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The Modelling and Simulation of Complex Systems: Methodology and Practice. An Overview

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Abstract **– This paper summarizes the research in the field of modelling and simulation of complex systems conducted in recent years at the Department of Modelling and Simulation of Riga Technical University under the supervision of the corresponding member of the Latvian Academy of Sciences, Prof., Dr.habil.sc.ing. Yuri Merkuryev (Jurijs Merkurjevs). The main attention is devoted to developments within integrated simulation methodologies that incorporate simulation with other scientific approaches for the analysis, optimisation and management of complex systems, with a special focus on logistics systems. Practical application of the developed methods is considered by referencing to implemented research projects. Future research directions are also discussed.**

Keywords **– discrete-event system simulation, logistics, modelling and simulation, optimization, supply chain management, sustainable development**

I. Introduction

The overview provides a summary of the main results of the research in the field of modelling and simulation (M&S) of complex systems conducted at RTU, the Department of Modelling and Simulation (RTU DMS) under the supervision of the corresponding member of the Latvian Academy of Sciences, prof., Dr.habil.sc.ing. Yuri Merkuryev (*Jurijs Merkurjevs*).

M&S research activities at RTU DMS are mainly related to discrete-event systems that change their state instantaneously, at discrete time moments. In particular, such systems are often considered in queuing and reliability studies, as well as in inventory management. At the same time, continuous systems and combined systems (that include both discrete-event and continuous ones) are discussed as well.

The M&S process generally incorporates the following main phases:

- development of a conceptual model of the considered system;
- transferring the conceptual model into a computer programme, i.e., development of a simulation model;
- experimenting with the simulation model.

For instance, a flow chart of the M&S process in case of discrete-event system simulation is presented in Fig. 1 [1].

In the subsequent sections, research results will be considered that are related to the main steps of the M&S process (e.g., design of simulation experiments), as well as to the application of simulation to solving different problems, inherent to operation of complex systems (e.g., analysis, optimization and management). The main attention will be devoted to developments within integrated simulation methodologies that incorporate simulation with other scientific approaches for the analysis, optimisation and management of complex systems, with a special focus on logistics systems.

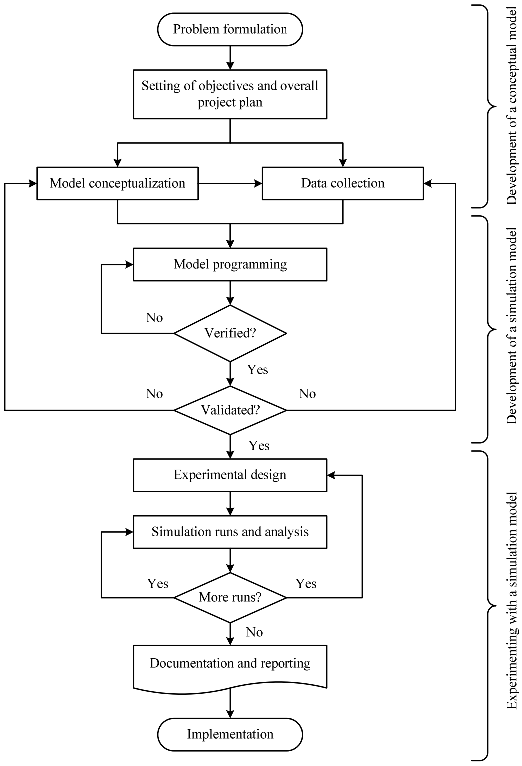

Fig. 1. Flow chart of the simulation study

II. Simulation of Logistics Systems

A. Simulation in Logistics

Simulation is considered to be one of the most effective technologies for the analysis and planning of logistics systems (in particular, for supply chains) [2]. Not always the power of the mathematical analysis proves to be sufficient for finding a complete analytical solution to complicated business tasks. In this case, the experimental study serves as an alternative solution. In particular, the use of simulation in logistics has become very popular. A survey of simulation applications in logistics is presented in [3], where the main logistics activities are analysed (see Fig. 2), and logistics tasks, which can be effectively solved with the help of simulation, are specified for each activity. Practical applications of simulation that demonstrate provided improvements of the operation of real logistics systems are described in the survey as well.

The performed survey of simulation practice in logistics confirms the effectiveness of the simulation technology in analysing and planning complicated logistics systems, which operate in a stochastic environment [3]. In order to establish the possibilities of effective operation achievement of an entire system, planning and control problems of modern logistics systems were investigated. The performed analysis determines the importance of the supply chain concept in order to improve operation of the entire logistics system due to a customer-oriented marketplace.

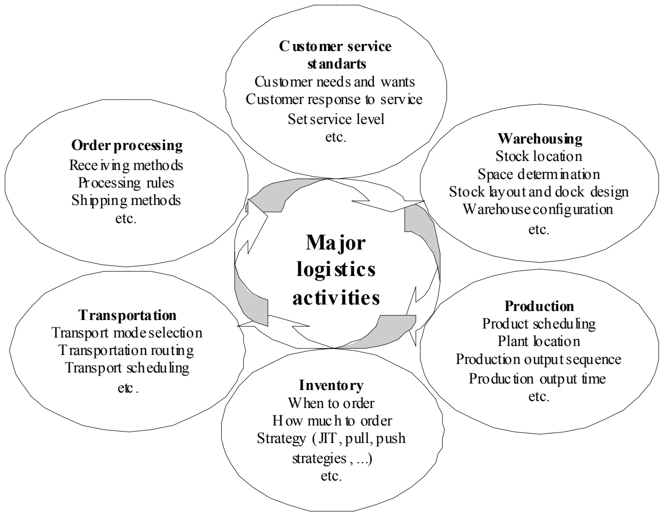

Fig. 2. Major logistics activities

Different methods of mathematical modelling that can be used for supply chain analysis were investigated and classified, in particular:

- analytical modelling – algebraic models, control theory, Petri-nets, queuing theory, Markov chains, etc.
- algorithmic modelling:
  - continuous system simulation – differential equations, difference equations, etc.
  - discrete-event system simulation – event or process oriented simulation, etc.

The performed analysis specifies discrete-event simulation as the most appropriate approach to modelling logistics systems that usually are complex dynamic ones, operating within a stochastic environment. On the other hand, the performed survey determines inventory management as one of the most critical logistics activities [4], [5].

Research results, related to both the development of simulation-based analysis, optimization and management methods in the logistics area and their practical implementation, are reviewed in the subsequent sections. In particular, the next section discusses the possibility of combining analytical and simulation approaches in the analysis of supply chain dynamics.

B. Simulation-Based Versus Analytical Analysis of Supply Chain Dynamics

In a supply chain, logistics activities are considered through a number of partners, involved into producing goods (or services) and providing them to final customers: from suppliers of raw materials, through production companies, and finally to retailers that provide produced goods to the market.

The impact of stochastic factors on the management of a supply chain is crucial. Stochastic nature of the customer demand is established as one of the most critical factors in decision-making. An order lead time largely affects supply chain operation stability as well, and its uncertainty has the worse influence exactly at the tactical planning level. That is why planning and controlling problems of a supply chain at the tactical level under the stochastic customer demand and order lead time are of special importance for the supply chain management community.

Operation of any supply chain depends on the customer demand and its fluctuation. However, internal demand between supply chain stages also plays an important role due to considerable changes in information about the required product amount. An important phenomenon in the supply chain management is the increase in variability of the demand as it moves through the supply chain in the direction from a customer to a supplier. This phenomenon is called the bullwhip effect because even small disturbances in demand at the customer level cause demand amplification for the next supply chain member. A measure of the demand variability is its standard deviation. Increase in this value at each supply chain stage indicates the existence of bullwhip effect.

The bullwhip effect is considered to be an important characteristic of supply chain operation stability. Therefore, it is important to have efficient means for evaluating its value. While simulation remains a general approach to bullwhip effect evaluation, availability of analytical techniques would serve for validation of the simulation-based analysis. Also, in some situations, the analytical approach could provide a faster solution, asking for less computational efforts.

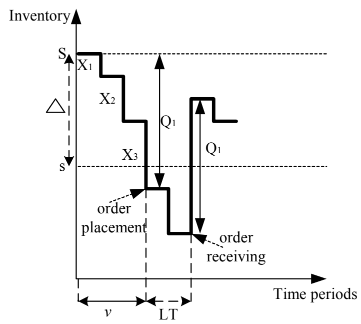

Fig. 3. Inventory control strategy in a supply chain stage

In [6], an analytical approach for estimation of the bullwhip effect was developed for a particular type of the inventory management strategy. Here a supply chain is analysed from the inventory management point of view, by representing it as a chain of serially connected inventory management systems. The considered supply chain consists of the end customer, retailer and supplier. The retailer supplies single-item products to a customer in accordance with the demand received and replenishes his inventory by placing orders to the supplier. Customer demand is stochastic and stationary. For managing the inventory, the s-S inventory control strategy (see Fig. 3.) is used.

The magnitude of increase in variability of the placed order quantity with regard to variability of received demand quantity characterises the bullwhip effect. Its value can be expressed analytically, taking into consideration numerical measures of the customer demand distribution – an expected value *E(X)* and variance *D(X)*.

Provided that the demand *X* is uncertain and the aforementioned inventory control method is employed, the placed order quantity *Q* is expected to be a random variable that depends on demand quantities. The expected value *E(Q)* and variance *D(Q)* of the function $Q = \varphi(X)$ are estimated using the following formulas:

$$\mathrm{E(Q)} = \mathrm{E(X)} + \mathrm{E(v)} \tag{1}$$

and

$$\mathrm{D(Q)} = \mathrm{E(v)} * \mathrm{D(X)} + \mathrm{D(v)} * [\mathrm{E(X)}]^2 \tag{2}$$

where *E(v)* – the expected value of a period number *v* between placed orders;

D(v) – the variance of a period number *v* between placed orders.

To consider correlation between demand quantity X_i and time period of order placement *v*, a probability density function of the order quantity *Q* should be defined [7]. It is obtained by integration of a total probability formula of the sum of received demand quantities ($S_Q=X_1+X_2+...+X_v$). The distribution function of the random variable S_Q with regard to the total probability formula is:

$$\begin{aligned} &F_Q(x)=P(S_Q<x)=P(X_1+X_2+...+X_v<x)=\\ &=P(S_Q<x/v=1)*P(v=1)+P(S_Q<x/v=2)*P(v=2)+\\ &+P(S_Q<x/v=3)*P(v=3)+...=P(X_1<x)*P(v=1)+\\ &+P(X_1+X_2<x)*P(v=2)+P(X_1+X_2+X_3<x)*P(v=3)+... \end{aligned} \tag{3}$$

where *P(v=i), i=1÷∞* – probability that the order will be placed in the i^{th} time period;

$P(S_Q<x/v=i)$ – probability that the order quantity will be less than *x* in time period *v*.

Analytically estimating the probability P(v=1,2,3,...) of the period when an order is placed and the probability P(X1+X2+X3+...<Δ) that the sum of demand quantities reaches the Δ quantity, it is possible to define the following distribution function FQ(x) of the order quantity:

$$\begin{aligned} &F_Q(x) = \int_0^x f(x_1)dx_1 * \left(1-\int_0^\Delta f(x)dx\right) +\\ &+\int_0^x f(x_1)\int_0^{x-x_1} f(x_2)dx_2dx_1 * \int_0^\Delta f(x_1)\int_{\Delta-x_1}^\infty f(x_2)dx_2dx_1 +\\ &+\int_0^x f(x_1)\int_0^{x-x_1} f(x_2)\int_0^{x-x_1-x_2} f(x_3)dx_3dx_2dx_1 *\\ &*\int_0^\Delta f(x_1)\int_0^{\Delta-x_1} f(x_2)\int_{\Delta-x_1-x_2}^\infty f(x_3)dx_3dx_2dx_1 +\\ &+\int_0^x f(x_1)\int_0^{x-x_1} f(x_2)...\int_0^{x-x_1-...-x_{i-1}} f(x_i)dx_idx_{i-1}...dx_1 *\\ &*\int_0^\Delta f(x_1)\int_0^{\Delta-x_1} f(x_2)...\int_{\Delta-x_1-x_2-x_{i-1}}^\infty f(x_i)dx_idx_{i-1}...dx_1 \end{aligned} \tag{4}$$

where $f(x_i)$ – the probability density function of the customer demand distribution;

Δ – the difference between the target inventory level *S* and reorder point *s*;

i – the number of random variable values; the more addends are, the more precisely the distribution describes the behaviour of the random variable *Q*.

To define the probability density function of the order quantity $f_Q(x)$, its distribution function $F_Q(x)$ should be derived:

$$\begin{aligned} &f_Q(x) = f(x) * \left(1-\int_0^\Delta f(x)dx\right) + \int_0^x f(x_1)f(x-x_1)dx_1 *\\ &*\int_0^\Delta f(x_1)\int_{\Delta-x_1}^\infty f(x_2)dx_2dx_1 +\\ &...+\int_0^x f(x_1)\int_0^{x-x_1} f(x_2)\int_0^{x-x_1-...-x_{i-2}} f(x-x_1-...-x_{i-1})dx_{i-1}dx_{i-2}...dx_1 *\\ &*\int_0^\Delta f(x_1)\int_0^{\Delta-x_1} f(x_2)...\int_{\Delta-x_1-x_2-x_{i-1}}^\infty f(x_i)dx_idx_{i-1}...dx_1 \end{aligned} \tag{5}$$

Knowing the random variable probability density function, it is possible to analytically define its numerical characteristics:

$$E(Q) = \int_\Delta^\infty x f_Q(x)dx \tag{6}$$

$$D(Q) = \int_\Delta^\infty x^2 f_Q(x)dx - [E(Q)]^2 \tag{7}$$

Variance *D(Q)* of the order quantity *Q* characterises a bullwhip effect value in the supply chain. It could be estimated, applying the developed probability theory based method and knowing the distribution function of the customer demand and its numerical characteristics.

In order to test the accuracy of the developed method, its practical application was performed. Supply chain operation with the customer demand distributed in accordance with an exponential distribution was analysed, and analytically obtained results were compared with those received by simulation. The results of both experiments were statistically identical [8].

Obviously, the simulation approach supports evaluation of the bullwhip effect in all supply chain configurations and demand patterns, and it could be taken as a general technology for the analysis and planning of supply chain operation. On the other hand, analytical approaches to analysing supply chain operation do not need specialised simulation software, and in some situations are more efficient (in terms of calculation efforts). At the same time, their application is restricted by supply chain complexity and demand pattern.

Continuing discussion on the role of simulation in the analysis and management of supply chains, the next section considers applying simulation to tactical planning of supply chain operation.

C. Simulation-Based Supply Chain Tactical Management

Supply chain management is a set of approaches used to efficiently integrate supply chain partners like suppliers, manufactures, warehouses and stores. The complexity of supply chain management is related to its non-linear nature, echelon number, as well as uncertainty.

According to the time horizon, supply chain management tasks are categorized into three planning levels, i.e. strategic (3-5 years), tactical (up to 1 year) and operational (daily) levels. Supply chain tactical management is the most essential of them because it is performed under the constraints imposed by strategic plans, and strictly affects operational decisions. Moreover, the tactical level is the most appropriate one for handling uncertainty, such as customer demand, lead time, etc. The application of mathematical modelling approaches, which operate with stochastic data, is not rational at the strategic level as the nature of stochastic data may vary dramatically during a long time horizon. Operational level provides more precise information about the system, so there is no need for applying stochastic modelling approaches. Moreover, the run time of stochastic models does not correspond to the operational time horizon.

Taking into account these considerations, a framework for supply chain tactical management has been elaborated, which includes simulation and modelling approaches as the main elements for providing mathematically grounded decision making.

D. Supply Chain Tactical Management Framework

The simulation-based supply chain tactical management framework is aimed at supporting mathematically based decision making in supply chain management over the tactical horizon by reasonable application of different modelling approaches with simulation as a basic element [9]. The framework is limited by tactical time horizon due to requirements to the run time of stochastic models (60-120 min.) and a number of model parameters. However, the elaborated framework can also be applied to strategic management tasks, as well if there is a rational number of parameters set up by stochastic data and time horizon.

The main idea of the simulation-based supply chain management framework is rational application of different mathematical modelling approaches, with simulation as a key one that allows realistic imitation of operation of the considered supply chain. Among models presented in publications related to supply chain management, the most popular are mathematical models. Besides, there are also descriptive models aimed at the analysis of supply chain processes and their interrelations. The elaborated framework includes mathematical models as the main element; however, it can use also descriptive models as a pre-analysis tool or a conceptual model for the simulation one. The framework is presented in Fig. 4.

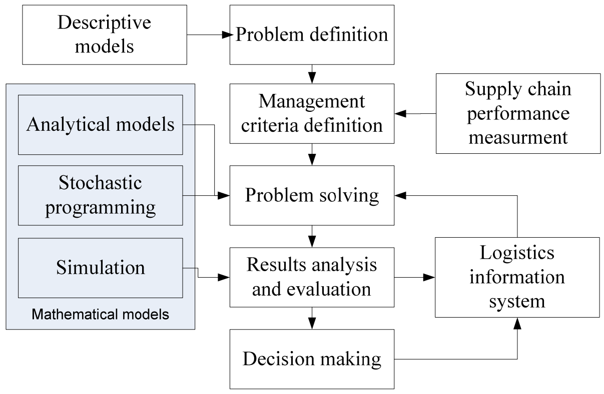

Fig. 4. Simulation-based supply chain tactical management framework

The formulation of supply chain tactical management problems is usually related to formulating and solving corresponding optimization tasks. Optimisation of supply chain performance is typically pursued around the goals of cost reduction, capital reduction, and service improvement. The most used in supply chain management optimisation technique for decision making under uncertainty is stochastic programming. The elaborated framework focuses on application of the stochastic programming scenario approach, as described in [9], [10]. This approach incorporates the following main steps: generating scenarios with regard to possible values of the involved random variables, replacing the original stochastic model by a set of deterministic models to be solved by mathematical programming methods, and deriving an overall (sub-optimal) solution that could be evaluated by simulation.

Finally, simulation allows testing the effect of alternative solutions obtained by optimization in order to select the most suitable one [11].

The elaborated simulation-based supply chain tactical management framework allows companies to perform mathematically based decision making and evaluate performance of their supply chains under changes produced by a stochastic environment they operate in. Practical value of the elaborated framework is demonstrated below in case studies performed for Latvian companies, which resulted in increasing their competitiveness within the European business market.

a) King Coffee Service: Supply Chain Inventory Management

The first case study is based on data from a Latvian company "King Coffee Service" that distributes coffee products in the Baltic countries [12]. It demonstrates how small companies may apply different modelling approaches to support tactical decision making while solving inventory management problems.

In the case study, several modelling approaches are applied, i.e., use of inventory analytical models, optimization models and a simulation model. An optimization model is created to calculate inventory control setting at all echelons in respect to minimizing the total supply chain costs, including both inventory costs and backlog costs. It allows verifying different inventory management approaches, for example, centralized and decentralized supply chain management, as well as testing different inventory control algorithms, e.g., with and without outsourcing.

A simulation model of the same supply chain was developed by means of Excel Spreadsheet. It allows estimating the supply chain performance under optimized inventory control parameters through the time horizon of one year. Based on simulation results, the following performance metrics are evaluated: service level, average inventory level, and system robustness with regard to service level.

b) Biosan Inventory Management

In the second case study, the developed framework does not require applying it in a holistic way. If analytical models are sufficient for solving a particular problem, they can be used instead of optimization models. The case study of a Biosan company is focused on the enhancement of the packaging department inventory management system. The conducted study applies inventory management analytical models (namely, "up to S" and "s-S" models) in order to calculate inventory control parameters. Then, both inventory management scenarios are verified by applying an Excel-based simulation model. It allows estimating the performance of the packaging department inventory system by such criteria as service level, average inventory level and backlogs. Applying the developed models, Biosan now is able to conduct a variety of "What if" analysis for company's needs.

c) Zepter Supply Chain Design

Although the developed simulation-based supply chain management framework addresses the tactical level, it can also be applied to solving strategic problems by simplifying some elements, as for example replacing customer stochastic demand by its average value. In this way, it is applied to solving a supply chain design problem at Zepter Baltic Company [13]. The problem is focused on developing and evaluating different supply chain scenarios. There are three alternative scenarios developed for Zepter Baltic supply chain: (1) centralized supply chain with a distribution centre in Riga (Latvia), (2) decentralized supply chain with three distribution centres in capitals of the Baltic region (Riga, Vilnius and Tallinn) and (3) centralized supply chain with a distribution centre located by means of a mathematical model, which implements the centre of gravity method. After elaborating the alternative scenarios for supply chain design, all of them were evaluated by means of a LORD simulation model. As a result, Zepter Baltic was able to perform mathematically based decision making regarding the supply chain design problem.

III. Enhanced Simulation-Based Technologies

Experiences in performing M&S application studies led to realizing the necessity of some methodological developments, aimed to enhance the power of the simulation-based approach. The subsequent sections provide an overview of research results in the developments within simulation-based methodologies that integrate simulation with other scientific approaches to analysis, optimisation and management of complex systems.

A. Simulation-Based Optimization

A typical task of simulation-based studies is operation improvement of a considered system in terms of finding such combination of its parameter values that provide the best (in the defined sense) operation of the system. For instance, this could be a tuning task for inventory policy parameters (i.e., s and S levels in the s-S policy) in the above-mentioned supply chain tactical management problem. Thus, an optimization problem arises that asks for combining an optimization algorithm with a simulation model that is used for evaluating solutions, received at each step of the iterative optimization procedure. Such a problem is defined as a simulation-based optimization problem.

Simulation-based optimization studies have been performed at RTU DMS since early 1990-ies, starting with the development of a two-stage simulation-based optimization algorithm [14] and proposing an interval approach to simulation-based optimization [15]. The main idea of the two-stage algorithm is to divide the optimization procedure into two steps. At the first stage, random variables of the simulation model are substituted by their average values, thus receiving a deterministic model that is optimized using traditional optimization methods. At the second stage, the original stochastic simulation model is optimized using appropriate optimization methods [16], starting with a solution found at the 1st stage. A knowledge-based support system could be used for back searching for a suitable optimization method [17], [18]. The two-stage algorithm allows decreasing computational efforts necessary to find a feasible solution of the optimization problem [19], [20]. The interval approach to simulation-based optimization takes into account interval uncertainty of stochastic factors, defined in the simulation model (e.g., in terms of their confidential intervals). As a result, the optimization problem could be solved with regard to the worst possible case; it is important, for instance, in risk-related studies.

Modern developments in the area of computational hardware and software, as well as the appearance of advanced optimization methods and algorithms have affected further directions of simulation-based optimization research at RTU DMS that are led by prof. G. Merkuryeva and allowed using more computation-consuming approaches. Recent research in this area is based on exploring the concept of simulation metamodelling. In particular, a simulation-based optimization environment for solving supply chain tactical management problems was proposed in [21]. Generally, a metamodel is defined as a model that reflects another model. In the case of simulation, a metamodel is constructed by processing results of simulation experiments and therefore is called “simulation metamodel”. Different types of mathematical models could be used for this aim, e.g., those based on the response surface methodology (RSM) or on the neural network approach. Using a simulation metamodel within the optimization procedure provides an essential decrease in computational efforts, as in the most of its iterations the values of an objective function are calculated by employing the metamodel instead of running the simulation model each time.

Different architectures could be used while implementing simulation metamodel-based optimization. In the simplest case, there is just one circuit with a simulation metamodel applied to evaluating the results of optimization iterations. In more complicated designs, several optimization circuits are combined. For instance, a sequential hybridization scheme is used in [22] to tune supply chain parameters (namely, lengths of production cycles and order-up-to levels at different echelons). Here two optimization circuits are sequentially connected. In the first circuit, a global search optimization is performed by applying a meta-heuristic (in that particular case, a multi-objective genetic algorithm has been used) that deals with a simulation model itself. In this case, the optimization algorithm is aimed at exploring a search space, providing a Pareto-optimal front which defines a set of non-dominated solutions. In the second circuit, those solutions are improved by applying a simulation metamodel-based local search optimization, aimed at the careful analysis of the explored area. In the referenced research, an RSM-based simulation metamodel was used.

B. Simulation and Visualization of Combined Systems

In simulation-based studies, visualization is of significant importance. More specifically, it supports model validation, analysis of modelled system operation, and simulation-based education and training. In order to enhance visualization capabilities in simulation, an integrated approach to simulation and visualization of combined systems that incorporate both discrete-event and continuous ones, was developed at RTU DMS [23], [24]. It extends the discrete-event simulation specification (DEVS) that is intended for specifying dynamics of discrete-event systems. On that basis, a visual extension of DEVS was developed under the name “V-DEVS”. It supports 2D/3D visualization of simulation models, allows simulation of combined systems, as well as provides an interactive interface to the simulation model that enables communication with it during simulation runs. The last feature is especially important for performing verification and validation steps of model building (see Fig. 1). The V-DEVS formalism provides a seamless component-oriented coupling and synchronization of simulation processes, user interaction and visualization. Its implementation architecture is presented in Fig. 5. A visualization example of an automotive manufacturing system in Fig. 6 was developed with the V-DEVS simulation prototype. Here the simulated system includes a conveyer (a continuous subsystem) and assembling stations (discrete subsystems).

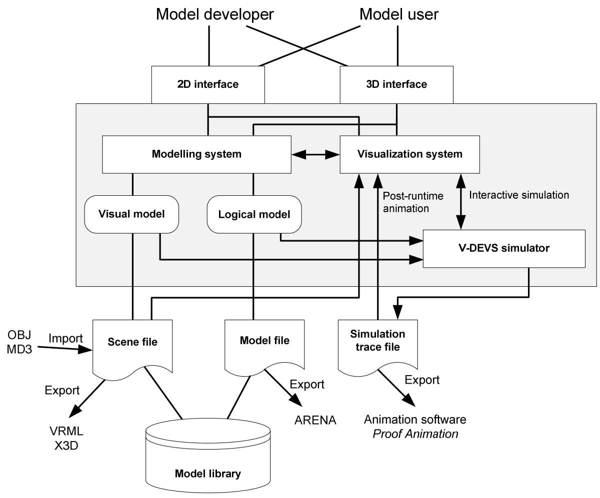

Fig. 5. Implementation architecture of V-DEVS visual simulation environment

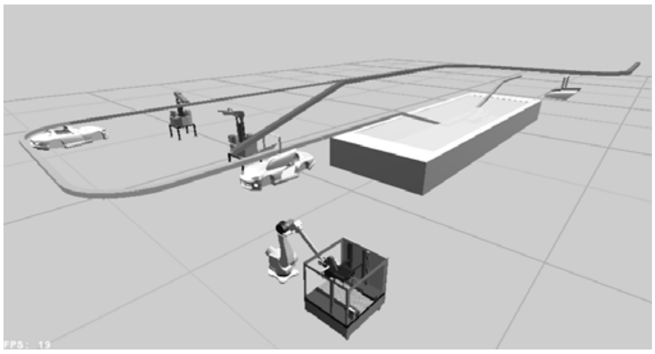

Fig. 6. Sample model in V-DEVS visual simulation environment

C. Simulation-Based Risk Management

Operation of complex systems is typically subjected to risks of various critical and even dangerous situations. The M&S approach provides rich possibilities for risk management, e.g., while analysing potential risks or taking decisions on decreasing their negative consequences.

The following is a brief summary of research results in the field of simulation-supported risk management in three different areas, namely, information technology, supply chains and agriculture.

a) IT risk assessment

A domain specific simulation language (DSSL) for assessment of IT risks was developed [25]. It allows the analysis of potential company’s IT risks like hardware failure, poor backup solution, communication channel interruption, insufficient access control, lack of competence, etc. The DSSL is designed by unifying possibilities provided by the following technologies: Unified Modelling Language (UML), Misuse Case Alignment Method (MSAM), and a security risk modelling, analysis and documentation language CORAS. Here the UML provides describing the analysed information system (in terms of Use Case and Activity diagrams), MSAM supports analysing IT risk management problems (by extending UML Use Case diagrams), while CORAS is used for completing the IT risk analysis scope (by means of its Treatment diagram that includes a number of risk analysis entities).

In order to extend possibilities of UML to describing dynamics of modelled systems, it is proposed in [26] to allow transformation of ULM models into a simulation environment; in particular, the ARENA simulation environment is considered in the paper.

For testing the proposed approach to IT risk assessment, a tool prototype was developed on the basis of Microsoft Visualization and Modelling SDK. The implemented modelling tool is functioning inside Microsoft Visual Studio Shell [25]. An example of a dialog window of the tool prototype is depicted in Fig. 7.

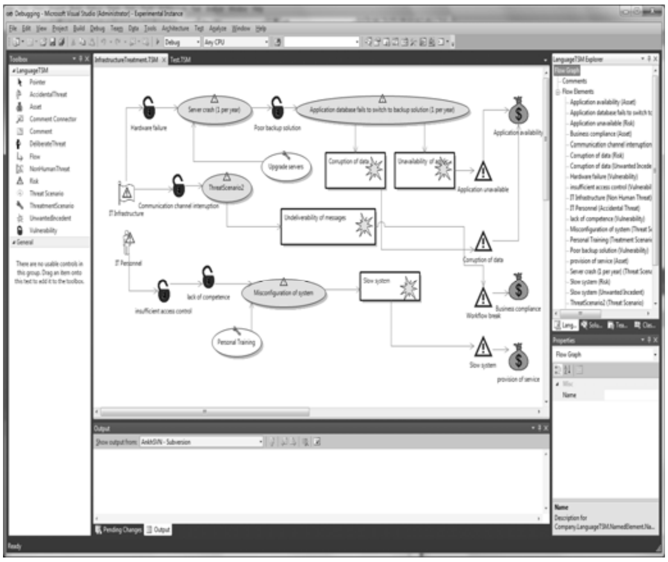

Fig. 7. Dialog window of the IT risk analysis tool

b) Supply Chain Risk Management

A theoretical framework of supply chain risk management is proposed in [27], [28]. Within this framework, risks are determined by possible disruptions (for instance, delivery failure by a supplier) that affect supply chain ability to function normally. In that sense, a risk analysis framework should consist of techniques for the study of fluctuations in supply chains with different structural abilities and in various cases of disruption. Thus, supply chain performance parameters (e.g., delivery reliability, flexibility, profitability, etc.) are taken as the basis for the risk management system. Correspondingly, supply chain reliability parameters and performance fluctuations are studied in order to manage risks.

In the proposed framework, simulation is used as a supply chain performance measurement tool that provides possibilities for disruption analysis and risk evaluation (see Fig. 8). The use of simulation permits conduction of this analysis for supply chains with different structural parameters. Hence, simulation models constitute a risk mitigation support tool which is necessary for effective supply chain management under risk and uncertainty.

The implementation of the proposed approach to supply chain risk management is illustrated in [28] for a sample three-echelon supply chain with backordering.

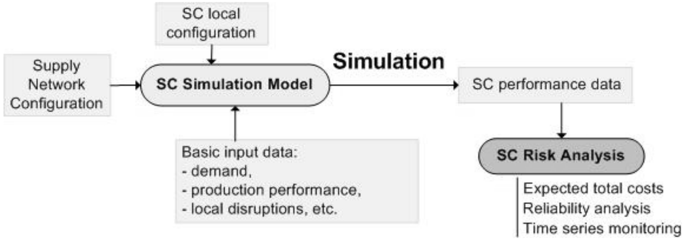

Fig. 8. Simulation role in the supply chain risk management framework

c) Agricultural Risk Management

In the area of agricultural risks, the performed research is aimed at analysing the influence of environmental uncertainty on efficiency of agricultural operations. A methodology to analyse farmers' strategies under uncertainty of the environment (in particular, weather conditions) was developed [29], [30]. For this aim, a concept of an agricultural function was introduced. It defines an average yield value for a particular agricultural crop, in function of a time moment when the agricultural operation (e.g., sowing) was started. An example of the agricultural function is shown in Fig. 9.

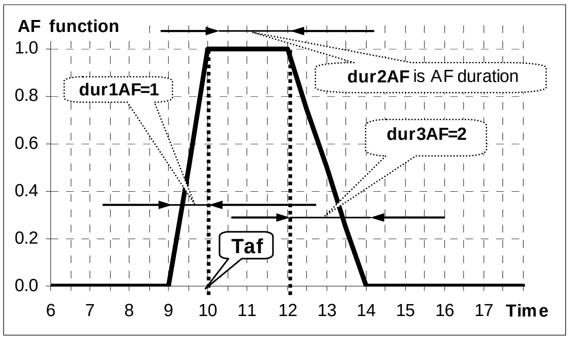

Fig. 9. Sample agricultural function

The environmental uncertainty is described in the agricultural function by defining its parameters; in particular, the length of a period of the maximal value and its beginning (denoted as Taf in Fig. 9) as equally distributed random variables.

A farmer's strategy is defined in terms of a starting moment of the operation and its intensity (i.e., how many days it will take to complete the operation). The efficiency of different strategies is evaluated by use of simulation that provides collecting statistical information (i.e., average, minimal and maximal values) of the expected yield.

By analysing simulation results, a farmer could estimate results of different strategies. For instance, it was found that in case of essential uncertainty of agricultural function parameters, in order to expect a stable average yield (which will be relatively low in this case), a farmer should start the operation earlier and work with a smaller intensity. The analysis of different farming strategies from the point of view of different decision making criteria (e.g., Laplace, maximax and Wild criteria) is discussed in [31].

The results of the research could also be used in other fields that allow analogical interpretation of performed actions and their results, for instance, in the analysis of investments.

IV. Simulation Implementation

Experiences gained within the implementation of research projects combine the application of the already discussed results with performing the investigations that were initiated by needs of particular projects. The following is an overview of research results achieved in response to such practical requirements.

A. Supply Chain Modelling and Simulation Environment

In this section, developments within a European research project ECLIPS (that stands for “Extended Collaborative Integrated Life Cycle Supply Chain Planning System”, 2006-2009) are discussed [22], [32]. This project addressed the state of the art in supply chain management. Six partners from Belgium, Czech Republic, Germany, France and Latvia (RTU DMS), representing the industrial, academic and consultancy sectors, have worked together on this project, including two industrial partners: a German company Huntsman and a Czech company PLIVA-Lachema Diagnostika. The main research subjects of the project were related to the minimisation of overall supply chain inventories during different phases of the life-cycle of a product, from introduction of a new product to the market, through the maturity phase, and up to leaving the market for out-dated products. For this aim, the advanced supply chain management approach was developed, which was based on the idea of cyclic planning of supply chain processes.

Simulation has been extensively used in the ECLIPS project in order to support different stages of project implementation, namely, to back up decision making and optimization processes (for instance, while performing simulation-based optimization of supply chain management parameters during the maturity phase), to validate developed algorithms and train in their practical application, as well s demonstrate the efficiency of the developed approach to its potential users.

During project implementation, the necessity for developing an approach to support supply chain simulation was realized. In response to this need, the methodology of multi-echelon supply chain modelling and simulation, as well as environment for its realization, were developed. A short overview of the developed simulation methodology is provided below [22].

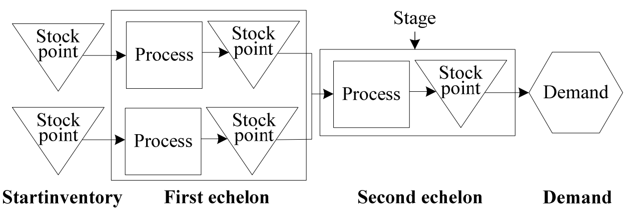

Fig. 10. Sample supply chain conceptual model

The simulation process starts with developing a conceptual model of the considered supply chain that is designed as a process oriented model with one-directional flow of goods. It is presented by two types of atomic elements: (1) stock points and (2) processes that are graphically represented by triangles and rectangles, correspondingly (see Fig. 10).

The stock points correspond to stock keeping units (e.g., buffer or storage), while processes denote transformation activities (assembly, packing and transportation operations). The processes and stock points are grouped in stages. A set of stages that belong to the same supply chain network level creates an echelon. Input parameters, decision variables and constraints are assigned to atomic elements. Different combinations of process-stock points or sub-networks such as linear, convergent and divergent ones are linked to form a network. The replenishment and delivery logic for each sub-network is defined. If stock points stand for multiple products located at the same site, they can be grouped together in one container (the same goes for the processes), where stock points inside stock containers are controlled by inventory planning policies, while processes inside process containers are based on a bill of materials.

The supply chain network topology is represented as a matrix in the Excel worksheet (see the upper table in Fig. 11). Here rows and columns correspond to stock points, while cells assign the processes that connect a couple of “FROM” and “TO” stock points.

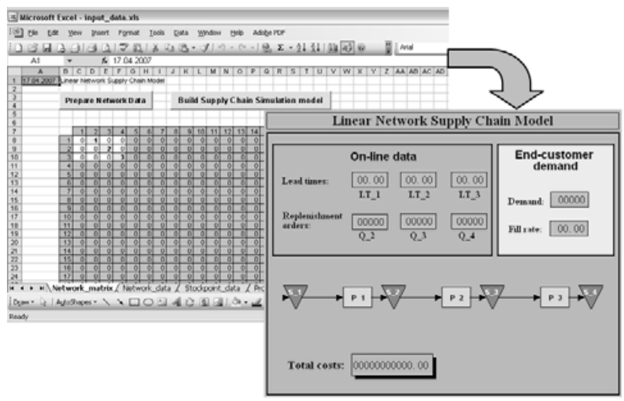

Fig. 11. Generation of a supply chain simulation model

The supply chain modelling and simulation procedure comprises the following steps: (1) describing simulation input data (network topology, stock point data, process data, cost data and customer demand) and storing it in an external file; (2) automatically generating (see Fig. 11) and running the supply chain simulation model; 3) collecting simulation output data (performance measures) and storing it in an external file. To verify automatically generated supply chain models, chart-based tracing is used. In particular, a tracing table in the Excel worksheet calculates data that is compared with tracing results from the simulation model. An example of the resulting supply chain simulation model is shown in Fig. 12.

A simulation environment for implementing the described methodology was developed [22] in the ProModel simulation software using ProModel, MS Excel and VBA integration possibilities (see Fig. 13).

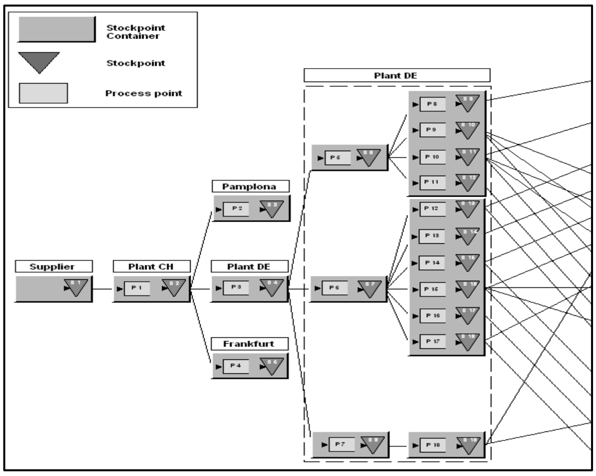

Fig. 12. Sample supply chain simulation model

It provides automatic generation of the simulation model of a generic network described in the Excel format by using the ProModel ActiveX technology, allows definition of an initial point for simulation optimization using analytical calculus, supports realization of a simulation-based optimization algorithm to find optimal parameters of a multi-echelon cyclic schedule and optimize network simulation model performance measures, as well as supports generating rules for switching from a cyclic policy to a non-cyclic and vice versa.

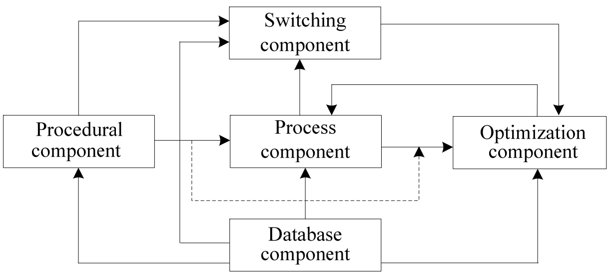

Fig. 13. Basic components of the simulation environment

Automation capability allows the program to automatically generate simulation models from external applications by using the VBA programming language. The ActiveX-based VBA program developed in MS Excel consists of subroutines that provide ProModel operational control and allows accessing the model information, i.e. loading a blank simulation model; definition of a model title, a path to a graphical library, an animation speed, the simulation length and number of replications; creating entities, locations of stock points and processes, path networks used to establish links between stock points and processes; creating arrays, variables, functions and procedures; and definition of entity arrival schedule, sequence of processes and their operational logic.

An example of using the described simulation environment for analysing a supply chain (that is partly presented in Fig. 12), used by the German industrial partner of the ECLIPS project, is given in [22]. Practical implementation of the developed supply chain management approach, based on the cyclic planning of supply chain processes, confirmed its efficiency for industries with batch and semi-batch processes, under a relatively stable demand pattern. Simulation experiments have demonstrated the possibility of the developed approach to provide decrease of overall supply chain inventories by up to 30% [33].

A simulation-based business game "ECLIPS game" was developed for teaching the elaborated supply chain management approach ([34], [35]). Here different supply chain structures could be designed by means of atomic models that represent various supply chain elements, e.g., a production facility, warehouse, transportation (by track or ship), distribution, retailer, customer demand (see Fig. 14). The developed ECLIPS game could be used for teaching different inventory management strategies in supply chains of different structures.

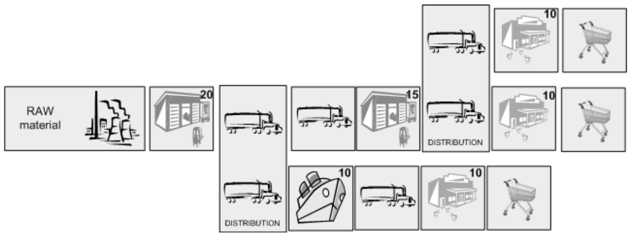

Fig. 14. Sample supply chain design in the ECLIPS game

B. Dynamic Management of LTS Sustainable Development

A project "Information Technology for Providing Sustainability of the Electrical Transmission Network and Generation" was implemented in the period 2006–2008 under the financial support from the European Regional Development Fund. It was aimed at developing information technology (IT) to support sustainable development of power systems, namely, electrical transmission networks and generation [36].

The developed IT "LDM-PG'08" has been worked out in cooperation with the Laboratory for Power System Mathematical Modelling of the Institute of Physical Energetics (IPE LPSMM). It incorporates methods and algorithms for the modelling and analysis of complex power systems, a methodology on their appropriate usage, as well as implementation software. Sustainable development of a particular power system is provided by taking into account technical, economical, environmental and reliability criteria, as well as uncertainty in its future evolution. The resulted data are aimed at supporting decision making on planning future development of the considered power system.

During project implementation, it was found that the developed approach and its IT implementation could be used not only for power systems; it is also applicable for providing sustainable development of various large technical systems (LTS). A brief overview of the developed approach to sustainable management of large technical systems is provided below [37].

As the first step, a dynamic model of the considered LTS is prepared. An example of the LTS model structure is given in Fig. 15 that could serve as a conceptual model for a simulation model; in particular, in case of a power system, "production" means "generation". Then, by taking into account different management plans (scenarios), as well as LTS dynamics and environmental uncertainties, a system development graph is prepared. Here nodes represent various states of the system that reflect influence of the above-mentioned impacts, while edges denote transitions between nodes as a result of corresponding management decisions (e.g., on planned investments, installation of new facilities or shutting the existing ones). An optimization problem is solved in this graph, aiming to find an optimal (in the sense of a formulated optimization criterion) sequence of management decisions, i.e., an optimal LTS development plan.

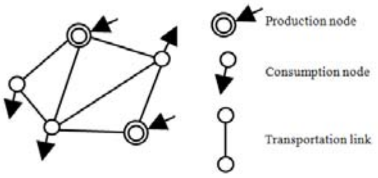

Fig. 15. Example of LTS model structure

The optimization is performed by using the method of optimal initial states (OIS method) that had been elaborated at IPE LPSMM. It is based on the concept of a “set of optimal initial states” that is a set of such initial states of the considered LTS, from which optimal transitions exit to any another state. Here optimal transitions are those that increase the value of the optimization criterion. An example of such a set that includes nodes ω(1), ω(2) and ω(3), is given in Fig. 16. The OIS method provides overcoming the “curse’ of Bellman’s dynamic programming method, where the increase in the number of variables is followed by the exponential growth of calculation time. It was found that the OIS method provides decreasing of the amount of stored data by keeping information only on calculated optimal initial states. In practice, it allows solving tasks on dynamic management of LTS sustainable development, when there are up to about 50 alternative scenarios, and for a time-period of up to 50 years.

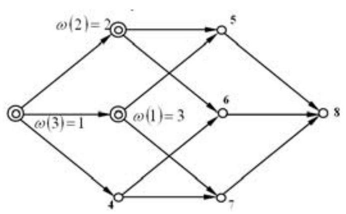

Fig. 16. Sample set of optimal initial states

The described optimization process typically results in about 10 development plans that are further evaluated by experts. For instance, the best development plan could be chosen by risk analysis methods, e.g., by minimizing the maximal risk R(i,j):

$$\max_{i \in \mu} R(i, j) \rightarrow \min_{j \in \nu} \tag{5}$$

where i – the number of a current forecast,
μ – the total number of forecasts,
j – the number of a current scenario,
ν – the total number of scenarios.

Here risk values are determined in accordance with specifics of a particular LTS. For example, they could be calculated as the increase in price for imported energy under different forecasts of world-wide energy prices (for power systems) or out-of-stock probability under different demand forecasts (for logistics systems).

C. Monitoring and Control of Complex Systems

The ongoing project ELRI-184 “Integrated Intelligent Platform for Monitoring the Cross-Border Natural-Technological Systems” (INFROM, 2012-2014) is carried out under the Estonia-Latvia-Russia cross-border cooperation Programme within ENPI (European Neighbourhood and Partnership Instrument) 2007-2013 [38]. It aims at developing an integrated platform for monitoring and control of natural and technological systems in cross-border areas of Latvia and Russia, based on heterogeneous data received from both ground-based and space information sources (see Fig. 17).

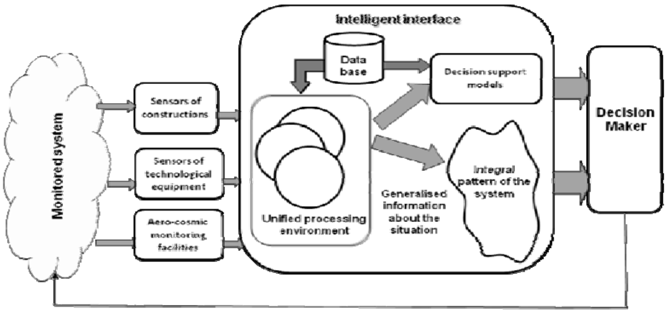

Fig. 17. Integrated monitoring and control environment

Processing data from ground-based (e.g., installed on technological equipment or civil engineering constructions) and space (e.g., aerospace pictures, - in various ranges, including visible and infrared ones, - and radar data, received from Earth satellites) information sources allows obtaining an integral pattern of the monitored system. Comparing information about the actual state of the monitored system with its forecasted state serves as the basis for making decisions on control actions, aimed at bringing the system into a desirable state. For instance, these could be decisions on preventing measures to avoid a fire if the increase in temperature has been observed for some fire-critical objects (e.g., chemical cargo or tank with a transported fuel).

Dealing with an integral pattern of the monitored system asks for a modelling approach that supports description of the considered system from various points of view. Thus, the necessity for multi-model complexes arises where different classes of models are used for reflecting different aspects of system operation, e.g., combined analytical–simulation models, logical-algebraic models, etc. [39]. In such complexes, a problem of coordinating information that comes from various models should be considered. In particular, there should be possibilities for quality analysis of different models and justified selection of particular models for a multi-model complex. On the other hand, the information fusion problem should be taken into account that means fusion of information which is provided by different models.

An approach dealing with the above-mentioned range of problems is called "qualimetry of models". Its methodological aspects are discussed in [39]. In particular, the importance of model properties for the conceptual basis of the qualimetry of models is emphasized. The following properties are considered in this regard: adequacy (including both qualitative adequacy and quantitative adequacy), simplicity, flexibility (adaptability), task orientation and universality, reliability, openness and accessibility, intelligence, efficiency of computer implementation, identifiability, stability, sensibility, observability, self-organization and self-learning.

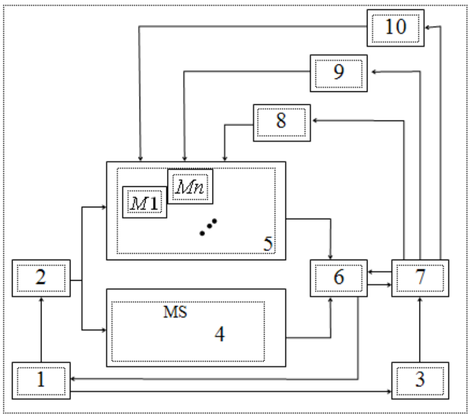

Fig. 18. Generalized approach to analysing the quality of models

Let us assume that the modelled system allows conducting experiments and obtaining values of some characteristics by measurements. All technical systems and complexes working in an autonomous mode are examples of such systems. On the contrary, large-scale economic and social systems, as well as complex technical systems, which operate under essential uncertainty, do not belong to this class of systems; a human factor plays an important role in these systems. A general approach to analysing the quality of models of the assumed class of systems is given in Fig. 18. Here, the following steps and elements are included: 1 – defining functioning goals of the modelled system; 2 – determining input actions; 3 – setting modelling goals; 4 – the modelled system itself; 5 – particular models of the considered multi-model complex; 6 – estimation of the model quality; 7 – controlling the model quality; 8 – correcting model parameters; 9 – correcting model structure; 10 – changing model concept.

The discussed considerations reflect initial steps toward the elaboration of methodological and implementation aspects of the qualimetry of models within the INFROM project. The research in that direction is foreseen to be continued.

V. LIST OF RESEARCH PROJECTS

The reviewed research results have been used and are further developed in the following European and national projects:

Programmes of the European Commission:

1. IST-2000 Accompanying Measure IST-2001-33030 BALTPORTS-IT "Simulation and IT-solutions: Applications in the Baltic Port Areas of the Newly Associated States" (2001-2003)
2. Leonardo da Vinci pilot project LV-PP-138.003 LOGIS "Long-Distance Tutorial Network in "Logistics Information Systems" Based on WEB Technologies" (2000-2002)
3. Leonardo da Vinci pilot project 2004-LV/04/B/F/PP-172.013 LOGIS-MOBILE "Competence Framework for Mobile On-site Accelerated Vocational Training in Logistics Information Systems" (2004-2006)
4. Leonardo da Vinci pilot project PP-172.00 SocSimNet "Competence Network for Introduction of Modern ICTE Technologies in Vocational Learning in Social Systems Simulation and Research" (2004-2006)
5. IST-2004 Coordinated Action 511285 ELOGMAR-M "Web-Based and Mobile Solutions for Collaborative Work Environment with Logistics and Maritime Applications" (2004-2006)
6. Specific targeted research project NMP-032378 ECLIPS "Extended Collaborative Integrated Life Cycle Supply Chain Planning System" (2006-2009)
7. No. ELRI-184 INFROM "Integrated Intelligent Platform for Monitoring the Cross-Border Natural-Technological Systems" of the Estonia – Latvia – Russia Cross Border Cooperation Programme within European Neighbourhood and Partnership Instrument 2007-2013 (2012-2014)

National programmes:

8. Latvian Council of Science (LCS) project No. 01.0864 "Development and Application of Simulation-Based Tools for Analysis and Optimisation of Logistics Systems" (2001-2004)
9. LCS project No. 05.1653 "Development and Implementation of Simulation-Supported Training Methodology in Logistics Based on Case-Studies and Business Games" (2005-2008)
10. LCS project No. 09.1201 "Simulation-Based Optimisation Using Computational Intelligence" (2009)
11. LCS project No. 09.1564 "Simulation and Computational Intelligence Methods for Logistics and e-Business Optimization" (2010-2012)
12. LCS cooperation project No. 02.0016 "Risk Factors, Risk Assessment and Risk Management in Latvian Agriculture" (2002-2005)
13. LCS cooperation project No. 0040.1.4 "Agricultural Risk and Crisis Management Systems in Latvia" (2006-2009)
14. ERAF project No. VPD1/ERAF/CFLA/05/APK/2.5.1./000014/P "Information Technology for Providing Sustainability of the Electrical Transmission Network and Generation" (2006-2008)
15. Ministry of Education and Science of the Republic of Latvia project No. R7384 "Information Technology Governance: Research of Operational IT Risks in Financial Institutions" (2008)
16. RTU project No. ZP-2008/6 "Development of IT Risk Multilingual Management Portal" (2008-2009)
17. RTU project No. FLPP-2010/17 "Functional Modelling of IT Risk Assessment Support System" (2010)

18. RTU project No. FLPP-2011/7 "Concept Elaboration for Development of the Kipsala complex of RTU" (2011)

The research results have been reported at many international conferences, congresses, symposia and workshops.

Conclusions

Modelling and simulation provide the basis for efficient solving of various problems related to the operation of complex systems like analysis, optimization and management, etc. In integrated M&S methodologies, modelling and simulation are incorporated with other scientific approaches, aimed at the analysis, design and operation improvement of complex systems. The reviewed research in M&S area, in its turn, is directed towards enhancing methodological support for performing particular steps of the M&S procedure (like strategic planning of simulation experiments (through simulation-based optimization) and validation of simulation models (through enhancing visualization capabilities)). At the same time, the reviewed developments have been initiated by experiences in performing numerous simulation-based projects (e.g., development of the supply chain M&S environment, and research in the area of dynamic management of sustainable development of large technical systems).

Future research directions include further development of M&S methodological and implementation aspects, in particular (but not limited to), along the following lines: qualimetry of models; simulation-based sustainable management of complex systems, optimization and planning, and risk management; geosimulation (i.e., enhancing the simulation approach by possibilities provided by geographical information systems); knowledge-based M&S.

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Jurijs Merkurjevs. Sarežģītu sistēmu modelēšanas un simulēšanas metodoloģija un prakse. Pārskata raksts

Dažādus ar sarežģītu sistēmu darbību saistītus uzdevumus var sekmīgi atrisināt, izmantojot modelēšanu un simulēšanu, piemēram, tas attiecas uz šo sistēmu analīzes, optimizācijas un vadības uzdevumiem. Rakstā ir apkopoti pēdējo gadu pētījumu rezultāti sarežģītu sistēmu modelēšanas un simulēšanas jomā, kas ir veikti Rīgas Tehniskās universitātes Modelēšanas un imitācijas katedrā profesora, Latvijas Zinātņu akadēmijas korespondētājlocekļa Dr.habil.sc.ing. Jurija Merkurjeva (Yuri Merkuryev) vadībā. Apskatītie pētījumi, no vienas puses, nodrošina metodoloģisko atbalstu atsevišķu imitācijas modelēšanas procedūras posmu īstenošanai. Tai pašā laikā to aktualitāte izriet no vairāku ar imitācijas modelēšanu saistītu projektu īstenošanas pieredzes. Galvenais akcents ir likts uz ar integrētu modelēšanas metodoloģiju saistītiem pētījumiem, kas apvieno imitācijas modelēšanu ar citām zinātniskām pieejām sarežģītu sistēmu analīzei, optimizācijai un vadībai, un to rezultātu pielietošanu dažādās sfērās, īpašu uzmanību pievēršot loģistikas sistēmām. Proti, tiek apspriestas šādas ar imitācijas modelēšanu saistītas pieejas: imitācijas modelēšanā sakņota optimizācija, riska vadība (ar pielietojumu informācijas tehnoloģijā, piegādes ķēžu vadībā un lauksaimniecībā), kā arī kombinētu sistēmu imitācijas modelēšana un vizualizēšana. Loģistikas jomā ir apskatīti šādi jautājumi: imitācijas modelēšanas pielietošana loģistikas problēmu risināšanai; piegādes ķēžu dinamikas analīze, pielietojot analītiskās un imitācijas modelēšanas metodes; piegādes ķēžu taktiskās vadības ietvara izstrāde, demonstrējot tā efektivitāti uz uzņēmumu „King Coffee Services", "Biosan" un "Zepter" piemēriem. Pārskatot pētījumus, kas saistīti ar konkrētu projektu īstenošanu, ir aplūkoti šādi darba virzieni: piegādes ķēžu imitācijas modelēšanas vides izstrāde, lielu tehnisko sistēmu ilgtspējīgas attīstības dinamiskā vadība, sarežģītu sistēmu darbības monitorings un vadība. Nobeigumā tiek apspriesti turpmāko pētījumu virzieni.

Юрий Меркурьев. Методология и практика моделирования и имитации сложных систем. Обзорная статья

Имитационное моделирование предоставляет широкие возможности для решения различных задач, связанных с функционированием сложных систем, в частности, задач по анализу, оптимизации и управлению такими системами. В статье обобщены результаты исследований последних лет в области имитационного моделирования сложных систем, выполненных на кафедре имитационного моделирования Рижского технического университета под руководством члена-корреспондента Латвийской академии наук, хабилитированного доктора инженерных наук, профессора Юрия Анатольевича Меркурьева. Рассматриваемые в статье исследования, будучи мотивированными участием в выполнении многочисленных научных проектов, направлены на обеспечение методологической поддержки отдельных этапов процедуры имитационного моделирования. Основное внимание уделено исследованиям, связанным с интегрированной методологией моделирования, объединяющей имитационное моделирование с другими научными подходами к анализу, оптимизации и управлению сложными системами, а также результатам их практического применения, в частности, на примере логистических систем. При этом рассматриваются следующие подходы на базе имитационного моделирования: оптимизация, управление рисками (с приложением в областях информационных технологий, управления цепями поставок и сельского хозяйства), а также визуализация комбинированных систем. Применительно к логистическим системам рассматриваются следующие вопросы: использование имитационного моделирования при решении логистических задач; анализ динамики цепей поставок с использованием аналитического подхода и имитационного моделирования; тактическое управление цепями поставок, с демонстрацией полученных результатов на примере компаний „King Coffee Services", "Biosan" и "Zepter". При рассмотрении результатов исследований, выполненных в рамках конкретных проектов, обсуждаются такие вопросы, как разработка среды имитационного моделирования цепей поставок, динамическое управление устойчивым развитием больших технических систем, мониторинг и управление сложными системами. В заключение обсуждаются основные направления дальнейших исследований.