time moment $t > t_0$ is determined by the operator H, this state is dependent on the previous state of the bunker:

$$z(t) = H[z(t_0), t], \tag{12}$$

In general not only a single trajectory $z(t)$ but multiple ones correspond to the specified state z_0. These trajectories are the instances of random functions and depend on the type of the operator H.

The state of a bunker changes at event time moments that may be the following: an incoming flow rate change moment, which is an event that is an external one in relation to the bunker itself; the time moment, when bunker contents become B_{max} or when it becomes empty. The bunker incoming flow is

$$x(t) = \lambda^{ien}(t). \tag{13}$$

The finite number of bunker incoming flow changes occurs during any finite time period. The finite number of bunker state changes occurs during any finite time period.

The outgoing signal is obtained from the bunker

$$y(t) = \lambda^{iz}(t). \tag{14}$$

Output signal is formed, depending on bunker state $z(t)$ in accordance with the output operator G:

$$y(t) = G[z(t)], \tag{15}$$

The functioning of a bunker can be described as follows. At simulation start time moment t_0 the bunker state is z_0. Suppose that t_1 and t_2 are time moments when the incoming flow rate changes. Let's consider the state of a bunker in a time interval $(t_0, t_1]$. This time interval can be interpreted as $(t_0, \tau_1, t_1]$, where $\tau_1 \le t_1$. τ_1 is a time moment when bunker state changes and $t_1 < \tau_2 \le t_2$.

The changes of state $z(t)$ during this time interval are described in Table 2.

The bunker state changes in subsequent moments of time in the same manner.

In accordance with the description of the operator *H* the status changes at the special moments of time, which are the moments of incoming or outgoing flow changes and the moments, when the bunker becomes empty or full.

The mentioned above clears that the simple single-channel bunker is an object, which can be described as a simplified aggregate, characterized by the following features [40]:

- There is no control signal that changes the bunker properties.
- The incoming signal is a piecewise constant function.
- The outgoing signal is a piecewise constant function.
- The state trajectory $z(t)$ of a bunker is a piecewise linear function.

The bunker in combined models performs the same functions that in discrete event models are performed by the component of process or equipment type: the discrete entities that arrive at some rate are delayed and after a processing are allowed to continue their movement.

The simulation results that characterize the functioning of a bunker should provide information about the total flow volume, which run through the bunker, about the average flow substrate amount in the bunker, about the utilization of the bunker capacity and about average delay of a flow objects in the bunker within simulation run time. The similar simulation results are provided in the traditional framework of DESS.

The number of state transitions should be decreased for simplification of

Table 2

The state of a bunker $z(t)$ during time interval $(t_0, t_1]$

λ_1^{ien}	τ_1	$z(t)$
$\lambda_1^{ien} \le \mu_{\max}$	$b_0 > 0,$ $\tau_1 = \dfrac{b_0}{\mu_{\max} - \lambda_1^{ien}}$	$z(\tau_1) = H[z(t_0), \tau_1] = \{\lambda_1^{ien}, \mu_{\max}, 0, t_1 - \tau_1\}$ $z(\tau_1 + 0) = \{\lambda_1^{ien}, \lambda_1^{iz}, 0, t_1 - \tau_1\}$ $z(t_1) = H[z(\tau_1, t_1)] = \{\lambda_1^{ien}, \lambda_1^{iz}, 0, 0\}$ $z(t_1 + 0) = \{\lambda_2^{ien}, \lambda_2^{iz}, 0, \tau_2\}$
$\lambda_1^{ien} \le \mu_{\max}$	$b_0 = 0,\ \tau_1 = t_1$	$z(t_1) = H[z(t_0), t_1] = \{\lambda_1^{ien}, \lambda_1^{iz}, 0, 0\}$ $z(t_1 + 0) = \{\lambda_2^{ien}, \lambda_2^{iz}, 0, \tau_2\}$
$\lambda_1^{ien} > \mu_{\max}$	$\tau_1 = \dfrac{B_{\max} - b_0}{\lambda_1^{ien} - \mu_{max}} \le t_1$	$z(\tau_1) = H[z(t_0), \tau_1] = \{\lambda_1^{ien}, \mu_{\max}, B_{\max}, t_1 - \tau_1\}$ $z(\tau_1 + 0) = \{\mu_{\max}, \mu_{\max}, B_{\max}, t_1 - \tau_1\}$ $z(t_1) = H[z(\tau_1, t_1)] = \{\mu_{\max}, \mu_{\max}, B_{\max}, 0\}$ $z(t_1 + 0) = \{\lambda_2^{ien}, \mu_{\max}, B_{\max}, \tau_2\}$
$\lambda_1^{ien} > \mu_{\max}$	$\tau_1 = \dfrac{B_{\max} - b_0}{\lambda_1^{ien} - \mu_{max}} > t_1$	$z(t_1) = H[z(t_0), \tau_1] = \{\lambda_1^{ien}, \mu_{\max}, B_{\max}, 0\}$ $z(t_1 + 0) = \{\lambda_2^{ien}, \mu_{\max}, B_{\max}, \tau_2\}$

the simulation process within the framework of combined approach. This is possible when the state trajectory can be divided into the subsets of sequential event times (t_q, t_{q+1}, ..., t_{m-1}, t_m), $t_q \le t_{q+1} \le ... \le t_m$, which should provide a possibility not to simulate events in the time period (t_q,t_m), but to calculate directly from $z(t_q)$ the event time t_m for any event e_m and all the states $z(t)$, $t \in (t_q,t_m)$. Or in other words it is possible if the conditions of decomposition are true. Let's verify whether the conditions of decomposition within the framework of the new approach are satisfied.

For the correct replacement of the discrete object flow with the piecewise-constant flow it is necessary to ascertain that the indices obtained as simulation results provide the identical information about the functioning of the components.

Let us examine an example of simulation run using the components "device" and "bunker" with identical parameters.

To calculate the functioning results of the single-channel bunker we assume that the events during the simulation experiment occur at the same moments of time as in the discrete event model. The maximum capacity of a bunker is assumed as $B_{\max} = 1$. Taking into account the features of a bunker it is possible to show all the state changes during specific time intervals in the form of a Table 3. The corresponding time-series of the simulation run are shown in Figure 5 b), c) and d). The utilization of a bunker can be calculated as a part of bunker's maximum available capacity $B_{\max}*T$ that was in use during the current simulation run. Figure 6 shows the bunker state function in detail that is necessary for the explanation of further calculations. The usage of available capacity is equal to the integral of function $z_k(t)$ in the interval $[0,T]$. Let us calculate the integral value, starting from moment t_1, see Figure 6. The integral value is equal to area under the curve $z_k(t)$ and can be represented as the sum of the areas of the polygons:

$$\int_0^T z_k(t)dt = S_{t_1 z_2 t_2} + S_{t_2 z_2 z_3 t_3} + S_{t_3 z_3 z_4 t_4} + S_{t_4 z_4 z_5 t_5} + \ldots + S_{t_{i\max} z_{i\max} z_{i\max+1} T}.$$

Moreover the area of polygon $t_3 z_3 z_4 t_4$ is equal to the sum of the areas of triangles $t_3 z_3 t_4$ and $t_3 z_4 t_4$, which gives the possibility to consider area under curve $z_k(t)$ as the sum of the areas of the polygons of separate portions (Fig. 7). The only special member in this sum is the area of the last polygon:

$$\int_0^T z_k(t)dt = S_1 + S_2 + S_3 + S_4 + \ldots + S_{t_{i\max} z_{i\max} z_{i\max+1} T}.$$

Taking into account expressions from Table 3, after simple conversions we could write down an expression for the area calculation of the jth polygon:

$$S_j = \frac{1}{2} \cdot \Delta t_{2j} + \frac{1}{2} \Delta t_{2j+2}, j = \frac{i+1}{2,}, i = 1,3,\ldots,i_{\max}.$$

Then

$$\int_0^T zk(t)dt = \sum_1^{i_{\max}} S_j = \frac{1}{2}\cdot \Delta t_2 + \sum_2^{i_{\max}} \Delta t_{2i} + \frac{1}{2}\Delta t_{i_{\max}} = \sum_2^{i_{\max}} \Delta t_{2i} + \frac{1}{2}\left(\Delta t_2 + \Delta t_{i_{\max}}\right).$$

Bunker utilisation during simulation run is

$$U_{\mathrm{k}} = \frac{\sum_2^{i_{\max}} \Delta t_{2i} + \frac{1}{2}\left(\Delta t_2 + \Delta t_{i_{\max}}\right)}{B_{\max} T} = \frac{\sum_2^{i_{\max}} \Delta t_{2i} + \frac{1}{2}\left(\Delta t_2 + \Delta t_{i_{\max}}\right)}{T} = U_{\mathrm{d}} - \frac{\Delta t_2 + \Delta t_{i_{\max}}}{2T},$$

where U_{d} is the utilization of a discrete device.

The accumulated throughput of a bunker during simulation run is

$$N_{\mathrm{k}} = \int_0^T \lambda^{\mathrm{iz}}(t)dt = (i_{\max+1})\, div\, 2 + \frac{T - t_{i\max}}{\Delta t^*_{i\max}} = N_{\mathrm{d}} + \Delta^*,$$

where $\frac{1}{\Delta t^*_{i\max}}$ is outgoing flow rate in the interval of time (T - $t_{i\max}$), this value depends on T value and on the events, planned after the end of simulation. N_{d} is an accumulated throughput of a discrete device.

From the obtained expressions we could draw the conclusion that the simulation results within the framework of the discrete event and combined approaches differ; however, with large T:

$$\Delta U = U_{\mathrm{d}} - U_{\mathrm{k}} = \frac{\Delta t_2 + \Delta t_{i_{\max}}}{2T}\underset{T\to\infty}{\to} 0.$$

Thus, the simulation results for the bunker within the framework of combined approach give the necessary and precise information about its utilization and throughput.

Although it is assumed within the framework of the approach, that a single flow object identification and distinction is not required, an average time that flow portion spends in a bunker could be estimated as

$$\bar{t}_{\mathrm{b}} = \frac{1}{\overline{\lambda^{\mathrm{iz}}(t)}} = \frac{1}{\sum_{i=1}^{i\max} \lambda_i^{\mathrm{iz}} \Delta t_i / \sum_{i=1}^{i\max} \Delta t_i}, \qquad (16)$$

where λ_i^{iz} is a rate of outgoing flow, $\lambda_i^{\mathrm{iz}}>0$.

In general case the bunker is a multichannel component that must be considered as the main component of models within a combined approach. Each jth channel of an m-channel bunker (j=1, 2... m) corresponds to a single flow class that flows through the bunker. Bunker channels are running asynchronously but the partial capacity $B^j_{\max}$ of a single jth channel and its

Table 3. The bunker state function during the simulation run

Event number i	Event time t_i	Time interval after previous event Δt_i	The intensity of incoming flow $\lambda^{ien}(t_i)=\lambda^{ien}(\Delta t_i)$	The intensity of outgoing flow $\lambda^{iz}(t_i)=\lambda^{iz}(\Delta t_i)$	The state function $z_k(t_i)$
0	t_0	$\Delta t_0 = 0$	0	0	$z_k(t_0) = 0$
1	t_1	$\Delta t_1 = t_1 - t_0$	$1/(t_3 - t_1)=$ $=1/(\Delta t_3 + \Delta t_2)$	0	$z_k(t_1) = z_k(t_0) + (\lambda^{ien}(\Delta t_1) - (\lambda^{iz}(\Delta t_1)) \cdot$ $\cdot \Delta t_1$
2	t_2	$\Delta t_2 = t_2 - t_1$	$1/(t_3 - t_1)=$ $=1/(\Delta t_3 + \Delta t_2)$	$1/(t_4 - t_2)=$ $=1/(\Delta t_4 + \Delta t_3)$	$z_k(t_2) = z_k(t_1) + (\lambda^{ien}(\Delta t_2) - (\lambda^{iz}(\Delta t_2)) \cdot$ $\cdot \Delta t_2$
3	t_3	$\Delta t_3 = t_3 - t_2$	$1/(t_5 - t_3)=$ $=1/(\Delta t_5 + \Delta t_4)$	$1/(t_4 - t_2)=$ $=1/(\Delta t_4 + \Delta t_3)$	$z_k(t_3) = z_k(t_2) + (\lambda^{ien}(\Delta t_3) - (\lambda^{iz}(\Delta t_3)) \cdot$ $\cdot \Delta t_3$
…	…	…	…	…	…
i	t_i	$\Delta t_i = t_i - t_{i-1}$	$1/(t_{i+2} - t_i)=$ $=1/(\Delta t_{i+2} + \Delta t_{i+1})$, if $i=2k+1$, or $1/(t_{i+1} - t_{i-1})=$ $=1/(\Delta t_{i+1} + \Delta t_i)$, if $i=2k$, k is integer	$1/(t_{i+1} - t_{i-1})=$ $=1/(\Delta t_{i+1} + \Delta t_i)$, if $i=2k+1$, or $1/(t_{i+2} - t_i)=$ $=1/(\Delta t_{i+2} + \Delta t_{i+1})$, if $i=2k$, k is integer	$z_k(t_i)=z_k(t_{i-1}) + (\lambda^{ien}(\Delta t_i) - (\lambda^{iz}(\Delta t_i)) \cdot$ $\cdot \Delta t_i$
…	…	…	…	…	…
i_{max}	t_{imax}	$\Delta t_{imax} =$ $= t_{imax} - t_{imax-1}$	$1/(t_{imax+2} - t_{imax})=$ $1/(\Delta t_{imax+2} + +\Delta t_{imax+1})$, if $i_{max}=2l+1$, or $1/(t_{imax+1} - t_{imax-1})=$ $=1/(\Delta t_{imax+1} + +\Delta t_{imax})$, if $i_{max}=2l$, l is integer	$1/(t_{imax+1} - t_{imax-1})=$ $1/(\Delta t_{imax+1} + +\Delta t_{imax})$, if $i_{max}=2l+1$, or $1/(t_{imax+2} - t_{imax})=$ $=1/(\Delta t_{imax+2} + +\Delta t_{imax+1})$, if $i_{max}=2l$, l is integer	$z_k(t_{imax}) = z_k(t_{imax-1}) + (\lambda^{ien}(\Delta t_{imax}) -$ $- (\lambda^{iz}(\Delta t_{imax}))\ \Delta t_{imax}$
i_{max+1}	T	$\Delta T=T - t_{imax}$	…	…	$z_k(T) = z_k(t_{imax}) + (\lambda^{ien}(\Delta t_{imax+1}) -$ $- (\lambda^{iz}(\Delta t_{imax+1}))\ \Delta t_{imax+1}$

maximum rate $\mu^j_{\max}$ may not exceed the values that are to be considered as bunker parameters

$$\sum_{j=1}^{m} B^j_{\max} \le B_{\max} \text{ un } \sum_{j=1}^{m} \mu_j \le \mu^j_{\max} \tag{17}$$

Partial maximum rate $\mu_j(t)$ as an adjustable parameter can be set at any time.

Multichannel bunker can be considered as the association of single-channel bunkers.

Bunker output signal can be an input signal of another combined model component, such as other bunker, or transport element or a sink.

Transport element serves for the mapping of all forms of planned delays in the model, for example, transportation or holding time in case, when such delays are significant in the simulated process. The delay in the bunker occurs as a result of congestion only. As a result of this the bunker contents increases. Forming of bunker outgoing flow takes no time.

The incoming flow rate of a transport element is $\lambda^{\text{ien}}(t)$. Transport element description must contain the only parameter - delay time. The rate of the outgoing flow $\lambda^{\text{iz}}(t)$, is the same as the rate of an incoming flow with delay τ. Transport element, like the bunker can be a single channel or multichannel component. The content of transport element is formed as the difference of incoming and outgoing flows during the simulation run.

If necessary, the transport element with variable delay times can be simulated.

The model closing components – sinks – also can be either single channel or multichannel ones. These components are necessary, when the simulated system is not closed. Let us examine the features and simulation results of a

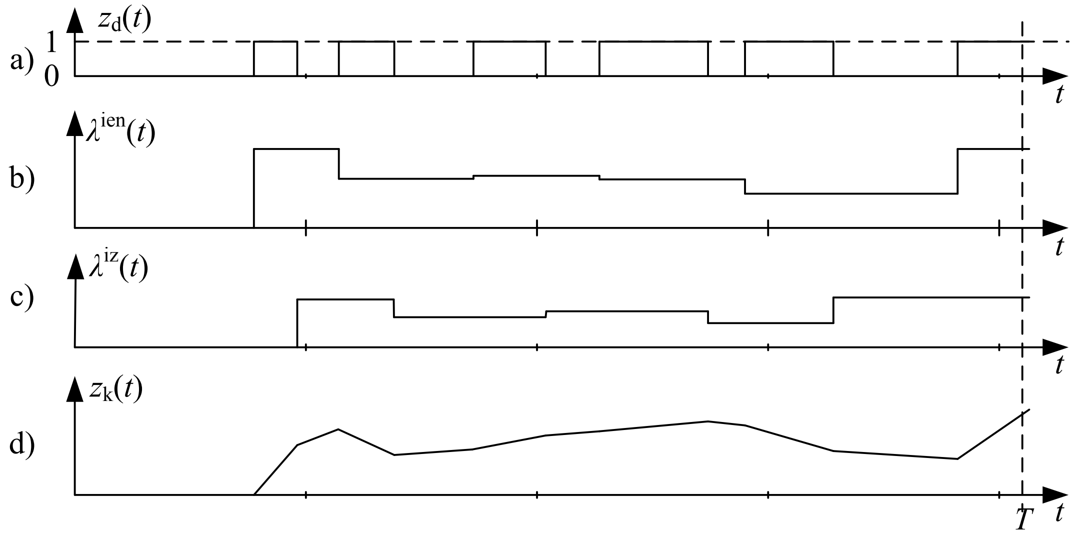


Figure 5. a) the state trajectory of a discrete device, b) the incoming and c) the outgoing flow intensities and d) the state trajectory of a bunker

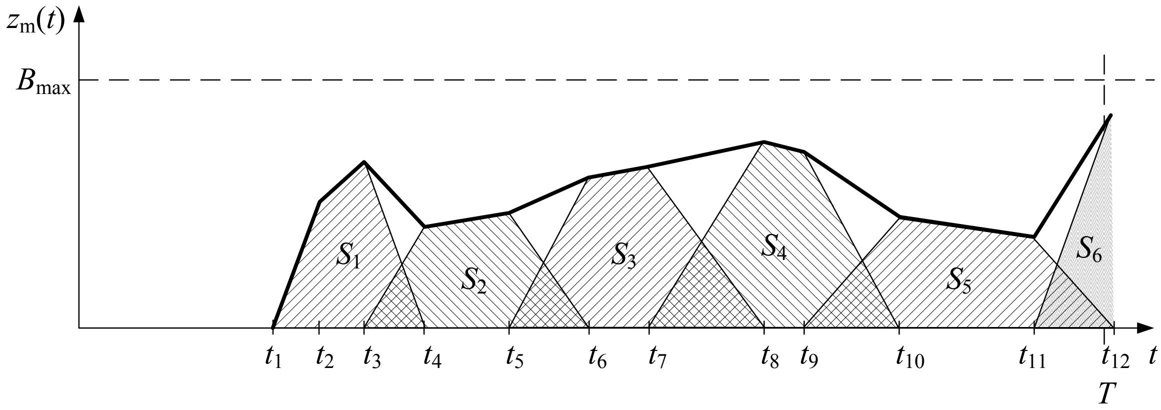


Figure 6. The bunker state function $z_k(t)$ in detail

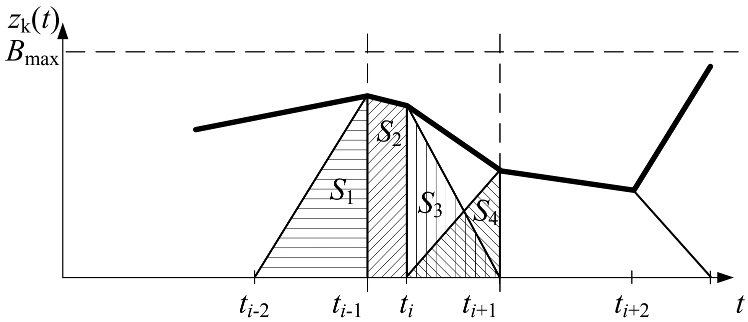


Figure 7. The calculation of the definite integral of a function $z_k(t)$

single-channel sink. The model closing components – sinks – also can be either single channel or multichannel ones. These components are required, when the simulated system is not closed. We examine the features and simulation results of a single-channel sink. The sink is the final point of a flow in a combined model. Its input signal is a flow with rate $\lambda^{in}(t)$, there is no output signal. During the simulation run the data about a quantity of flow substance are accumulated and the value of accumulated quantity of flow substance is available at the end of the run.

The necessary main components of combined models, which provide the possibility of constructing of such models, are described above. From the description of components it is clear that all basic components can be formalized in the form of simple aggregates. In the process of model construction the separate components are connected in accordance with the structure of simulated system. This association is possible, since the input and output signals of all components are formalized in the form of mesoscopic flows. An example of the association of basic components in the model of a simple system is depicted in Figure 8.

The model, shown in Figure 8, includes the flow source A, two bunkers B_1, B_2, transport element T and a sink N. The dotted line designates the boundary of the combined model. The control signals that are the elements of a control signal set $\Gamma = \{g_A, g_1, g_2\}$ act on the components. In this example the source provides generation of the object flow, that is why the model input is not defined. At the output of the transport element output signal $Y = \{y_T\}$ is formed, which is the input signal of a sink. All the signals of the components are internal ones.

Dynamic combined models are used as instruments for obtaining information on researched systems. Flows, which are integral parts of these models, represent flows of the real system in aggregate form. The level of detail of simulation results corresponds to mesoscopic level of detail of object flow, that is, within the combined approach the simulation results are provided as aggregated ones. It is pertinent to recall that the DESS is quite often used as a way, from the task in aggregated form to results, which are also aggregated. In this case obtaining results is connected with the decomposition of the original data and with aggregation of data from the events protocol of a simulation run. Data loss or corruption in this case is inevitable. The fundamental advantage of the combined approach is based on the dynamic transformation of initial data into the simulation results, where both initial data and results are of the same mesoscopic level of detail.

If we consider the model as the association of components, we could accept the concept of aggregate [40], then a combined model can be formalized as a classical piecewise linear aggregate, see Fig. 9.

In Fig. 9. $X(t)$, $\Gamma(t)$ and $Y(t)$ are the input, control and the output signal sets, $z(t)$ is the model state, H is the model transition operator and G is the model

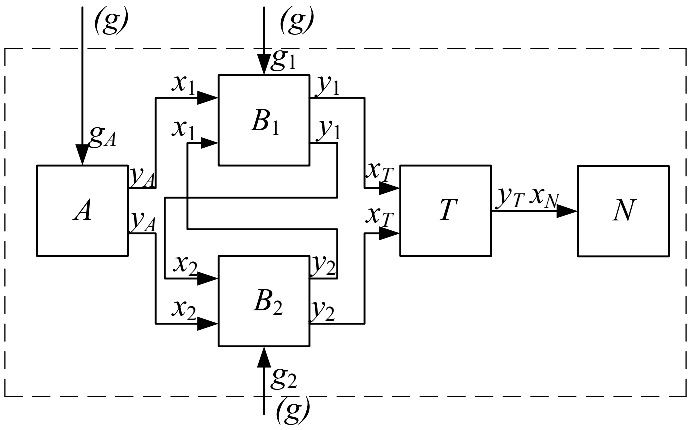


Figure 8. An example of the association of the components

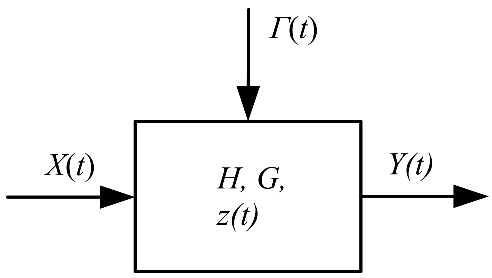


Figure 9. The combined model in the form of the aggregate

output operator. The input or control signal sets of internal aggregates of the aggregate system, which get such signals from the environment, are the input and control sets of a model. The set of output signals of aggregate system form the signals of its internal elements, which are the output signals of entire system. The concept of incoming and outgoing flows in the framework of a combined approach makes it possible to state that the input and output signals of combined models are flows. Then it is possible to define the types of simulation results and the equations necessary to calculate them. As well as the individual components the model may be either the single channel or multi-channel aggregate.

Below we consider the results of a single channel combined model.

The quantity of flow objects in the model at any time moment t can be calculated as

$$B_{\mathrm{m}}(t) = B_{\mathrm{m}}(0) + \int_0^{\mathrm{t}} \lambda_{\mathrm{m}}^{\mathrm{ien}}(t)dt - \int_0^{t} \lambda_{\mathrm{m}}^{\mathrm{iz}}(t)dt\,,$$

where the subscript “m” indicates that the results are related to the model;

$B_{\mathrm{m}}(0)$ is a quantity of flow objects at the beginning of the simulation run;

$\lambda_{\mathrm{m}}^{\mathrm{ien}}(t)$ and $\lambda_{\mathrm{m}}^{\mathrm{iz}}(t)$ are intensities of incoming and outgoing flows as time functions.

The cumulative volume of the flow that is observed as the output of the model is

$$B_{\mathrm{m}}^{\mathrm{iz}} = \int_0^{t} \lambda_{\mathrm{m}}^{\mathrm{iz}}(t)dt\,.$$

The average rate of input and output flow is

$$\overline{\lambda}_{\mathrm{m}}^{\mathrm{ien}} = \frac{\int_0^{\mathrm{t}} \lambda_{\mathrm{m}}^{\mathrm{ien}}(t)dt}{t}\,,\quad \overline{\lambda}_{\mathrm{m}}^{\mathrm{iz}} = \frac{\int_0^{\mathrm{t}} \lambda_{\mathrm{m}}^{\mathrm{iz}}(t)dt}{t}\,.$$

The average time the units of the flow spent in the model is

$$\bar{t}_{\mathrm{m}} = \frac{1}{\overline{\lambda}_{\mathrm{m}}^{\mathrm{iz}}(t)}.$$

The implementation of models of systems can be mentioned as a special case, where the junction or separation of flows inside of the system takes place. The flow composition or decomposition and the appropriate result calculation should be performed there.

Types of results, mentioned in this section, refer to one simulation run. It is obvious that the results of the replications can be used to calculate the required point and interval estimates of the indices using conventional methods of mathematical statistics.

The following results are obtained: the theoretical substantiation of the combined approach is developed, based on discrete event approach; the components of the combined models are developed and the requirements to component connections are formulated in general form.

The main conclusions are:

- the proposed combined approach is based on the concepts of the theory of material flows;
- the proposed combined approach ensures simplified in comparison with traditional discrete event approach, creation of models;
- the combined models provide efficient and reliable simulation results.

Application of the developed approach to the simulation of the material flow handling system

As an example of implementation of combined approach the model of a railway transport junction in a cargo terminal is considered in the fourth chapter.

Simulation of the railway transport junction is executed as in the discrete-event paradigm as well as implementation of the theoretical principles developed for the combined approach. The main goal of model development is to show advantages of the developed combined approach in comparison with traditional discrete event one. The results of the discrete event and combined models are compared.

The simulated system is a MFHS – a railway junction in a cargo terminal – transport junction that provides the reception of the trains, the appropriate "processing" and sending to other railway junctions. There are intensive flows of moving objects, both trains and wagons, in this system.

Some special features of the simulated system, parameter values, random variable distribution functions and additional information, used for the development of a model, are described in the appendixes.

In the course of a study the discrete event model of a railway transport junction in a cargo terminal was developed. The model adequacy is checked by verification and validation. The experimental results are obtained and applied for the analysis of the usage of wagons and locomotives [14].

The simulation results include the estimates of such indices of the system functioning as:

- a quantity of entering and outgoing wagons;
- the quantity of performed operations and utilization of equipment;
- the quantity of performed operations and utilization of locomotives;
- time carried out in the transport junction for different types of wagons and other indices.

The simulation results are used for the analysis of the correlation between the accessibility of locomotives and the time, spent by wagons in the system, for the evaluation of locomotives and railway equipment utilization.

The subsystem of a simulated system – the first zone of coal terminal – is selected as the object of experimental application of the combined approach. The first zone deals with the 80% of all coal trains. The structure of a simulated system is depicted in Fig. 10.

The coal terminal, or simply the terminal, is situated at the railway transport junction. The trains of coal wagons, which arrive from the marshalling yard, are “processed” (both unloaded and loaded) on the terminal. The wagons are brought to the terminal by the first harbour locomotive. The interarrival times of trains and the train length are random variables. The appendixes to the thesis present the coal terminal main parameters, the special features of terminal functioning algorithm and wagon flow parameters.

The discrete event model, which is applied to test the adequacy of the combined model, is developed with the use of the present information about the functioning of the system and its parameters.

The analysis of the formulation of the problem provides the statement that this system can be examined as a MFHS. Furthermore flow features, applied in the formulation of the problem, allow to use both DESS and combined approach for the evaluation of the system performance measures.

The creation of the combined model can begin from the development of conceptual model. The simplified process diagram of the first zone of a coal terminal is depicted in Fig. 11 a), where the simulated system elements are marked in accordance with the components of the combined model: the source $A1$ is a point of coal trains arrivals, the bunkers $B1$,$B2$ and $B3$ simulate the first position, the buffer zone and the second position. The transport elements beginning from $T1$ to $T7$ correspond to the stages of the flow object displacement to the boundary of the coal terminal. The change of locomotive takes place in $Z1$.

The transport element $T8$ simulates the stage of the displacement of the flow objects from the boundary of coal terminal to the boundary of the railroad junction. Transport elements are necessary for the simulation of displacements, when the resource, in this case – locomotive, and time are required. Several assumptions and simplifications are accepted in the model. For example, the time of the displacement of the empty locomotive between the trains is not simulated separately, it is included in the total time of the train displacement, the enginemen are working without interruption, and locomotives do not break. The scheme of the combined model, which corresponds to the process diagram, is depicted in Fig. 11 b).

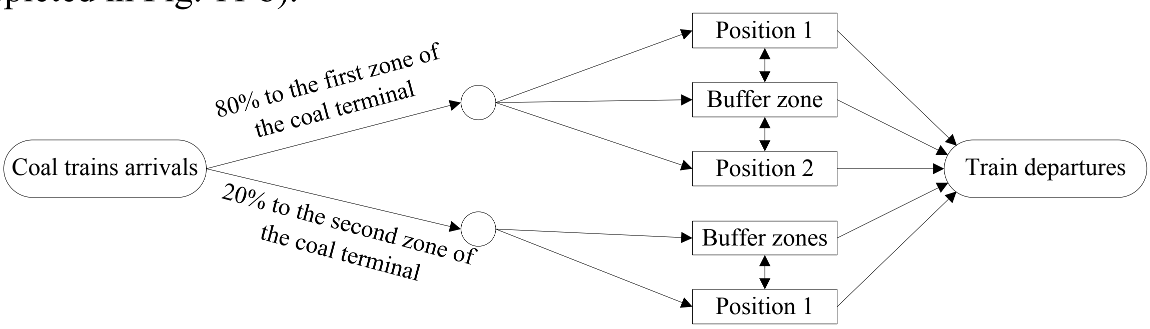


Figure 10. The simplified structure of the coal terminal

The combined model is developed with DESS software, which includes the system dynamic objects, which are *reservoirs* or *stocks* and *flows*. The properties of the software standard components may be changed using built-in scripts.

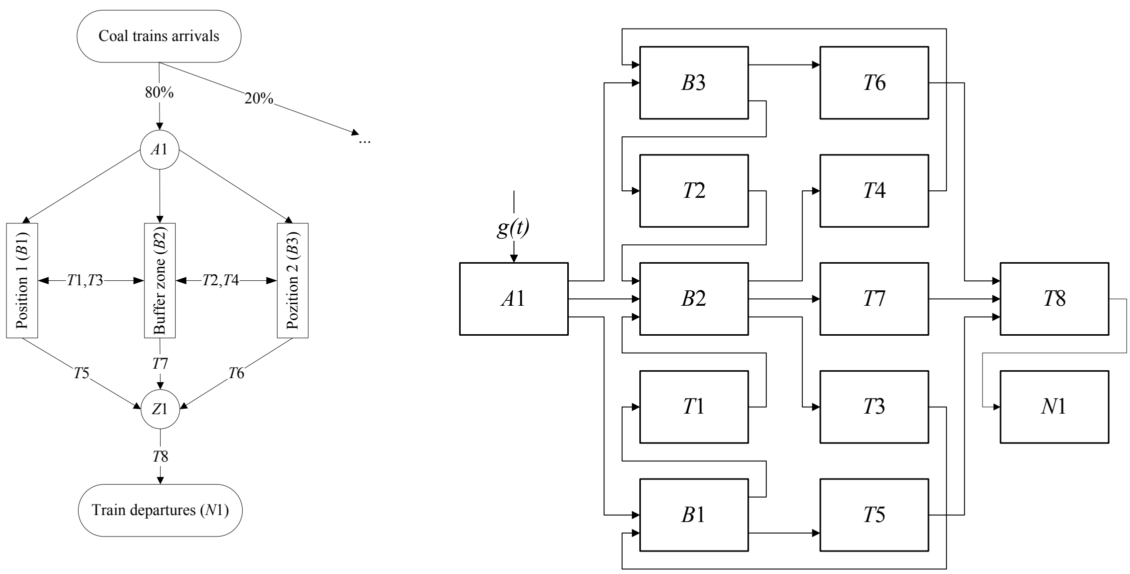
As it was noted earlier, within the framework of combined approach flow processes are determined using rate $\lambda(t)$ and cumulative rate functions. At the object under consideration, i.e., at the coal terminal, the flow consists of one object type – coal wagons, but at the railroad junction there are various flows, which consist of the wagons of different types. The incoming flow is represented in the form of impulses, which are wagon "portions" or trains. In the model components the "remainder" or contents is formed as a difference of the incoming and outgoing flow.

The combined model of the first zone of the coal terminal is created on the base of the process diagram, which is depicted in Fig. 11 a).

The train arrivals are simulated in the form of impulses. This way of flow generation provides the instant increment of the wagon quantity at the terminal at the moment of the train arrival.

The flow source *A*1 in the combined model simulates wagon arrivals to the system in portions. Interarrival time is a random variable so the arrival time moments can be simulated using traditional discrete event entity source.

After arrival to the coal terminal the trains are placed to one of two cargo positions *B*1, *B*3 or into the buffer zone *B*2. Both the buffer zone and cargo positions in the combined model are simulated as bunkers. The bunkers are simulated using the DESS software non-standard objects - *Tank* and *Pipe*, which



a) The process diagram of the first zone of the coal terminal

b) The structure of the combined model of the first zone of the coal terminal

Figure 11. The presentation of the conceptual model of the first zone of the coal terminal

perform all the necessary bunker functions: *Tank* provides capacity simulation and *Pipe* both incoming and outgoing flow of specified rate simulation.

The time of displacement between the source *A*1 and bunkers *B*1, *B*2 and *B*3 is not taken into consideration, the objects of a discrete flow are immediately placed into one of two bunkers *B*1 or *B*2, which simulate the loading/unloading operations, or into bunker *B*3 or the buffer zone in case the bunkers *B*1 and *B*2 are not empty. The flow portion volume is equal to the number of wagons. The bunker selection is performed using the accumulated simulation results; the next flow portion is placed into bunker with a smallest utilization at a moment, when current flow portion arrives. The outgoing flow rate $\lambda_{1,2}{}^{iz}$ is the same for both bunkers and is equal to 25 wagons per hour or to 0.416(6) wagons per minute.

After loading/unloading operations or after standby different displacements should be simulated, for example, from cargo position to the boundary of the coal terminal. It is possible to simulate the stages of displacement process using transport elements, which in discrete event simulation environment are realized as the combinations of objects *Process Oven* and *Tank*.

After transportation to the boundary of the coal terminal the transportation to the boundary of transport junction takes place and it takes average 32.5 minutes per train. This stage of a process is simulated with one transport element, *T*8.

After the simulation of all process stages the flow ends at a sink *N*1.

The image of the developed combined model is shown in Fig. 12.

In the process of development of new approach the models of different level of complexity are created and they simulate both the functioning of a transport junction and its separate areas. In this chapter the simulation results of the discrete-event transport junction model are under consideration as well as the simulation results of the coal terminal both discrete event and combined model. The last results are compared between themselves.

The estimates of numerical characteristics are summarized in Table 4. For the comparison such characteristics of the model objects are selected, which are

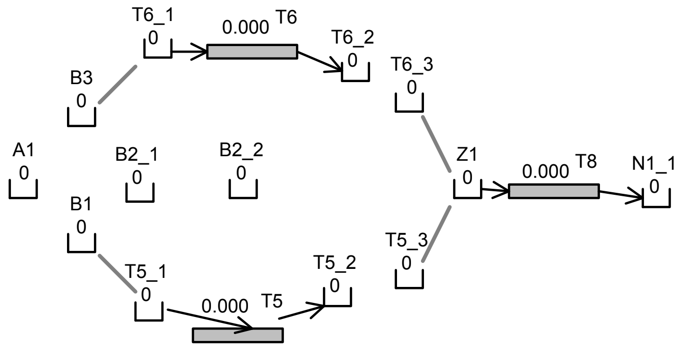


Figure 12. The screenshot of the combined model of the first zone of the coal terminal

used for the analysis of the effectiveness of the object functioning. The model under consideration makes it possible to estimate the usage of loading/unloading positions and of port locomotives.

The statistical comparison of simulation results is carried out and provides possibility to state that there is no significant difference between the average values of performance measures of discrete event and combined model. The example of confidence interval for the difference between two average values is shown in Fig. 13.

In this chapter the components of combined model are created using DESS software, the combined model of MFHS is developed and simulation results are obtained as well as the ways of result presentation and interpretation are defined.

Table 4

Interval estimates of some performance measures obtained from 100 simulation runs of discrete event and combined model with 95% confidence level

Performance measure	Discrete event model	Combined model
Summary utilization of loading/unloading positions (%)	71.85±2.55	70.19±2.63
The total quantity of processed flow objects at the terminal (wagons)	578.34±21.20	582.04±20.99
The usage of the free port locomotive (%)	21.06±0.78	21.30±0.79
The usage of the second locomotive (%)	22.50±0.82	23.08±0.85
The number of processing operations	578.34±21.20	14.20±0.52

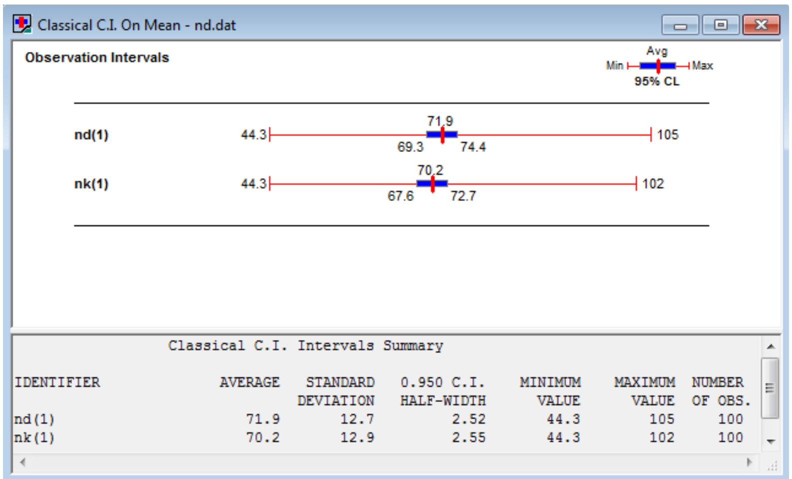


Figure 13. The test of loading/unloading positions utilisation estimates obtained from discrete event and combined model with 95% confidence level

After model development we could conclude that the models developed within combined approach are effectively usable and allow the simulation of MFHS and obtaining the reliable and precise estimates of performance measures.

THE MAIN RESULTS OF THE WORK

The combined approach to the simulation, which is intended to cover such material flow handling system simulation that can be formalized as discrete event systems and there are material flows in these systems represented with piecewise constant time functions. The approach is based on the aggregated description of the material flow handling systems elements. Within the approach framework the simplified formalization of material flow is used, that increases the effectiveness of the model execution due to the decrease of the volume of the calculations associated with events.

In the course of a research the complete and correct theoretical substantiation of the approach is developed. Traditional approaches ensure the simulation of material flows with the different levels of detail. Nevertheless the combined approach gives the possibility to create such models, which provide more effective studies in comparison with the traditional approaches.

The obtained results of the tasks to be solved in a dissertation study are the following:

- The executed survey of material flow theories and material flow types provides a basis to determine the method of formalization of material flows used and to define the functioning concepts of material flow handling systems.
- The performed comparative analysis of simulation approaches in the area of material flow handling system (MFHS) simulation makes it possible to determine the weak places of these approaches and to advance requirements for the simulation of MFHS.
- The new components set and their functioning algorithms within the framework of approach base the creation of the conceptual models of the MFHS.
- The developed approach unites the principle of the time advancing with the piecewise-linear state variables. In comparison with the traditional discrete event approach that simulated MFHA more effectively.
- The developed algorithms, state variable transition rules and formulas for performance measure estimations ensure the creation and application of combined models for MFHS analysis.
- The approval of the developed combined approach is executed in the course of applied research of a coal terminal. The obtained results confirm the effectiveness of both the approach and developed combined model. A quantity of events under consideration is substantially decreased with the retention of the accuracy of the estimates of performance measures.

The thesis completes by the approval of the developed combined approach to the simulation of MFHS. The results of the applied research of coal terminal confirm the effectiveness of the approach and developed model application. . The quantity of events under consideration is substantially reduced; nevertheless the accuracy of the obtained estimations remains sufficiently high.

The developed approach can be applied to the analysis of the MFHS in cases, where the use of other approaches can be complicated in domains of manufacturing, logistics and in other material flow existence domains.

After summing up the results of thesis, the further development and evolution opportunities of the proposed approach could be seen, such as: (a) the development of specialized simulation software; (b) the extension of the application area of the combined approach; (c) the design of visualization concepts of combined models.

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