

OVERVIEW OF FLOW SYSTEMS INVESTIGATION AND ANALYSIS METHODS

Mihail Savrasov

*Transport and Telecommunication Institute
Lomonosov str. 1, Riga, LV-1019, Latvia
Ph.: +371 29654003, e-mail: mms@tsi.lv*

This paper presents the results of the overview of flow systems research methods and approaches. Under the flow systems it could be understood the artificial, technical and controlled systems created for material and non-material objects processing (generation, transportation, transformation, accumulation and termination). The set of objects could be fixed by direct measurement or could be presented conceptually in separate system points (on the network links). They are presented as the sequences of discrete batches or as the continuous flow. Flow systems cover not only different systems of the material flow processing but also the systems themselves, the financial and tasks flows are processed, for example. For this moment there are a lot of methods, which could be used for the flow systems research. The classification of methods is presented. The classification on the high level contains: the analytical modeling and simulation. Under analytical modeling there is shown a wide range of methods and theories. The simulation branch is presented by three approaches. They are the simulation on microscopic level, simulation on mesoscopic level and simulation on macroscopic level. The advantages and disadvantages of using every approach are described here.

Keywords: *flow system, modeling, flow systems investigation*

1. Introduction

During last years a new term "flow systems" appears in the scientific papers and in the practical spheres. But clear definition of the term could not be found. First exact definition of the term was done in [1]. Under the term "flow systems" it could be understood the artificial, technical and controlled systems, created for material and non-material objects processing (generation, transportation, transformation, accumulation and termination). The set of objects could be fixed by direct measurement or could be presented conceptually in separate system points (on the network links). They are presented as the sequences of discrete batches or as the continuous flow. Flow systems cover not only different systems of the material flow processing but also the systems themselves, the financial flows and tasks flows are processed, for example. According to this definition the majority part of the existing systems could be treated as flow systems.

Under flow systems scientific papers consider only logistic systems, such as warehouse or supply chain etc. This is done because products income and outcome could be presented as flows without any problems. But also transport, information and financial systems could be threatened as flow systems. Of course if we look deeper inside the system the nuances could appear, for example the type of flow could be different from system to system. The enumeration and description of flow types could be found in [2]. Such kind of nuances can play a big role during choosing the methods of investigation and analysis of flow systems. But for a moment, the scientific literature does not contain the overviews of methods and theories, which could be applied exactly to the flow systems. The main tasks of this paper are to enumerate and to describe existing methods of flow systems analysis and investigation.

2. Analytical Approach

Various theories and methods, based on analytical calculation could be understood as analytical approach. It is necessary to mention that this article enumerated the methods which could be applied for flow system research. We see in Figure 1, that two theories could be used for flow systems research under analytical branch they are: queuing system [3] and network queuing theories [4] and graph theory [5].

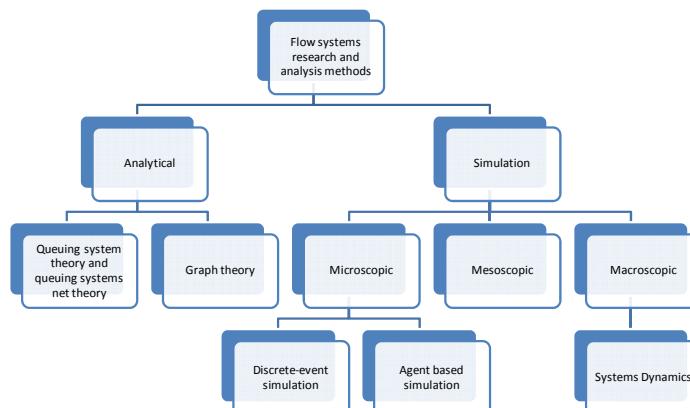


Fig. 1. Classification of methods of flow systems investigation and analysis

Queuing system and network queuing theories

The queuing system theory is well known at the moment. The first publication was done in 1909 by Agner Krarup Erlang, after that event, in 1953 David G. Kendall introduced A/B/C queuing notation. The theory enables the mathematical analysis of several related processes, including arriving at the (back of the) queue, waiting in the queue (essentially, a storage process), and being served by the server(s) at the front of the queue (Figure 2).

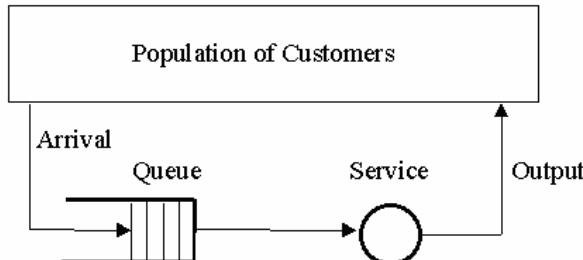


Fig. 2. Single server queue system

The theory permits the derivation and calculation of several performance measures including the average waiting time in the queue or the system, the expected number waiting or receiving service and the probability of encountering the system in certain states, such as empty, full and having an available server or forced to wait a certain time to be served. Concluding from the discussion connected with queuing system net, we could say there exists a set of queuing systems, which are linked in net. But those theories have a lot of limitations, because they are often too mathematically restrictive to be able to model all real-world situations exactly. This restriction arises because the underlying assumption of the theory does not exist in real world. For example, the mathematical models often assume the infinite number of customers, infinite queue length; concrete theoretical distributions for arrival and service (For example, poison income flow and exponential service). So the restrictions of those theories are high and thus, they could be used only for the superficial real-world systems estimation.

Queuing system and queuing net system theories advantages

- Fast calculation – if the investigated system can be presented as queuing system, having the analytical solution, the only problem is to calculate formulae and get the result. Queuing system and queuing net system theories disadvantages
- Are not able to model real-world situations – there is no analytical solution for queuing system of type G/G/n – according to Kendall notation.
- Absence flexibility – in case of some changes in the model, it is necessary to change the numbers of servers in the systems that will lead to total formulae change or no solution at all.

Graphs theory

Graph theory deals with the structure called graph. From the mathematical point of view graphs G is a collection of vertices or nodes and edges that connect pairs of vertices. For the first time the graph theory was mentioned in 1736 by Leonhard Euler. There are some graph theory problems which could be applied for flow systems. Routing and network flow problem are considered to be the most applicable. The routing problem is mainly connected with different routes of finding in the graph. The flow network is a directed graph where each edge has a capacity and receives a flow. The amount of flow on an edge can not exceed the capacity of the edge. A flow must satisfy the restriction that the amount of flow into a node equals the amount of flow out of it, besides the situation when it is a source, which has outgoing flows, or sink, which has incoming flows. The network can be used to model traffic in a road system, fluids in pipes, currents in an electrical circuit, or anything similar in which something travels through a network of nodes.

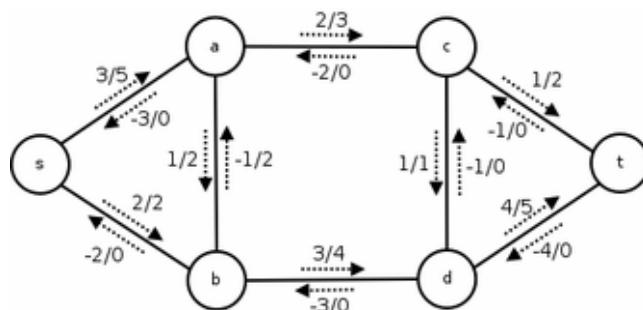


Fig. 3. Flow network showing flow and capacity

So graph theory could be used to solve some flow systems problems. But graph theory is unusable for real-world problems.

Graph theory advantages

- Algorithms are well known – if existing problem in flow system could be presented in graph notation and the problem is described in graph theory, so it will not be difficult to apply the algorithm.
- Graphical representation – the results of the problem solving could be presented graphically, so it will increase the representation of results

Graph theory disadvantages

- Are not able to model real-world situations – modern flow systems are big and complex, with collection of parameters, so well known graph algorithms are not useful for such systems.

According to the description of the analytical approaches these theories and methods could not be applicable for solving real-world problems in flow systems, because of their assumptions. Of course, sometimes those theories and methods are useful for system quick research and solving, but simplification of the problem should be done and the result will not have the required exactness. All mentioned classes of the analytical models should be used only for static problems analysis. It means that using these models, makes possible only to estimate numerical indicators of the systems functioning, which could not be presented as functions of time. That is why simulation branch should be taken into account.

3. Simulation Approach

Simulation is a powerful tool for various systems analysis and investigation. We could mark universality of this tool as main advantage of the simulation. The universality means the ability to model different. As we have seen from Figure 1 simulation branch is presented by three approaches, they are simulation on microscopic level, simulation on mesoscopic level and simulation on macroscopic level. Different methods of simulation are located under each approach.

Microscopic simulation

The simulation on microscopic level is widely used for a moment. The main idea of the simulation on microscopic level could be described in the following way: objects and resources are highly detailed in their description. The algorithm of object conduction is described in details. Thus, each experiment needs a number of runs and only after that the data could be aggregated to get the final result. At present two methods of simulation on micro level are well known. They are: discrete-event simulation and agent-based simulation. The discrete-event simulation is the paradigm which is realized in the major part of software tools (for example, GPSS, Extend, Arena, Witness, Automod, FlexSim, em-Plant etc). This approach is known since 1960s, when it was described by Geoffrey Gordon. A discrete-event simulation model is defined by three attributes [6]:

- stochastic – at least, some of the system-state variables are random;
- dynamic – the time evaluation of the system-state variables is important;
- discrete-event – significant changes in the systems state variables are associated with event that occur at discrete time instance only.

Also the concept of approach could be described using Figure 4.

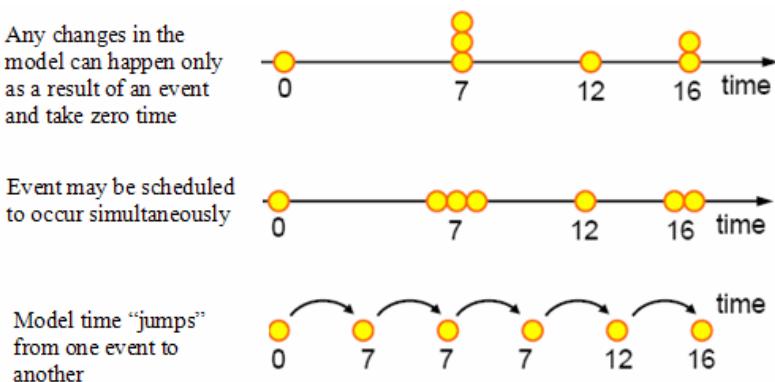


Fig. 4. Concept of discrete event approach [7]

The model of the realized system using this approach could be presented as a sequence of blocks (figure 5) which performs different operations: arrival, delay, resource use, split, combine etc. Those operations are being performed on the entities which could be presented as a flow.

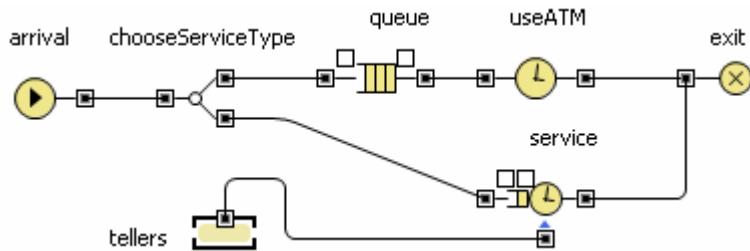


Fig. 5. Model realized by means of discrete event approach in AnyLogic [7]

A set of papers from Winter Simulation Conference could be named as the example of using the discrete-event approach for flow system modeling.

- *A simulation model of warehouse operations [8]*
- *Discrete Event Simulation Modeling of Resource Planning and Service Order Execution for Service Businesses [9]*
- *Using Event Simulation to Evaluate Internet Protocol Enhancements for Special Services[10]*

The second paradigm is not so well known now, but the popularity is growing. This paradigm is the agent-based modeling. The main concepts of paradigm appeared only in 1990s. At present there exist various definitions in the literature, from the practical point of view it can be defined as essentially-decentralized, individually-centric (as opposed to system level) approach to the model design. When designing an agent-based model the modeller identifies the active entities, the agents (that can be people, companies, projects, assets, vehicles, cities, animals, ships, products etc.), defines their behaviour (drivers', reactions, memory, states etc), puts them in a certain environment, perhaps, establishes connections and runs the simulation [11]. At present, there are only few software products available in the market; they are RePast, Swarm, ASCAPE, NetLogo and Anylogic. Graphically, the conception of the agent-based approach could be presented in Figure 6.

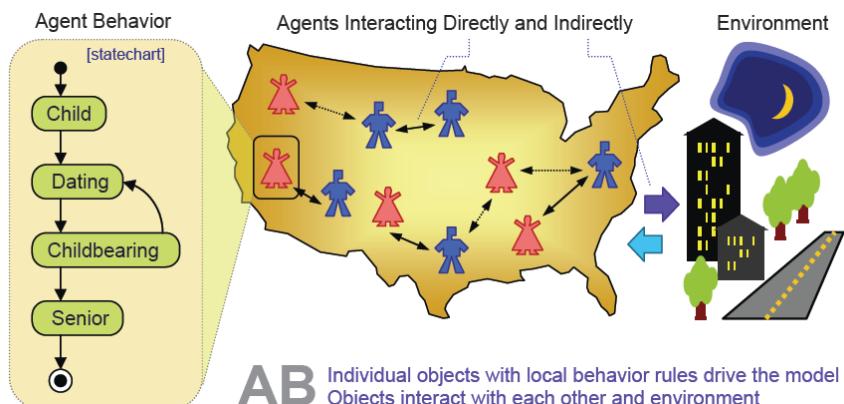


Fig. 6. Agent-based model architecture [12]

The model of the system consists of description of agents' behaviour and description of the environment where agents are "living". The agents' behaviour is mainly described by the finite state automata as presented in Figure 6. And of course, some agents' communication algorithms need to be given.

The popularity of the approach is growing and the number of works connected with modeling flow systems with agent-based approach could be enumerated.

- *Agent-based Simulation Framework for Supply Chain Planning in the Lumber Industry [13]*
- *From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools [14]*

Two approaches of the microscopic simulation are described. Both of them could be used to simulate flow systems for their analysis and investigation. Which one to use - it is a question of concrete task and concrete problem a concrete necessary to be solved. Sometimes it is easier to use discrete-event approach, but sometimes agent-based. There are different examples of using both of those paradigms for solving the same tasks with good results at the end [15].

Of course, there are some advantages and disadvantages of using simulation on microscopic level which should be taken into account at the choice between microscopic, macroscopic and mesoscopic simulation.

Disadvantages of simulation on microlevel:

- High requirements to resources (staff, computers, money, time etc) – big resources should be involved during model creation. First of all, special software for simulation should be bought. The second is a model construction; validation and experimentation are very time-heavy processes. The third is the high level to requirements hardware.
- High level of developers subjective system presentation – the models are developed by people and they could bring in their subjective understanding of the system. To minimize this effect a validation should be done.
- A set of runs for each experiment should be done to get the result – because of stochastic environment of the investigated systems a set of runs should be executed for each experiment. After that the results should be aggregated and the data analyses should be done using statistical packages.

Advantages of simulation on microlevel:

- Graphical representation of the model could be developed – all modern simulation softwares allow to create the graphical representation of the model. Such representation could be used for two purposes: for model validation and as the vivid example of the systems functioning. Many problems and bottlenecks of the system could be detected quickly because of the graphical representation.

Macroscopic simulation

Macroscopic simulation is presented only with only one paradigm. This paradigm is system dynamics. This approach was developed by Jay Forrester in 1950s. Firstly, Forrester applied developed approach, for analyzing industrial systems. According to [16] system dynamics deals with the time dependent behaviour of the managed systems with the aim of describing the system and understanding, through the qualitative and quantitative models, how information feedback governs its behaviour and designing robust information feedback structures and controls policies through simulation and optimization. In fact system dynamics it is a set of differential equation. That is why the system dynamics does not deals with particular object, but with the aggregated sets of objects which flow from one stock to another with strength which is defined with flow variables. For a moment, there are a lot of softwares which deals with system dynamic approach, and we can enumerate the following ones, the most popular: VenSim, PowerSim, iThink and AnyLogic. Mostly the difference between simulation software exists only in the model components visualization, user's interface and reporting module. The main elements of the systems dynamics model, which are presented in all software, are the following: stocks, flow variables and variables. The example of the dynamic system model is presented in Figure 7.

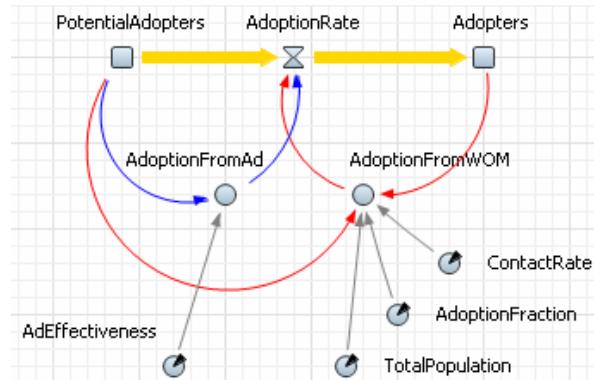


Fig. 7. Model realized using system dynamics approach in AnyLogic [17]

In general, the results of the modeling are presented as graphs of the processes (Figure 8). System dynamic models are very useful for experiments of type "what if".

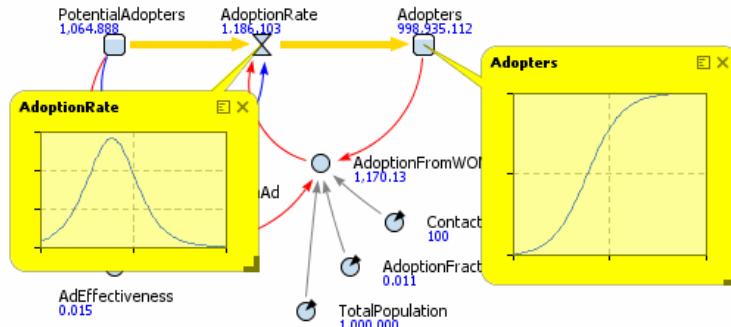


Fig. 8. Result of modeling using system dynamics approach [17]

A set of could be named as the example of using the system dynamics approach for flow system modeling.

- *System dynamics modeling in supply chain management: Research review[18]*
- *Modeling E-Material Supply Chain [19]*
- *Quantifying the bullwhip effect in a simple supply chain: The impact of forecasting, lead times, and information [20]*

The system dynamic approach is widely used for the complex system investigation.

The field of models, where system dynamics is applicable, contains the long-term and strategic models and assumes the high level of aggregation of objects being modeled. Of course, some disadvantages and advantages of macrosimulation should be underlined.

Disadvantages of simulation on macrolevel:

- Simulation representation – results are presented as the graphs of processes. Animation is not available on this level. Therefore, the simulation process is not as representative as in the simulation on microlevel.
- Results – results of simulation should not be treated as exact values, because of the object aggregation and system simplification.
- No flexibility – there no possibility to change algorithm of the system during simulation time, so sometimes it could cause problems and the system will not be similar to real-world system.

Advantages of simulation on macrolevel:

- Complex systems – very complex systems could be modeled and both qualitative and quantitative factors could be taken into account
- Graphs of process – there is no animation on this level, but still it is possible to get graphs of processes which are useful for whole system understanding

Mesoscopic simulation

Comparing mesoscopic approach with the other approaches is something in the middle of the microscopic and macroscopic approach. This approach should use advantages from both of them. Reviewing literature and modern works we can find a lot of approaches to these problems which could be classified as mesoscopic approaches. The major part of them is self-made and developed for the concrete problem solving. For example, [21] contains examples of mesoscopic approaches applied to traffic modeling. At present only one approach could be mentioned as the example of mesoscopic simulation. This approach is really universal and could be applied to any application area. In [22] this approach is mentioned as mesoscopic approach of simulation. The mesoscopic approach is innovative and its conception is still in progress of development. But the numerical solutions of solving problems by means of this approach could be found in [22, 23, 24]. The philosophy behind this approach can be described with the phrase “discrete time/ continuous quantity” [23]. The representation of individual flow objects that reproduce persons, job orders, goods etc is dispensed with. The only employed members that are used in the model represent the respective quantities of objects or materials and can be modified with mathematical formula in every step of the discrete simulation time. This type of mesoscopic modeling and simulation is the method helping to complete planning tasks in production. Also results of simulation on mesoscopic level can be introduced as graphs of the processes, which are very useful in practice. The concept of simulation on mesoscopic level specifies the development of the principally new class of models.

Mesoscopic modeling shows only discrete changes of the corresponding continuous flows. It means, that flow intensity $\lambda(t)$ stays unchangeable in each interval of time between flow changes Function $\lambda(t)$ could be called slice constant function. Figure 9 presents functions of income and outcome flow for simple store. Last graph presents contents of the store for the given input and output flow. Because $\lambda(t)$ is slice constant function the graph of contents of store could be only the piecewise-linear function. The main advantages of such process representation in mesoscopic modeling are probably forecasting (to planning, calculating) moments of time, when contents of store and cumulative value of flow reach the given values.

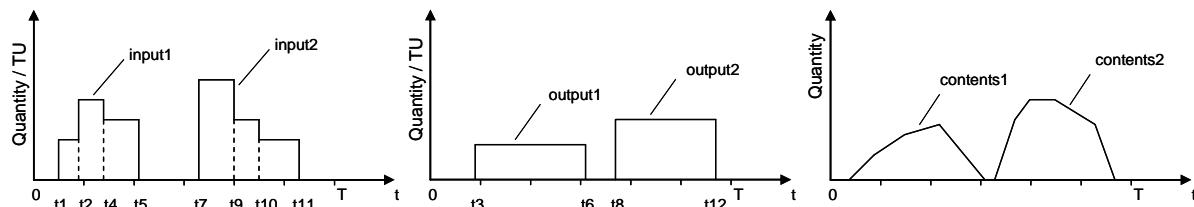


Fig. 9. Process presentations in mesoscopic level

So dual properties are characteristic of the mesoscopic model:

1. Its flow processes are characterized by intensity $\lambda(t)$ (as in case of model of continuous type)
2. For processes in store and for cumulative values of flows the future events (as in case of models of discrete events) could be planned.

The single continuous fragments of flow, that will be called the batches of product, could be treated as objects. The mesoscopic model feature is the possibility to control the path of any batch of product during its movement through the model structure. In Figure 10 an example of mesoscopic model is presented. Instead of stores it presents the so called multichannel funnels. Because of the parallel channels, batches of products in the same funnel at the same time could be divided. Funnel channels (see funnels stock1 and stock2 in Figure 10) have numbers, which are numbers of parallel flows of products (see products Pr1 and Pr2 in Figure 10). Conformity between products batches, which are created and processed in the model, and the numbers of parallel flows, are given in frame of conceptual model.

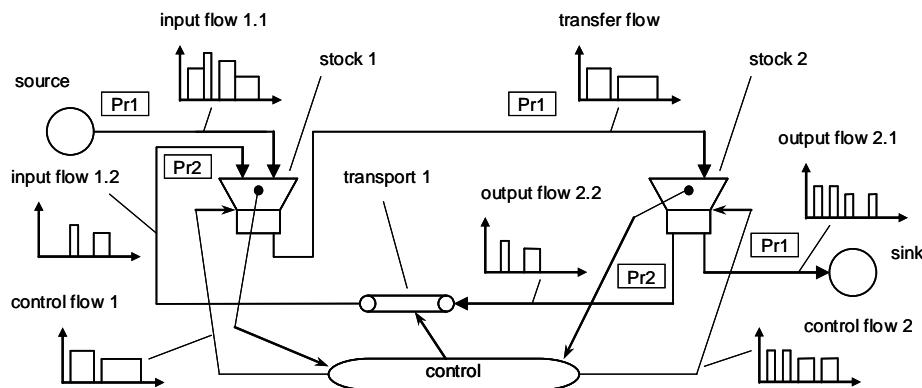


Fig. 10. Example of mesoscopic model structure

Disadvantages of simulation on mesoscopic level

- Theoretical background has not yet implemented fully
- There is no specialized software

Advantages of simulation on mesoscopic level

- Models could be created faster, than models of microscopic levels
- There no need to do a lot of runs for experiment
- The result will be more precise than the results from macro level because the system algorithm is modeled in high details
- As models could be created faster, they could be used on tactical and operational level of decision making

Conclusions

1. Overview of flow systems investigation and analysis methods was done in this work.
2. Described theories and methods of the analytical approach could be used to solve real-world problems which occur in the flow systems. They could be used only with some simplification of the system, but it will always lead to increasing the quality of result.
3. Simulation can give good results in flow systems research and analysis. The results of simulation are more representative and more informative.
4. During simulation it is necessary to choose a level of aggregation during system analysis. There exist three levels of aggregation: micro, macro and meso levels. Each level has its own advantages and disadvantages, which should be taken into account before creating a simulation model.
5. Microscopic simulation is the most popular for today. But there are a lot of disadvantages, which sometimes make this approach unusable. The biggest of them is resource requirement and time requirement for model creation validation and verification. Animation possibility on this level is an advantage.
6. Macroscopic level is used for complex system analysis and mostly applicable for the strategic level of decision-making. The model could be constructed faster, than in microscopic level, but the results will be aggregated.
7. Mesoscopic level should include advantages from both micro and macro level. But for a moment there is no strict and universal definition of this level, but the perspectives approaches are available. From the current point of view, the mesoscopic approach could be used on tactical and operational level.

References

1. Schenk, M., Tolujew, J., Reggelin, T. Mesoskopische Simulation von Flusssystemen: algorithmisch steuern und analytisch berechnen. In: *Beiträge zu einer Theorie der Logistik*, Nyhuis, P. (Hrsg.), Springer, 2008, S. 463-485.
2. Schenk, M., Tolujew, J., Reggelin, T. A Mesoscopic Approach to Modeling and Simulation of Logistics Networks. In: *Logistics and Supply Chain Management: Trends in Germany and Russia*, D. Ivanov, C. Jahns, F. Straube, O. Procenko, V. Sergeev (eds.), Publishing House of the Saint Petersburg State Polytechnical Institute, 2008, pp. 58-67.
3. Gross, D., Harris, C.M. *Fundamentals of Queuing Theory*. 3-rd ed., John Wiley & Sons Ltd, 1998. 404p.
4. Ivnitsky, I. *Network Queuing Theory*. Moscow: Physic-Mathematical Literature, 2004. 772 p.
5. Ore, O. *Graphs Theory*. Moscow: Nauka, 1968. 352 p.
6. Lawrence M. Leemis, Stephen K. Park, "Discrete-event Simulation: a first course", New Jersey: Person Prentice Hall, 2006. 604 p.
7. <http://www.xjtek.com/anylogic/approaches/discreteevent/>
8. <http://www.informs-sim.org/wsc07papers/250.pdf>
9. <http://www.informs-sim.org/wsc07papers/277.pdf>
10. <http://www.informs-sim.org/wsc07papers/284.pdf>
11. <http://www.xjtek.com/anylogic/approaches/agentbased/>
12. <http://www.xjtek.com/file/92/>
13. <http://www.wintersim.org/abstracts07/PhD.htm#santaeulalial8705p>
14. Borshchev, A. and Filippov, A. From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools. *The 22nd International Conference of the System Dynamics Society*, Oxford, England. 2004.
15. Allen Pugh, G. *Agent-Based Simulation of discrete-event systems*. ASEE Illinois-Indiana Section, 2006.
16. Coyle, R.G. *System Dynamics Modelling*. Chapman & Hall/CRC, 2001. 413 p.
17. <http://www.xjtek.com/anylogic/approaches/systemdynamics/>
18. Angerhofer, B. J. System dynamics modeling in supply chain management: Research review. In: *Proceedings of the 2000 Winter Simulation Conference*, 2000, pp 342-351.
19. Saleh, Mohamed. Modeling E-Material Supply Chain. *The 24th International Conference of the System Dynamics Society*, July 23-27, 2006 Nijmegen, The Netherlands.
20. Chen, F., Drezner, Z., Ryan, J. K. and Simchi-Levi, D. Quantifying the bullwhip effect in a simple supply chain: The impact of forecasting, lead times, and information, *Management Science*, 46, 2000, pp. 436-443.
21. Doctoral Dissertation Hybrid microscopic-mesoscopic traffic simulation by Wilco Burghout, Royal Institute of Technology, Stockholm, Sweden 2004.
22. Tolujew, J., Alcalá, F. A Mesoscopic Approach to Modeling and Simulation of Pedestrian Traffic Flows. *18th European Simulation Multiconference*, Horton G. (Ed.), SCS International, Ghent, 2004, pp. 123-128.
23. Schenk, M., Tolujew, J., Reggelin, T. Mesoskopische Modellierung und Simulation von Flusssystemen. In: *Logistics Collaboration*, D. Ivanov, E. Müller, V. Lukinskiy (eds.), Publishing House of the Saint Petersburg State Polytechnical Institute, 2007, pp. 40-49.
24. Tolujew, J., Savrasov, M. Mesoscopic approach to modelling a traffic system. *International Conference, Modelling of Business, Industrial and Transport Systems*, 2008, pp.147-151.