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MODELLING-BASED MULTI ECHELON SUPPLY CHAIN TACTICAL MANAGEMENT

Summary of Doctoral Thesis

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DOCTORAL THESIS
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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.

Oksana Soshko …………………………….(Signature)

Date: ………………………

The doctoral thesis is written in Latvian. It consists of introduction, 4 sections, conclusions, bibliography and 11 appendixes. It includes 48 figures and 36 tables. The thesis is printed on 145 pages. The bibliography comprises 130 entries.

GENERAL DESCRIPTION OF THE THESIS

Introduction and topicality

In spite of the variety of approaches, methods and tools available, a challenge of effective scientific methods application to supply chain management still remains vital. Moreover, due to limited financial potential, this issue is highly important for small and medium-sized companies, which are dominant in Latvian business. The necessity of systematisation of methods and tools for supply chain management is an important issue to ensure mathematically based decision making thus increasing competitive strengths of companies. The additional requirement for such methods is related to the ability of handling uncertainty which is a permanent factor in supply chain management tasks. And finally, the requirement coming from logistics companies' managers is related to simplicity of the methods to be applied as usually the complexity of scientific methods does not allow them to be implemented in solving real-life problems.

This research is focused on the application of modelling and simulation methods to solving supply chain tactical management problems in order to provide mathematics-based decision making in multi echelon supply chain management under uncertainty of both demand and lead time, which are main stochastic parameters in supply chain tactical management.

In particular, in the doctoral thesis multi echelon supply chain inventory management problem is solved as a common task of supply chain tactical management. The goal of this task is to ensure stochastic demand of supply chain end-consumer within minimum overall supply chain costs by spreading the inventory among all supply chain echelons. This allows achieving effective inventory management by decreasing safety stocks and bullwhip effect in supply chain.

Nowadays, the effective multi echelon supply chain inventory management preconditions are related to the application of information technology achievements and supply chain information systems expansion. Effective multi echelon supply chain management requires application of optimisation and simulation model development, which extend the functionality of existing information system with new analytical capabilities. Moreover, multi echelon supply chain inventory management involves an application of optimisation methods because traditional inventory management methods and control algorithms are developed for single echelon inventory management and therefore are not effective for multi echelon supply chain inventory management, especially with uncertain parameters. Due to the stochastic nature of customer demand value and order lead time, the main focus in the thesis is put on the stochastic optimisation scenario approach, which presents stochastic values by means of scenario trees.

The goal and the tasks of the thesis

The goal of the thesis is to develop an approach to simulation-based multi echelon supply chain tactical management. To achieve the goal, the following tasks are defined to be done:

1. To analyse supply chain management parameters, development trends and supply chain information systems functionality.
2. To study the application of different simulation and modelling approaches in supply chain management.
3. To formulate a simulation-based supply chain management approach.
4. To implement the simulation-based supply chain management approach to multi echelon supply chain inventory management task.
5. To develop multi echelon supply chain inventory management models with stochastic demand and lead-time.
6. To perform an approbation of the developed approach.

Thesis to be defended

1. Application of the stochastic programming scenario approach to supply chain inventory management task with stochastic demand.
2. Multi echelon supply chain optimization models for inventory management task.
3. Application of the stochastic programming scenario approach to multi echelon supply chain inventory management tasks allows solving inventory problems with stochastic parameters for tactical planning time horizon.

The research object and subject

The object of the doctoral thesis is multi echelon supply chain management under stochastic demand. The subject of the thesis is an inventory management task in a multi echelon supply chain with stochastic parameters. Following are a limitation and simplification of the conducted research:

1. The developed approach is approbated for single product inventory models.
2. The developed models are not related to stochastic control and random search methods.

The research methods

The theoretical background of the doctoral thesis in the context of supply chain management is based on a variety of fundamental works, including such logistics experts as *R. Ballou*, *M. Christopher*, *D. Simchi-Levi*, as well as Latvian researchers and experts *Sprancmanis N.*, *Krūmiņš N.*, *Grabis J.*, *Praude V.*, *Beļčikovs*, *Gringlazs L.*, *Kopitovs J.* The fundamentals of simulation and optimization modelling techniques are based on publications of *S. Robinson*, *J. R. Birgs*, *Nico Di Domenica*, and *A. Shapiro*. The theoretical research is based on an analysis of specific and professional literature and scientific papers.

Practical experiments include application of simulation approach and stochastic programming. For modelling stochastic parameters of the supply chain, the scenario generation approach is applied as well as mathematical statistics and probability theory methods. Supply chain tactical management tasks are solved using operation research methods, including inventory control algorithms.

The scientific novelty

The scientific novelty is as follows:

1. The developed approach to simulation-based multi echelon supply chain tactical management.
2. The application of the developed approach to multi echelon supply chain inventory tactical management allows avoiding the necessity to express customer demand and lead team in form of normal distribution which is not always possible by presenting stochastic parameters as scenario tree.
3. Application of the sample average approximation method to supply chain simulation model allows evaluating in one procedure both optimisation results and system performance under optimized parameters.

During the research, some intermediate results are obtained regarding to supply chain inventory control optimisation model development, application and analysis: application of the sample average approximation method for evaluation of optimization solution is simplified by means of spreadsheets; the multi-criteria comparative analysis of different inventory control algorithms for multi echelon supply chain is performed, different scenario tree generation methods are analysed in order to find the most appropriate ones for the actual problem.

Research practical value and approbation

The practical value of the doctoral thesis is related to the developed approach and models, which promotes mathematically based decision making in supply chain management strategic and tactical planning levels by this minimizing logistics costs and improving supply chain business processes.

The developed models are implemented in several real-life case studies. Optimisation and simulation models for distribution centre location problem are developed for "Zepter International AG" company. Based on this research, the academic case study is elaborated and published in „Application in Retail: Locating a Distribution Center. Supply Chain Configuration: Concepts, Solutions, and Applications" Ed. by J. Grabis and Charu Chandra (Springer, 2007. p. 303-333). Besides, the key elements of the developed simulation-based approach to inventory management are implemented at companies „*Biosan*" and „*King Coffee Service*"; the results of the last are presented at RTU 52nd International Scientific Conference (2010). Both companies provided a positive feedback regarding the achieved results. Moreover, the advantages of simulation-based decision making in supply chain management are discussed in a workshop "Joint logistics decision – better or as usually?" (organized by

Investment and Development Agency of Latvia, Seminar chair N. Krumins, logistics expert, 10.06.2010).

The results and developments of the doctoral thesis are used for practical lessons in the following study courses: “Supply chain management” and “Logistics systems’ optimization” (responsible lecturer is prof. Y. Merkuryev), as well as „Logistics information systems” and „Information system modelling tools” (responsible lecturer is assoc. prof. A. Romanovs).

Scientific conferences and workshops

The results of the doctoral thesis are presented at 11 scientific conferences: RTU 53rd International Scientific Conference (Latvia, 2012), RTU 52nd International Scientific Conference (Latvia, 2011), RTU 51st International Scientific Conference (Latvia, 2010), RTU 50th International Scientific conference (Latvia, 2010), 6th EUROSIM Congress on Modelling and Simulation” (Slovenia, 2007), 5th International Conference on Operational Research: Simulation and Optimization in Business and Industry” (Estonia, 2006), RTU 47th International Scientific Conference (Latvia, 2005), 11th International Power Electronics and Motion Control Conference” (Latvia, 2005), RTU 46th International Scientific Conference (Latvia, 2004), International Conference „Harbour, Maritime and Multimodal Logistics Modelling & Simulation” (Latvia, 2003), International Conference “Traditions and Innovations in Sustainable Development of Society” (Latvia, 2002).

List of publications

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The structure of the thesis

The doctoral thesis is written in Latvian. It consists of introduction, 4 sections, conclusions, bibliography and 11 appendixes. It includes 48 figures and 36 tables. The thesis is printed on 145 pages. The bibliography comprises 130 entries. The structure of the thesis is as follows.

Introduction describes the topicality of the doctoral thesis, defines a goal of the thesis as well as describes tasks, research methods and novelty of the thesis. It presents the object and subject of the research and discusses the results obtained. C**hapter 1, "Supply chain tactical management"** focuses on the analysis of supply chains management tasks. Supply chain management parameters are analysed, as well as functionality of logistics information systems. **In Chapter 2, "Analysis of modelling approaches in supply chain management tasks"** an analysis of application of different modelling approaches to supply chain management is performed. **Chapter 3, "Simulation-based approach for multi echelon supply chain tactical management"** is aimed at describing conceptually the developed approach and its application to multi echelon supply chain inventory management problem. **Chapter 4**, **"Application of the simulation-based approach in Latvian companies"** describes case studies on the application of the developed approach and its elements in the companies. Finally, conclusions of the doctoral thesis provide a list of results and findings of the research, as well as define directions of future research. The thesis ends with the list of references and annexes.

A SUMMARY OF THE THESIS CHAPTERS

Chapter 1, "Supply chain tactical management" introduces to the topics of the research. A particular focus is on multi echelon supply chain management. The chapter provides explanations of the main terms of the research. At the end of the chapter, the functionality of supply chain management systems is analysed.

Multi echelon supply chain management

There are two approaches to defining supply chain: object and process approaches. In traditional way, a supply chain is defined from the object point of view as a system with complex structure, which consists of several geographically spread facilities and distribution channels which ensure processes of end customer service. In the context of process approach, supply chain is an integration of several processes like supply, planning, stocking, transportation, service, demand planning, supply and delivery planning, supply management etc. [LAM 2000, BOC 2008]. For each supply chain this set of processes is different, however they can be divided into main processes which are inherent for each supply chain (for example, customer service and transportation) and specific processes. The analysis of the definition of supply chain allows concluding that applying the process approach to definition of supply chain management is more perspective as it ensures integration of supply chain planning and management, as well as promotes outsourcing.

A general supply chain consists of suppliers, which are the beginning of the suppliers, manufactures, warehouses and consumers (called a customer or buyer), which are at the end of supply chain. End customers initiate all process in supply chain by submitting demand to distribution centres or retail shops, which forward information through the supply chain to suppliers of raw material.

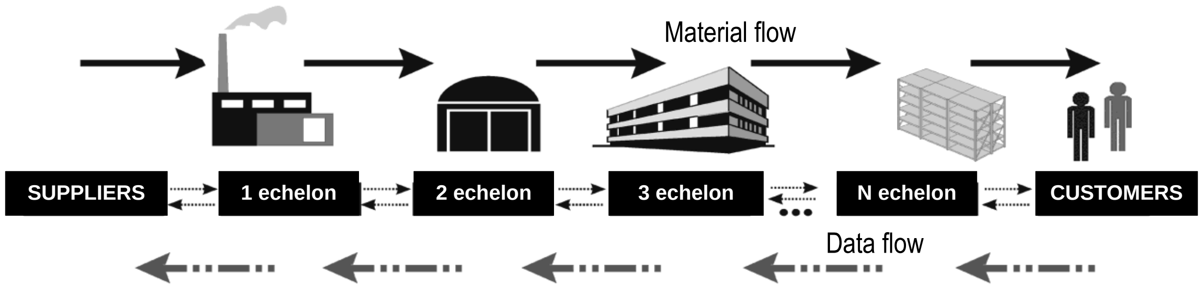


Fig. 1. Multi echelon supply chain

All supply chain facilities where inventory is held on its way to the end customer are called echelons; so a supply chain consisting of many echelons is called a multi echelon supply chain (see Fig. 1). The number of echelons and its position in supply chain structure affect the complexity of the supply chain. The goal of multi echelon supply chain management is to provide a required customer service level with minimum inventory by splitting them among echelons.

There are several planning levels in supply chain management decisions [BAL 1999]:

- Strategic planning level (from 3 to 10 years) defines supply chain management goals and achievement directives.
- Tactical planning level (from 3 months to 2 years) defines supply and production approaches, as well as inventory management approach and delivery policies.
- At operational planning level daily routine tasks are planned and implemented as work scheduling, routing planning, and loading-unloading operations.
- Executive level.

The complexity of decision making at each planning level also depends on the number of supply chain partners, product quantity, transportation mode variety etc. However the most complex issue in supply chain management is non-linear dynamics of information flows and uncertainty of customer demand, lead time and costs.

In the doctoral thesis, among all tactical decisions the focus is on a particular problem, which is typical tactical planning decision in supply chain, namely supply chain inventory management including selecting the most appropriate inventory control algorithms and calculating its parameter values. Within the research this problem is solved for multi echelon supply chain.

Multi echelon supply chain inventory management

Multi echelon supply chain tactical inventory management has a lot of challenges as compared to traditional inventory management. One of them is an inability to perform inventory optimisation because replenishments of the echelons are done separately without considering the needs for inventory among all echelons simultaneously.

There are two approaches applied in multi echelon supply chain management:

1. Applying traditional inventory control models to separate supply chain echelons. This approach is called sequential inventory management [LEE 2003]. The shortcomings of the approach are:
    - lack of visibility from top level down the supply chain;
    - bullwhip effect;
    - non-estimated total supply chain costs.
2. The distributed requirements planning approach is an extension of the material requirements planning method that manufacturers rely on to determine and satisfy requirements for the components used to assemble complex products.

Traditionally inventory control algorithms are developed for single-facility case; due to that, there is no perspective to apply them to multi echelon supply chains (see Table 1, [LEE 2003]).

Table 1

Inventory management approaches in multi echelon supply chains

Key area	Sequential approach	Distributed approach	Multi echelon approach
Optimisation goal	Meet immediate customer service goals	Satisfy net requirements	Meet end customer requirement
Demand forecasting	Independent forecasts in each echelon based on immediate customer demands	Forecasted orders without variations	Forecast based on end customer demand and its variations
Lead time	Uses immediate supplier lead times	Uses immediate supplier lead times	Uses all lead times
Bullwhip effect	Ignored	Ignored	Effects measured and accounted for in overall replenishment strategy
Visibility	Myopic view of the network	No upstream visibility	All echelons have complete visibility into other echelons
Synchronisation	Ignored	Maybe	Fully modelled

Supply chain performance indicators

The main idea of the research is application of optimisation and modelling approaches to tactical management tasks in multi echelon supply chain with stochastic parameters in order to achieve strategic goals.

To define supply chain optimisation criteria (or objective function) and simulation model output parameters, it is necessary to use supply chain management indicators. Selecting the criteria predetermine solutions of both models and thus system's further functionality. There are several attempts observed in scientific and research papers on systematisation of supply chain management indicators, which is an essential progress in forming the methodological background of supply chain management [KLE 2003, SLA 2007, SIL 2012]. In this context, the most valuable is a work performed by Supply Chain Council, which elaborated five supply chain performance metrics (see Table 2): reliability, responsiveness, flexibility, costs and asset management [SCOR].

Table 2

Supply Chain management performance indicators

Performance indicators	Explanation	Metrics
Reliability	The performance of the supply chain in delivering	• order fulfilment • service level • fill rates
Responsiveness	Ability to react on demand variations	• lead time
Flexibility	Ability to respond to changes in supply chain structure	• response time • production flexibility
Costs	Supply chain costs	• cost of goods sold • administration and managerial costs • warranty costs
Asset management	Management of all assets: fixed and working capital	• cash-to-cash cycle time • inventory (days) • assets turn

All the attributes of supply chain performance can be classified as either qualitative or quantitative indicators. Qualitative indicators are customer service (the level of customer satisfaction of receiving service or product), and supply chain flexibility (the ability to react to supply chain demand variability). If it is possible to express supply chain management indicators as mathematical equations and calculate corresponding target values, the indicators can be used as optimisation goal function. The most frequently used indicators in optimisation models are costs and customer service level.

Information systems in supply chain management

In the doctoral thesis, the functionality of supply chain information systems is analysed (see Fig. 2).

In the context of supply chain information systems, the developed simulation-based approach for supporting tactical management decisions can be classified as tactical optimisation information system (see Fig. 2.) and described with the following requirements [SHA 1999, SHA 2009]:

- planning horizon - 12 months;
- analysis frequency – once a month;
- planning time – 1 week;
- modelling time – 60-120 min.;
- optimisation criteria: total costs.

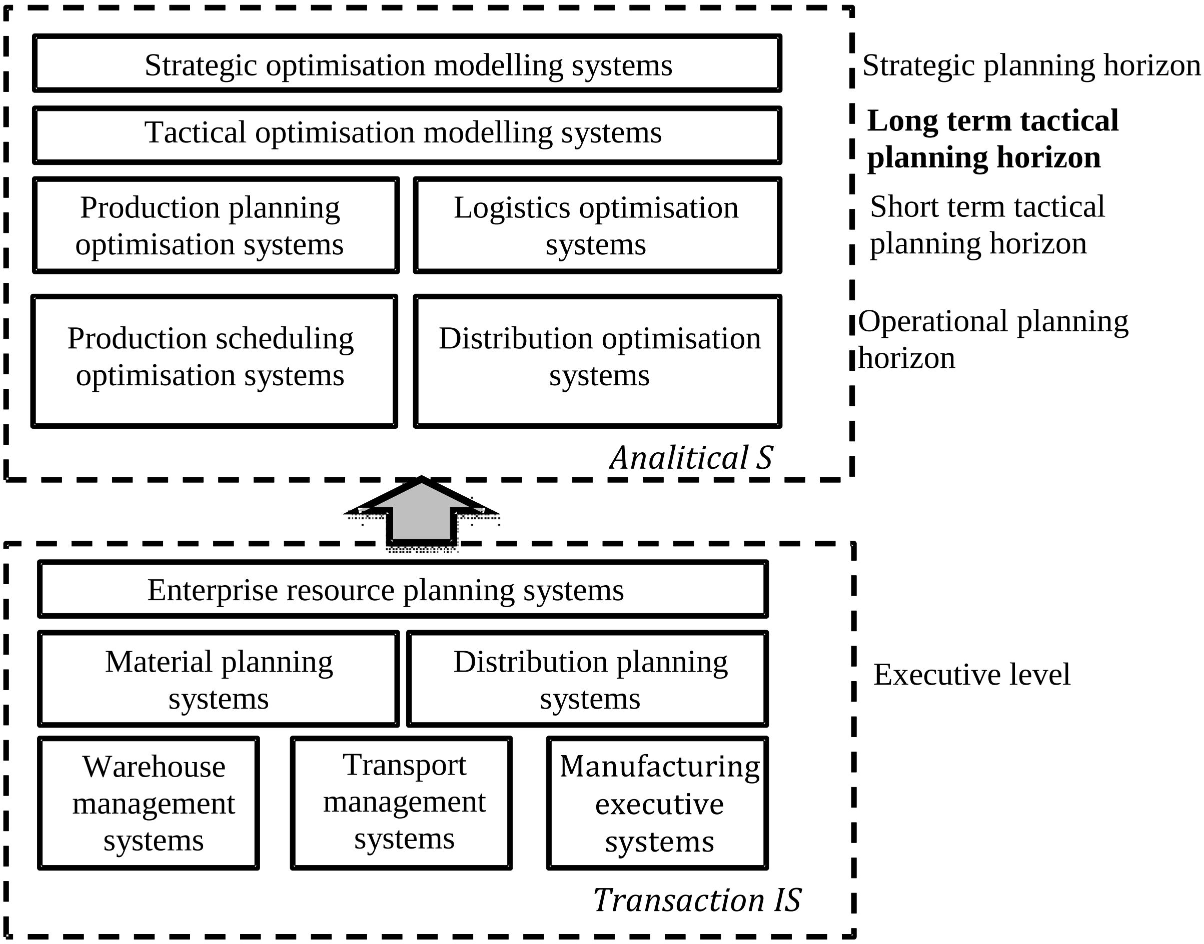


Fig.2. Logistics Information Systems

Conclusions of Chapter 1:

- *the topicality of process approach in supply chain management is evident as it provides supply chain integrated planning and management, as well as promotes outsourcing;*
- *multi echelon supply chain management requires development of a complex of optimisation and simulation models which can be used as analytical tool for mathematically based decision making in supply chains;*
- *in supply chain management the most popular are transaction information systems. However, they cannot provide analytical functionality which is necessary in supply chain management. Due to that, the necessity of the elaboration of analytical tools for supply chain management and their implementation in companies' information systems for supporting decision making.*

Chapter 2, **„Analysis of modelling approaches in supply chain management tasks"** is focused on the analysis of different modelling and simulation approaches and exploring their capabilities in supply chain management tasks.

There is a variety of methodological approaches, methods and algorithms for supporting decision making in supply chain management. The application of those methods throughout all planning levels allows decreasing supply chain costs and increasing effectiveness of business processes.

The proportion of scientific and research papers on quantitative approach dedicated to supply chain management is only a quarter of all publications [STO 2009]. 10% of papers are focused on mathematical modelling, 6% are dedicated to conceptual modelling and 5% to simulation approach. All of the mentioned papers on modelling can be divided to analytical modelling researches and empirical researches. Empirical papers are focused on solving a particular task by means of simulation and modelling, therefore methods and algorithms presented in those papers can be implemented to other problems with difficulties. On the other hand, analytical methods and models can be applied only to structured problem solving which is not always possible in real life. Therefore, as logistics experts note, including Latvian one, there is a topicality of developing an approach, which allows combining different research approaches for supporting mathematically based decision making in supply chain management [KRU 2006, LAS 2003, SLA 2007].

Although there are several attempts made for classifying those methods, this is still a vital issue in supply chain management methodological fundamentals [SHA 1999, TOL]. The leading expert in supply chain management Shapiro proposes to divide all models into descriptive and normative models [SHA 1999]. Normative models include optimisation models, and descriptive models are used for the description of system processes and their interconnections, as for example functional models. This classification is very similar to that used in decision making. While conducting this thesis, three modelling approaches are explored. The application of those approaches to supply chain management decisions depends on managerial goals and planning level (see Table 3).

The less used in supply chain management are business process models, which are applied to describe supply chain processes and information flows. The precognitions of business process models application in supply chain management are related to supply chain globalisation and integration, which requires comprehensive understanding and evaluating of supply chain processes. Universal business process modelling standards (for example, IDEF, UML, ARIS, DFD) are applied to supply chain analysis, design and enhancement [CHI 1999, HAI, HER 2008, REN 2010, VER 2010, STE 2006, MOH 2012].

In recent years, the most popular tool for business process modelling in supply chain has been Supply Chain Reference Model SCOR, developed and promoted by Supply Chain Council [BOL, YIL 2006].

Supply Chain SCOR model is a special tool for describing and improving supply chain activities. Its main advantage is supply chain performance indicators, whose application allows evaluating company’s supply chain performance and comparing different supply chain alternative scenarios in order to enhance company's business process.

Table 3

Application of modelling approaches in supply chain management

Approach	Modelling goal	Planning level	Format	Modelling environment
Business process modelling ***(descriptive)***	Supply chain design and process analysis *<How?>*	Strategic Tactical	Graphical figure, process diagrams	ARIS, CA ERwin, SCOR
Analitical modelling ***(normative)***	Supply chain process optimisation *<What is the best?>*	Strategic Tactical	Optimisation modes, questions systems	LINGO, ILOG
Simulation ***(descriptive)***	Supply chain scenario analysis *<What if?>*	Tactical Operational	Computer programme	ARENA, Promodel, Anylogic

Another model class is normative models, which include mathematical programming models that are usually called optimisation models. Optimisation models require defining mathematical rules which in the form of mathematical questions describe system elements and their interconnections. Application of optimisation models usually is restricted if a system has stochastic or uncertain parameters. In this case, development of optimisation model is not always possible or useful. Moreover, application of analytical methods to complex systems analysis is a complex task, which is the major shortcoming of analytical modelling approach. In this case, the most useful are simulation models.

Conclusions of Chapter 2:

- *There are a variety of modelling methods applied to supply chain management; the unified methods classification is still not achieved. In the doctoral thesis, a classification of models into descriptive and normative models is used.*
- *Simulation models are most popular among other descriptive models in supply chain management and planning. Less used are functional models, however recently their application to supply chain management is promoted by many factors, for example, expansion of process approach and the role of information technologies, as well as supply chain globalisation and integration. Despite a variety of business process methodologies, a specialized supply chain SCOR model is developed and promoted as a unique standard for describing and evaluating supply chain business process.*
- *Mathematical programming models belong to normative models. Usually those models are developed for each problem particularly. In tactical supply chain management, mathematical models are less applied comparing with*

others, mainly because of the necessity to handle stochastic data in a quite short time period.

Chapter 3, **"Simulation based approach for multi echelon supply chain tactical management"** is dedicated to the development of multi echelon supply chain tactical management approach, aimed at supporting mathematically based tactical decision making in supply chains which operate in uncertain environment (described by stochastic parameters as demand and lead time) by applying different elements of a variety of modelling approaches.

The conceptual description of the approach

The approach described in the doctoral thesis is based on the application of optimisation and modelling approaches to supply chain management decisions which have to be done under stochastic data The approach is aimed to support tactical decision making however it can be applied to strategic decision making if only the specifics of the task are not against the following precognitions of the developed approach:

1. The application of the approach is focused on tasks with stochastic input data (usually they are demand and lead time). The tactical planning level is the most appropriate among others for handling uncertainty. Strategic decision making has a long term planning horizon, so stochastic parameters can change its value until the decision should be implemented. The operational level requires the decision to be made within a short period which is either not enough to handle the uncertainty or is already known as a constant. In case if operational decision should be corrected, the deterministic methods are used operating with constant value of parameters.
2. While developing optimisation and simulation models, the restrictions for model execution time should be considered. For tactical optimisation models they are defined as follows: model run time is set up to 120 minutes and decision making period – 1 week). Optimisation model run time depends on the scale of the problem, planning horizon, variables number and stochastic parameters number. Therefore, it is important to select the appropriate number of variables according to planning horizon. Solving strategic problems, planning horizon are too long for a mathematical model to be solved by optimisation solvers. The most important it is when a model has more than one stochastic parameter. At the operational level, in its turn, there is no enough time for run optimisation model, as decision making requires time less than 1 hour.

The general idea of the developed approach is shown in Fig. 3. The core of the approach is a combination of stochastic and simulation models, which are the main elements of the approach. To facilitate adequate stochastic and simulation model development, application of analytical and business models is proposed in the doctoral thesis. Analytical models describe correlations among parameters of the defined problems; then business process models explain all activities and could be used as conceptual models for simulation.

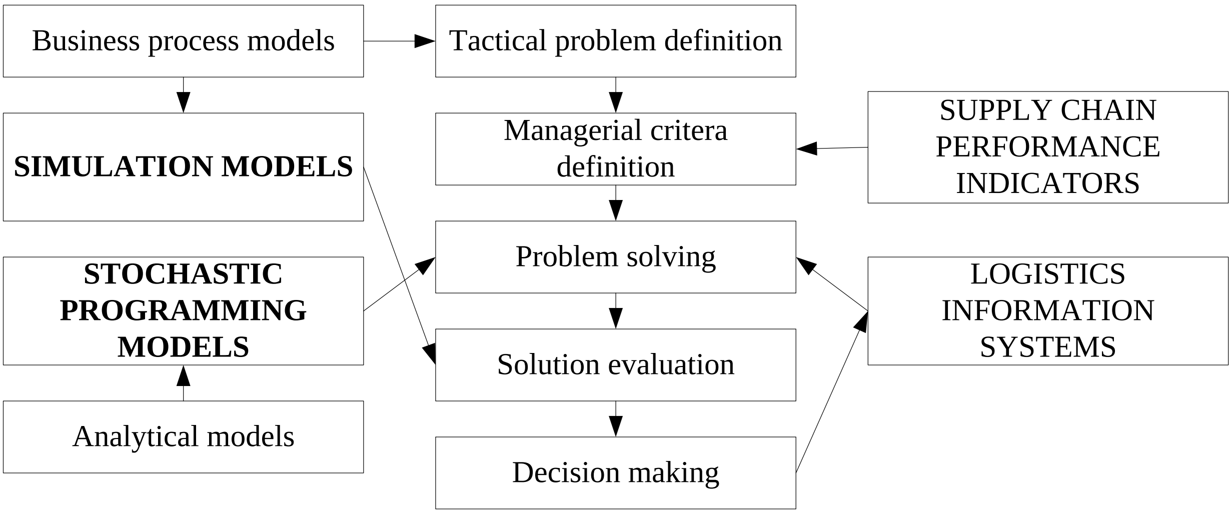


Fig. 3. Simulation-based supply chain tactical management

The stochastic programming model is aimed at solving supply chain tactical task under the defined criteria. In the doctoral thesis, the scenario approach of the stochastic programming is applied, which supposes describing stochastic data by means of a scenario tree [BAI 2002, BER, BIR 1997, GRO 2003, HOC 2007, KAU 2007, SAN 2005, PRA 2006]. Scenario means a data set generated from samples or random numbers according to particular algorithms, which describes stochastic nature of the modelled parameters in optimisation models. Due to the rapid development of computer computational ability, the scenario approach of stochastic programming has its own direction in optimisation approach. The most effective scenario approach is applied in finance engineering where multi-period planning optimisation models with uncertain parameters are vital. In supply chain management, the actual challenge of application of the scenario approach is related to increasing the number of scenarios caused by increasing either planning horizon or sample number.

Supply chain analytical inventory models suppose that stochastic data (namely, demand and lead time) are described by normal distribution. However, solving real tasks, historical data are not always available or cannot be described as normal distribution. While working on the research, different scenario generation and scenario reducing methods were analysed. All of them belong to scenario generation from sample or sample modelling technique which generates a scenario by a set of independent samples.

In case if samples are dependent, appropriate scenario generation methods and models should be selected as econometrics models, time series, statistics methods or methods which belong to artificial intelligence [DOM 2006].

In the scenario approach, a stochastic problem can be represented as a set of linear programming models with a finite number of scenarios. In this case it is called deterministic equivalent of stochastic problem. The scenario approach assumes solving stochastic models by a set of deterministic models with a reduced scenario tree, which does not present all possible scenarios of stochastic parameters. Due to that, it is important to evaluate the obtained optimisation solution. For that purpose, in the doctoral thesis sample average approximation method is used which is aimed at the evaluation of stochastic problem solution obtained with a reduced number of scenarios.

Following is a procedure of the developed approach to multi echelon supply chain tactical management:

1. To express the problem in the form of mathematical model following a structure of mathematical programming (defining variables, objective function, and boundary conditions). In this step application of functional and analytical models is rational as they provide information about problem variables and their interconnections. It may be especially helpful in the situation of multi echelon supply chain management throughout multi period planning horizon. For describing problems in terms of mathematical programming, a variety of mathematical programming languages can be used, for example, AMPL and GAMS.
2. To select the most appropriate scenario tree generation method that allows describing stochastic parameters of the problem. In this step, the initial experiments should be done in order to evaluate an impact of the number of scenarios to computation time taking into account a time requirement for tactical modelling systems set as 120 min.
3. To solve optimisation task according to optimisation criteria with a defined number of scenarios. In this step, different solvers are applied according to the specific requirements of optimisation model, e.g., CPLEX, MINOS etc.
4. As the optimisation problem is solved with a decreased number of possible realisations of full scenario tree, an obtained solution should be evaluated. For that purpose, the sample average method (SAA) is applied in the doctoral thesis. In this step, initial experiments are done in order to find appropriate values for SAA method's parameters as N, N' and M (M-number of samples, N – number of scenarios, N' – number of scenarios of evaluation sample). This step is the most time consuming as it requires both computational resources and results processing time.
5. To evaluate the obtained optimisation solution by means of simulation model. As simulation allows describing supply chain with a higher specification level than optimisation model, redressing simplifications of optimisation model and including additional stochastic parameters, a simulation model is a vital part of the developed approach. In this step, it is important to ensure the correspondence of the simulation model with optimisation model. For that purpose, descriptive models can be applied, similarly as for developing optimisation model.

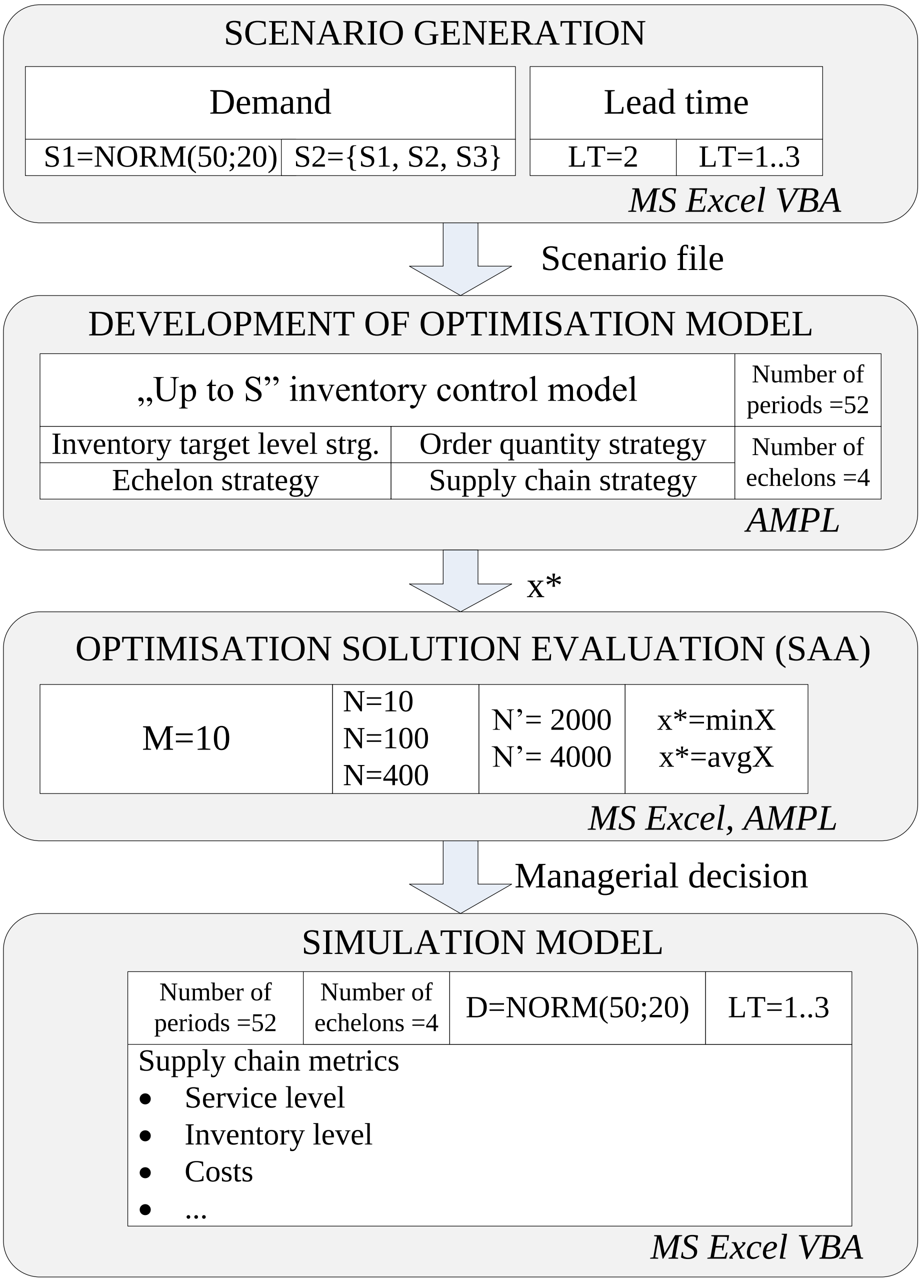


Fig. 4. A schema of experiments

The developed simulation-based management approach allows supporting mathematically based decision making in multi echelon supply chain tactical management and evaluating supply chain performance in different conditions including stochastic. To demonstrate the application of the proposed approach, experiments are done with four echelon supply chain (Beer Game supply chain), that is a well-known academic example in supply chain management. A schema of the experiments is shown in Fig. 4.

Multi-echelon supply chain optimisation model development

The experiments on the application of the developed approach are done for a four echelon supply chain model (see Fig. 5) solving the traditional tactical management problem, i.e., inventory problem. The structure of the supply chain is similar to a well known supply chain management game called “Beer game”. Developed in 1960, it is focused on the demonstration of different paradigms in supply chain management including benefits of supply chain integration approach [BGA]. Following are notations used in Fig. 5:

T – number of periods;
Dt – demand value within period t;
O*4t* – retalier order within period t;
O*3t* – wholesaler order within period t;
O*2t* – distributor order within period t;
S*4t* – shipment received by retailer within period t;
S*3t* – shipment received by wholesaler within period t;
S*2t* – shipment received by distributor within period t;

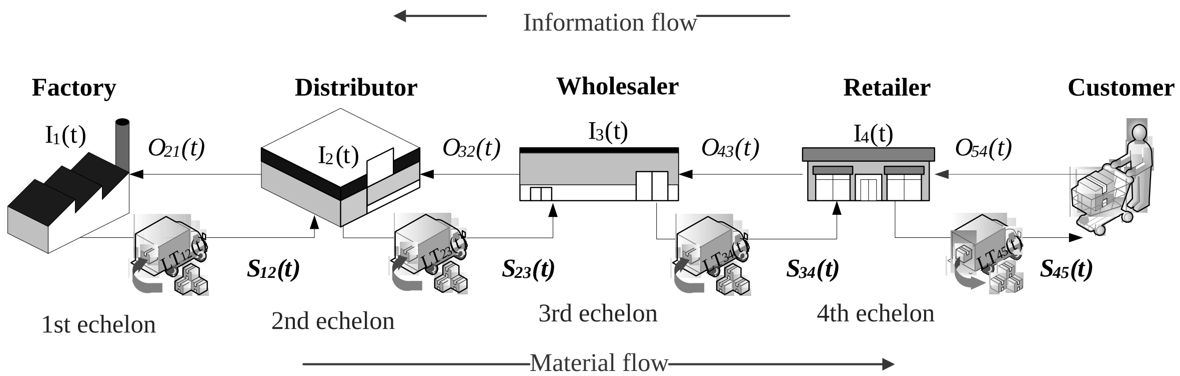


Fig. 5. Supply chain structure

In each period, two types of costs can occur in each echelon: backorder costs 2 c.u. and inventory costs – 1 c.u. The number of periods is 52 weeks, which is usual tactical planning horizon (1 year is almost equal to *N*=52 weeks). At the beginning of each week, the customer demand D_N occurs, which is described by normal distribution (50;20). Each participant of the supply chain receives a shipment *Slt* (*l* – echelon index, *t* – period index*)* from its direct supplier. If the supplier cannot provide the ordered amount, the backlog costs occurs and the rest of the order will be delivered next period, because all orders have to be satisfied. The lead time between echelons is 2 weeks (however, some experiments of the doctoral thesis are done with stochastic lead time). This means, that the order done in first period will be delivered at the 3rd period. Factory has an unlimited number of inventories, so distributor order is always delivered and inventory in factory is equal to distributor order value.

The task of each echelon is to define the order quantity *Olt* to be ordered from its direct supplier.

The goal of the game as well as managerial decision is to assure the performance of the supply chain with minimal both inventory *Ilt* and backlog costs *Blt*. Let there be no any factory breakdowns as well as any product breakdowns during delivery.

For mathematical model formulation, it is supposed that “up to S” inventory control model is implemented to the supply chain. This means that each period the order quantity is aimed to increase the current inventory to inventory target level [RUS 2009].

Applying scenario approach of stochastic programming, which supposes describing stochastic demand by means of scenario tree, the optimisation model is expressed as formula (1) shows [SOS 2006, SOS 2007a, SOS 2009]:

$$\min \sum P_s \left(\sum_{l=2}^{N} \sum_{t=1}^{T} c_{lt} \cdot i_{lts} + \sum_{l=2}^{N} \sum_{t=1}^{T} e_{lt} \cdot b_{lts} \right),$$

$$\begin{aligned}
& o_{0ls} = 0; \\
& i_{0ls} = 100; \\
& b_{0ls} = 0; \\
& r(l-1,-2,s) = r(l-1,-1,s) = 0; \\
& x_{5,t,s} = D_{ts}; \\
& x_{2,t,s} = r(1,t); \\
& x_{lts} = \zeta - i(l,t-1,s) + b(l,t-1,s) - o(l,t-1,s); \\
& o_{lts} = o(l,t-1,s) + x_{lts} - r(l-1,t-N,s); \\
& b_{lts} = b(l,t-1,s) + x(l+1,t,s) - r_{lts}; \\
& i_{lts} = i(l,t-1,s) + r(l-1,t-N,s) - r_{lts}; \\
& T, L, P_s > 0; \\
& \zeta, N, D_{ts}, c_{lt}, e_{lt}, x_{lts}, i_{lts}, b_{lts}, r_{lts}, o_{lts} \geq 0.
\end{aligned} \tag{1}$$

where o_{lts} – order quantity of echelon *l* within period *t*, in scenario *s*;
i_{lts} – inventory level in echelon *l* within period *t*, in scenario *s*;
b_{lts} – backorders in echelon *l* within period *t*, in scenario *s*;
r_{lts} – delivered goods in echelon *l* within period *t*, in scenario *s*;
x_{lts} – order quantity in echelon *l* within period *t*, in scenario *s*;
ζ – inventory target level;
c_{lt} – inventory costs at echelon *l* within period *t*;
i_{lts} – inventory level in echelon *l* within period *t*, in scenario *s*;
e_{lt} – backorder costs at echelon *l* within period *t*;
b_{lts} – backorders quantity in echelon *l* within period *t*, in scenario *s*;
T – time horizon;
N – number of echelon;
P_s – scenario probability.

The mathematical model of the problem is presented in full version of the doctoral thesis.

Generation of demand scenario tree

In the doctoral thesis, two approaches are used for scenario generation:

1. scenario generation from empiric distribution (in case if historical data are not available, expert evaluations of possible demand can be used);
2. scenario generation using theoretical distribution.

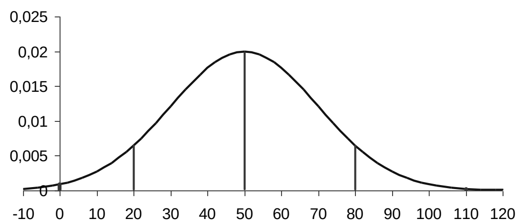
Sampling 2 $\mu \pm 1.5\sigma$; $\mu + 3\sigma$	**Value no.**	***D_i***	***$P(D_i)$***
	1	0	0.025
	2	20	0.187
	3	50	0.576
	4	80	0.187
	5	110	0.025

Fig. 6. Obtaining scenario samples from normal distribution

Scenario generation using theoretical distribution in its turn is tested in two ways:

1. as a random value generated by a certain distribution, as for example, in the experiments, demand is described by normal distribution (50; 20);
2. replacing theoretical distribution by a discrete distribution which consists of a certain number of samples calculated according the mathematical procedure [SOS 2006, SMO 2004]. The number of samples depends on expert evaluation. An example of this is shown in Fig. 6.

Application of Sample average approximation method to optimisation model

Sample average approximation method and its mathematical foundation is described in several scientific publications as [KLY 2002, SHB 2002, TOM 2007, VER 2004, WEI 2004, SHM 2006, GRE 2006]. The basic idea of *SAA* method is that a random sample is generated and the expected value function is approximated by the corresponding sample average function. The obtained sample average optimization problem is repeated several times, for increasing values of scenario number in each sample.

In the doctoral thesis, this method is presented in four steps as follows:

1. Generate M times random independent demand sample of N scenarios. For each sample, the optimisation problem should be solved and solution should be obtained, presenting the optimal decision variable value and optimisation criteria value, see correspondingly formulas $\hat{x}_N^j$, υ_N^m .
2. Calculate the expected value of the replicated SAA solutions and the variance of the estimator, see correspondingly formulas (2) and (3):

$$\bar{\upsilon}_{N,M} = \frac{1}{M}\sum_{m=1}^{M}\upsilon_N^m \qquad (2)$$

$$\delta^2_{\bar{\upsilon}N,M} = \frac{1}{(M-1)*M}\sum_{m=1}^{M}(\upsilon_N^m - \bar{\upsilon}_{N,M})^2 \qquad (3)$$

3. Choose a feasible solution among M solutions. In the experiments, the solution is selected which provides minimum value of the objective function (4):

$$\hat{y}^* \in \arg\min[v_N^M : y_N^1, y_N^2, ..., y_N^M] \qquad (4)$$

Using $\hat{x}*$, solve optimisation problem with scenario number N' and obtain the solution $\hat{\bar{\upsilon}}_{N,M}$. In this step, *N'* scenario number should be much more than N used in step 1, i.e. *N'>N*. Then calculate the variance of this estimate as in formula (5):

$$\delta^2_{N'}(\bar{x}) = \frac{1}{(N'-1)*N}\sum_{n=1}^{N'}(c^T\bar{x} + Q(\bar{x},\xi^n) - \tilde{f}_{N'}(\bar{x}))^2 \qquad (5)$$

4. Estimate the optimality gap by using formula (6) and calculate the obtained gap variance by using formula (7):

$$\delta^2_{gap} = \delta^2_{N'}(\bar{x}) + \delta^2_{\bar{\upsilon},N,M} \qquad (6)$$

$$gap_{N,M,N'}(\bar{x}) = \tilde{f}_{N'}(\bar{x}) - \bar{\upsilon}_{N,M} \qquad (7)$$

Additionally to the traditional method, in the experiments a parameter %gap is estimated [SOS 2009]. This parameter could be used for easier results interpretation, as follows: the smaller %gap is, the better (and stable) the obtained optimisation result is.

Applying the sample average approximation method to solving stochastic problems, the explanation of the optimality gap is as following: if the gap value is high, the probability that solution is less reliable is high. However, results evaluation by SAA depends on method's parameters and sometime is not reliable. As the scientific publications explain, sometimes the optimised solution provided sufficient system performance even with a high value of gap [KLY 2002, WEI 2004].

In each particular task the optimality gap depends on *M, N, N'* and the nature of stochastic parameters. Therefore, a set of experiments should be performed solving each problem to find the most appropriate settings.

However, SAA method should be applied only at the beginning of the developed approach for obtaining the most appropriate number of scenarios. If there are no changes in optimisation model and stochastic parameters, the SAA procedure can be run only once. In the doctoral thesis, the SAA method is implemented using both AMPL mathematical modelling language [AMPL] and Excel spreadsheets.

In the thesis, the realisation of SAA method is combined with corresponding simulation model. This allows one to facilitate implementation of SAA method and simultaneously evaluate the performance of the supply chain under optimised decision variables values by such performance indicators as inventory costs, service level and others [SOS 2009, SOS 2010]. Based on obtained performance indicator values, the decision can be made about the most appropriate inventory control model and its settings in tactical planning horizon.

In the doctoral thesis, a set of experiments is done (see Fig. 4) to achieve the following goals:

1. to evaluate the obtained solution with different number of scenarios *N* and *N'* in the SAA method;
2. to evaluate the obtained solution by changing *x** choosing criteria in the 3rd step of the SAA method (usually it is suggested to select the optimal *x** among all samples M, however, experiments are done applying the average value for decision variable obtained in the first step of SAA);
3. to test different approaches in scenario generation.

After running experiments, these results were obtained:

1. If *M*=10, the appropriate number of scenarios *N* is equal to 250 and *N'* is equal to 2000 (*M* = 10, *N* = 250, *N'* = 2000). It is evident that increasing the scenario number, the gap value decreases, however important is also optimisation model computational time. With *N'* = 2000 and *N'* = 4000 the difference in %gap is no significant (see Fig. 7), however computational time with *N'* = 4000 is longer than *N'* = 2000.
2. To select the better principle of selecting *x** in SAA method, a set of experiments were done. The experiments show that if *x** = argmin(v(*x*)), then %gap = 26.20, however within *x** = AVG(*X*) %gap = 10.14 (*M* = 100, *N* = 100, *N'* = 2000). A conclusion can be made that the most appropriate principle for selecting *x* is* it s average from M experiments.
3. For scenario generation the most appropriate way is scenario generation by random values from corresponding theoretical distribution. This provides %gap=10.14, while scenario generation from sampling results in %gap=4.09.

The results of the conducted experiments and the experiments process itself demonstrate a potential of application of the sample average approximation method to multi echelon supply chain management problem, as well as describes how the parameters of the method can be adjusted. The problem of scenario number definition is explored as well. While performing supply chain optimisation and modelling under uncertain parameters, sample average approximation methods should be used, however their application in each run of simulation or optimisation model is not necessary. When an appropriate number of scenarios is adjusted providing a necessary level of results evaluation, the step of applying SAA method can be skipped from the supply chain tactical management procedure described above.

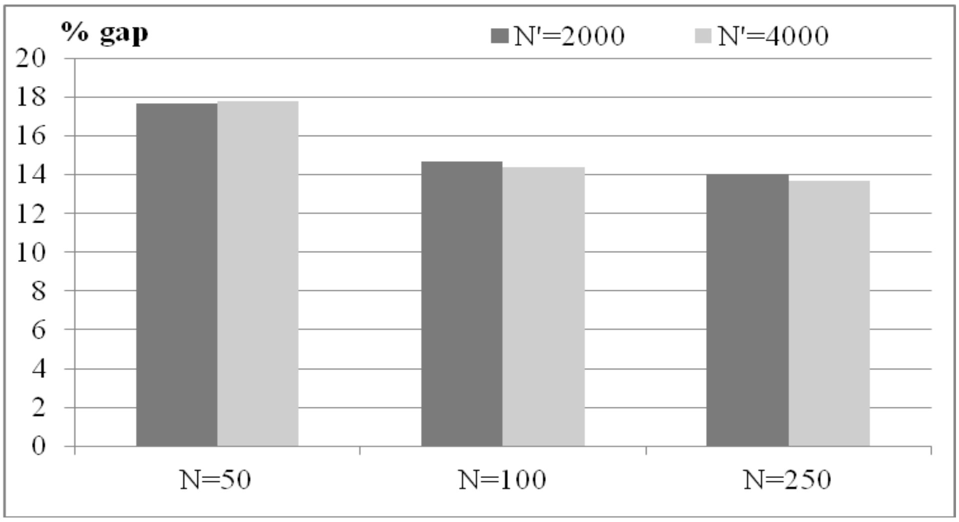


Fig 7. %gap variation with different N

Experiments with different supply chain inventory management approaches in optimisation model

In the doctoral thesis, experiments are made in order to compare different inventory management approaches in the optimisation model, namely:

- target level strategy and
- ordering strategy.

The implementation of the target strategy in optimisation model is done by setting inventory target level as a decision variable with an objective function of total costs minimisation. Ordering strategy means that order quantities for each echelon have to be found.

Table 4

Comparing results of target and ordering strategy simulation

Supply chain performance indicators	Target level strategy	Ordering strategy
Service level, %	73	96
Total costs	136	447.85
Average inventory, SKU.	60	395

Experiments show that ordering strategy applied to multi echelon supply chain with both stochastic demand and lead time is most robust, it provides lowest %gap value and higher service level; however, it is achieved by higher total costs. In the context of optimisation results implementation to real life situation, target strategy is more usable as it provides only a few variables to be controlled throughout all tactical planning horizon.

Table 5

Comparing SAA results with deterministic and stochastic lead times (*ordering strategy*)

	Lead time = 2			**Lead time = 1, 2, 3**		
M	*N* = 50	*N* = 100	*N* = 250	*N* = 50	*N* = 100	*N* = 250
1	6063.20	6179.70	6214.32	9445.13	9821.18	9803.12
2	6627.40	6189.80	6158.32	9942.00	9824.13	9750.86
3	7175.80	6003.40	6778.08	10394.50	9429.38	10478.10
4	6034.60	6994.50	6457.12	9440.18	10691.10	10101.80
5	6601.80	6520,50	6425.52	9975.50	10098.50	10175.30
6	5835.40	6250.20	6591.56	9119.35	9902.77	10274.60
7	7091.40	6181.80	5757.40	10434.30	9520.50	9409.16
8	6122.80	6301.60	6181.28	9405.97	9773.23	9782.36
9	6707.80	6508.30	6096.40	10179.50	10192.70	9749.89
10	6518.60	6830.00	6596.60	9855.63	10315.50	10021.30
v_N^j min	5835.40	6003.40	5757.40	9119.35	9429.38	9409.16
v_N^j max	7175.80	6994.50	6778.08	10434.30	10691.10	10478.10
$\bar{v}_{N,M}$	6477.88	6395.98	6325.66	9819.21	9956.90	9954.65
$\sigma_{\bar{v}_{N,M}}$	143.88	99.67	95.03	142.37	119.48	99.15
$\tilde{f}_{N'}(\bar{y})(2000)$	6780.17	5929.36	5793.39	11007.48	9121.48	9601.69
$\sigma_{N'}(\bar{y})(2000)$	70.39	68.65	68.44	68.66	62.95	64.21
gap(2000)	302.29	466.62	532.27	1188.27	835.42	352.96
%gap(2000)	4.46	7.87	9.19	10.80	9.16	3.68
σ_{gap} (2000)	160.17	121.03	117.11	158.06	135,04	118.13
$\tilde{f}_{N'}(\bar{y})(4000)$	6701.48	5932.05	5778.75	10414.01	10339.80	9626.24
$\sigma_{N'}(\bar{y})(4000)$	50.57	49.73	49.55	48.59	44.86	46.18
gap(4000)	223.60	463.93	546.91	594.80	382.90	328.41
%gap(4000)	3.34	7.82	9.46	571	3.70	3.41
σ_{gap} (4000)	152.51	111.39	107.17	150.43	127.62	109.38

Experiments with stochastic lead time

In the thesis, experiments are performed with stochastic values of optimisation model parameters. Inventory control analytical models suppose that both demand and lead time can be expressed as stochastic values described by normal distribution. Due to that, experiments are made for verifying optimisation model ability to handle two stochastic parameters; the experimental results are given in Table 5.

Analysing the data given in Table 5, one can conclude that results of stochastic model with two stochastic parameters are better as %gap value is two times smaller as compared to the results of optimisation model with one stochastic parameter. However, it is achieved by high value of inventory target level resulted in high total costs value. Efficient is also the increasing of the model run time (see Fig. 9) and SAA procedure time.

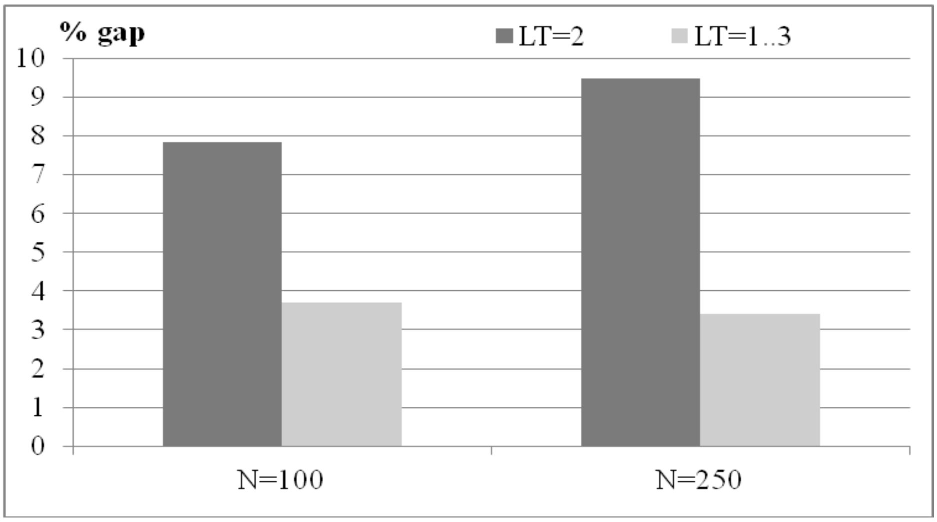


Fig. 8. %gap value in optimisation model with constant and stochastic lead time

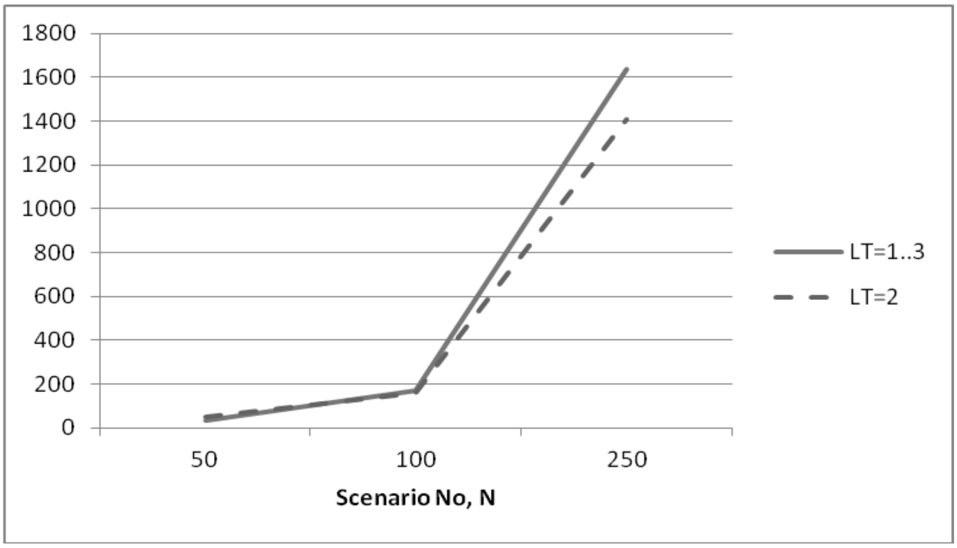


Fig. 9. Optimisation model run time, seconds
(Pentium Dual Core T2390, 1.86 GHz, 2048 MB RAM)

As a result of the experiments, a conclusion is done that in optimisation model with stochastic demand it is not rational to present lead time as a stochastic parameter, as it leads to increasing the computational time and providing the solution with high total costs. The developed approach of multi echelon supply chain tactical management suggests including one stochastic parameter to the optimisation model. The rest of stochastic parameters can be included to simulation model in order to evaluate their influence on optimised supply chain performance.

Experiments with supply chain simulation model

There are several experiments made in the doctoral thesis testing the performance of supply chain under different inventory control methods and strategies. While conducting experiments with multi echelon supply chain inventory optimisation model, the following strategies were modelled:

1. Echelon strategy, which means that inventory target level is calculated for each supply chain echelon;
2. Supply chain strategy, which means that inventory target level is equal among all supply chain echelons.

To compare different multi echelon supply chain inventory approaches and strategies and make a comparative analysis of results, supply chain simulation model is developed by means of MS Excel and several experiments are performed (see Fig. 10).

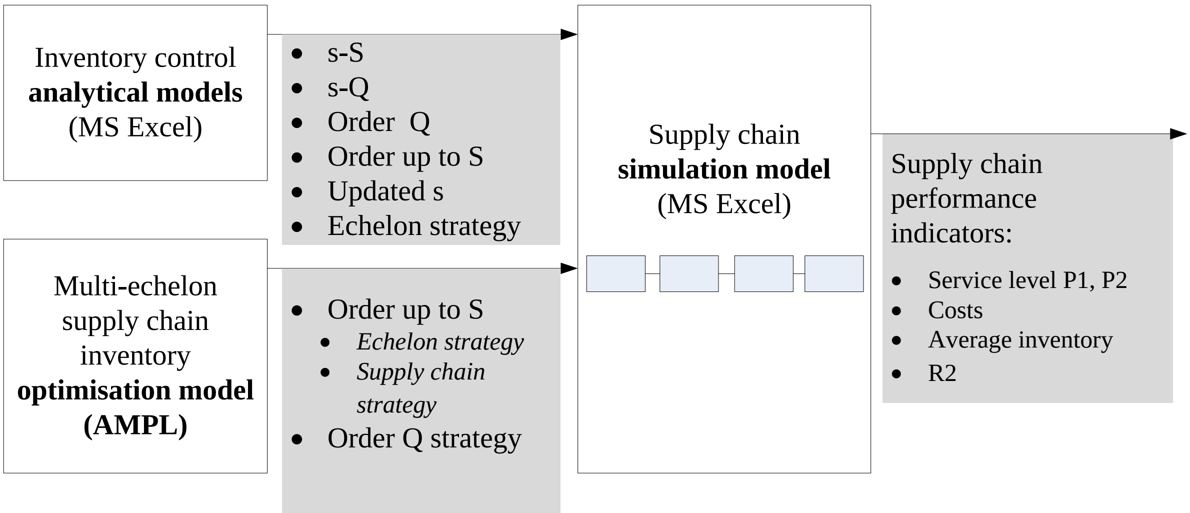


Fig. 10. A schema of simulation experiments

Simulation models are developed by using MS Excel spreadsheets. The model absolutely corresponds to the supply chain modelled in the research including its structure and input data. The model simulates supply chain performance under selected inventory management algorithm and its parameter values, which are calculated either by applying analytical inventory models or optimisation models for tactical planning period (i.e. 52 weeks). Simulation model input data are end customer demand, lead time between echelons and inventory control algorithms parameter value. As simulation output data, the following supply chain performance indicators are used:

- P1 service level;
- P2 service level which shows in % customer satisfaction in particular time period; it is a difference between demand of end customer and order sent in a particular time period;
- average inventory level;
- costs;

- R2: the trade-off between the service level P1 and the average supply chain inventory per period.

To compare the simulation results, they are normalized. To evaluate results of supply chain performance under different inventory management algorithms, the weighted sum method is used which is aimed at comparing different alternatives by different criteria. Table 6 shows a comparison of different inventory control algorithms by five supply chain performance indicators.

Table 6

Simulation results (a fragment)

Inventory control algorithm	**Supply chain performance indicators**					**Total**
	P1, %	P2, %	Average inventory, CKU	Costs	R2, %	
Results of application of analytical models						
s-S	99.36	99.61	239	268	5.00	0.68
s-Q	97.37	98.85	362	522	7.00	0.59
Order up to S	95.19	99.00	138	183	13.12	0.77
Order Q	90.13	99.29	352	420	20.84	0.56
updated s	92.18	95.66	143	182	12.79	0.76
Echelon	95.00	99.13	189	253	7.81	0.70
Optimisation results						
Echelon	78.72	94.42	65	138	18.23	0.92
Supply chain	71.60	93.03	66	140	22.61	0.89
Ordering policy	95.77	98.83	420	464	15.43	0.57

With equal weights of criteria, the better performance of the multi echelon supply chain is within the optimised inventory control parameter values. However, it would be wrong to conclude in general that optimisation provided better results than analytical models. This chapter is aimed at demonstrating the advantages of mathematical programming for making decision in multi echelon supply chain tactical management.

Conclusions of Chapter 3:

- *Application of the scenario approach of stochastic programming to inventory management tasks allows solving multi echelon supply chain inventory management tasks with stochastic demand and lead time.*
- *The sample average approximation method allows solving stochastic optimisation problems with a decreased number of scenarios after setting up all parameters of the method according to the specifics of the problem.*
- *Increasing sample number in the sample average approximation method enables decreasing uncertainty in optimisation results.*

- *Applying a small number of scenarios to optimisation model the obtained results will not catch the uncertainty effect to supply chain performance. However, a large number of scenarios produces interference in computational results and increases computational time dramatically.*
- *Implementation of the sample average application method to simulation model facilitates calculations and allows evaluating supply chain performance (inventory costs, service level) under optimized parameters values.*
- *Solving stochastic multi echelon supply chain inventory management problem with both stochastic demand and lead time by the scenario approach of stochastic programming dramatically increases computational time. Therefore, it is more rational to neglect the uncertainty of lead time in optimisation model. Here the effect of lead time uncertainty can be evaluated by means of simulation model together with the analysis of optimisation results on supply chain performance.*

Chapter 4, "**Application of the simulation-based approach in Latvian companies**" presents three case studies on applying the developed approach and its elements in Latvian companies. All the case studies are elaborated in cooperation with Latvian companies and obtained results have got positive evaluation (attached to the doctoral thesis). The most evaluated are developed simulation models, which are aimed at supporting mathematically based decision making in supply chain inventory management problem.

In the first case study the inventory management task in the „*King Coffee Service*" company [SOS 2010] is solved. As the company manages supply chain in the Baltic region, the case study has two stages. In the beginning, for demonstrating principles and advantages of the developed simulation-based supply chain tactical management approach, the inventory management task was solved for a single echelon, i.e. warehouse in Riga (Latvia). Then, following the extension of the company's supply chain the developed simulation models were extended to multi echelon supply chain models, including two distribution centres in Latvia and Lithuania.

During the approbation studies, the following models are developed and applied for companies managerial task support:

1. Inventory management analytical models with service level both 95% and 100%: s-S, "order up to S", s-Q, Q-p.
2. "order up to S" inventory management optimisation model developed by means of AMPL mathematical modelling language.
3. Supply chain simulation models implementing different inventory algorithms like s-S, "order up to S", s-Q, Q-p. Based on results of simulation models, managers of the „*King Coffee Service*" company can make a decision regarding the most appropriate inventory management method and its parameters.

To compare the results of simulation models, a multi criteria comparative analysis is done by using the weighted sum method. The results of single-echelon supply chain with 95% and 100% service level are summarized in Table 7.

Table 7

Inventory management models evaluation

Inventory management algorithm	Service level, %	Rating
s-S	95%	0.844
	100%	0.831
Order up to S	95%	0.834
	100%	0.765
s-Q	95%	0.849
	100%	0.832
Q-p		0.649
Order up to S *opt*		0.838

The case of two-echelon supply chain is more complex as it requires analysing both echelons performance indicators as well as whole supplying chain indicators. In fact, the developed models extend the functionality of the company's information system providing new analytical tools for decision making in inventory management.

A second case study is also dedicated to inventory management task in the "*Biosan*" company. To facilitate the implementation of modelling approach at the company, it was initially tested at the company's packaging department. The approbation resulted in development of simulation-based decision making framework. During the task solving these models were developed and applied:

1. business process model;
2. periodic and continuous inventory review analytic models;
3. ABC inventory classification model;
4. packaging department inventory management simulation models implementing both periodic and continuous inventory review analytic models.

As a result, data for comparing periodic and continuous inventory review models are obtained (see Table 8).

Table 8

Comparing periodic and continuous inventory review models

Inventory strategy	Service level 1, %	Service level 2, %	Avg. inventory, SKU	Backorders, SKU
Continuous	0.992	0.996	298	12
Periodic	0.968	0.986	185	66

In the course of working on this case study, the simulation-based framework for a logistics company is developed extending the functionality of its information system with new analytic features.

The third case study is dedicated to facility location and supply chain network design problem at the „*Zepter International AG*" company. The goal is to find a location for the company distribution centre in the Baltic region, based on product sales data. However this task doesn't belong to tactical planning level (as facility location is a long term strategic decision), its specifics allow applying such elements of the developed simulation-based supply chain management approach as analytic model, optimisation model and simulation model (developed by means of supply chain simulation tool LORD). The obtained results enable one to evaluate alternative scenarios of supply chain design and select the most appropriate one which supposes to use centralized supply chain structure with one distribution centre found by the Centre-of-gravity method [SOS 2007b].

Conclusions of Chapter 4:

- *In spite of wide application of transaction information at Latvian companies, they cannot assure analytic and planning functionality of decisions related for example to inventory management and planning.*
- *There is an interest coming from company managers in the application of modelling and simulation approach to supporting logistics decision making at the companies.*
- *The application of the developed simulation-based multi echelon supply chain tactical management approach and its elements to companies allow enhancing company logistics decisions and harmonize inventory management procedures by providing a complex of models for mathematically based decision making.*

RESULTS AND CONCLUSIONS OF THE THESIS

The simulation-based multi echelon supply chain tactical management approach is developed, which involves using stochastic programming scenario approach as a tool for task solving under uncertain parameters. The developed approach is approbated in four-echelon supply chain inventory management task with stochastic customer demand and lead time.

Following are the results obtained in the doctoral thesis:

1. Supply chain performance indicators are analysed, which allows evaluating the achieving supply chain managerial goals.
2. Different modelling approaches to supply chain management are considered and directions for selecting an appropriate model type are defined.
3. Simulation-based multi echelon supply chain management approach is developed.

4. The approbation of the developed simulation-based multi echelon supply chain management approach is performed.
5. Multi echelon supply chain inventory optimisation model is defined implementing “up to S” inventory model.
6. A series of experiments are conducted in order to adjust Sample Average Approximation method to the inventory optimisation model.
7. Practical case studies are developed for illustrating the developed simulation-based supply chain management approach to supply chain inventory management and facility location tasks.

Based on the achieved results, the following conclusions are made:

1. Multi echelon supply chain management requires simultaneous and integrated management of many logistics facilities with a total goal of increasing the performance of whole supply chain.
2. The role of the process approach becomes more topical in supply chain management. It supposes development and application of descriptive models which can further serve as conceptual models for simulation and optimisation model elaboration.
3. Tactical optimisation and modelling systems which belong to analytic supply chain information systems are less spread in supply chain management, therefore topical is enhancing transaction information systems with analytic functionality.
4. Application of stochastic programming scenario approach in solving supply chain tactical management tasks allow managing challenges related to the stochastic nature of model input parameters. To select appropriate scenario generation method and number is a vital challenge in the application of stochastic programming scenario approach.
5. Implementation of the sample average approximation method to simulation model allows decreasing model run time, as well as evaluating optimized solution and modelled system performance.

After summing up the results of the doctoral thesis these further developments and evolution opportunities of the proposed approach could be seen:

1. Application of supply chain SCOR model as a conceptual model for elaborating both simulation and optimisation models.
2. Analysis of the robustness of multi echelon supply chain managerial decisions by applying the gap interval of the sample average approximation method.
3. Enhancement of supply chain inventory management decisions by defining service level coefficient as optimization model objective function.
4. Elaboration of supply chain stochastic parameter scenario generation and its integration to stochastic model providing stochastic parameter forecasting over tactical planning horizon.

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