MODEL-SUPPORTED AND SCENARIO-ORIENTED ANALYSIS OF OPTIMAL DISTRIBUTION PLANS IN SUPPLY NETWORKS

Dmitry Ivanov
Berlin School of Economics and Law,
Chair of International Supply Chain Management,
10825 Berlin, Germany
E-Mail: divanov@hwr-berlin.de

Boris Sokolov, Alexander Pavlov
Institution of the Russian Academy of Sciences,
Saint Petersburg Institute of Informatics and Automation
39, 14 Linia, VO St. Petersburg, 199178, Russia
E-mail: sokol@iias.spb.su, pavlov62@list.ru

KEYWORDS

Supply network, distribution planning, transportation model, scenario, sensitivity analysis.

ABSTRACT

A real case study of distribution planning is considered. An original approach to analysis of multi-stage, multi-commodity distribution network in the multi-period mode with adaptive update of demand, capacity, and supply information is proposed. Optimal distribution plans are calculated for optimistic and pessimistic scenarios. Subsequently, these plans are analyzed subject to different disturbances and regarding distribution network design and sourcing planning decisions. The performed sensitivity and structural analysis reveals some interesting managerial insights into building robust distribution plans and interconnecting decisions on distribution network design, planning, and sourcing.

INTRODUCTION

Distribution network (DN) planning is a referenced research problem that is vital in many supply chains (SC) in order to successfully meet the customer needs while improving the performance efficiency (*Mula et al. 2010*). Given a location structure from facility planning, customer demand from forecasting, and order quantities from inventory management and sourcing planning, the aggregate distribution volumes in the DN and to customers need to be determined for a middle-range period of time (e.g., one month) so that the total costs (e.g., transportation and inventory) and service level (e.g., the relation of the planned and actual product flow) are improved (*Tayur et al. 1999*). The problem is typically constrained by limited capacity of nodes and arcs (*Akkermann et al. 2010*).

Due to increase in complexity of modern supply chains (SC), the multi-stage, multi-period, and multi-commodity DN planning challenges the decision-making in this domain (*Amiri et al. 2006*). Another challenge is uncertainty of demand and supply. This forces the companies to build up inventories, transportation capacities, and use additional distribution centers as alternative distribution channels (*Santoso et al. 2005*). All these counter-measures cause the *excessiveness* of DN which in turn requires additional investments subject to an increase in fixed costs as the price for robustness (*Bertsimas and Sim 2004, Peng et al. 2011*).

Along with the importance of the optimization approaches to DN planning, research community has also recognized importance of the DN analysis.

The research focus of this study is subject to dynamic analysis of (1) the impact of different disturbances on distribution execution and (2) the actual usage of the created robustness excessiveness and nevertheless possible bottlenecks. Such an analysis has a great practical importance since the companies are very interested in the results of those studies which would help them to estimate the investments into different redundancies to mitigate uncertainty or their reduction and the impacts of these investments/reductions on the changes in SC performance (*Craighead et al. 2007*).

STATE OF THE ART

The preliminary analysis of the problem has shown that it could be modelled as stochastic maximal flow model, i.e. as maximal flow models or minimal cost flow models (*Lin 2001, Chou et al. 2011*) and fuzzy-models. However, the existing studies in this research area have not explicitly considered possible structure dynamics and its impact on the flows and cost.

First, deviations or failures in the network structures and operations are possible, but not unrealistic or describable with some probabilistic assumptions. In addition, the DN structural states do not change permanently, but rather in some intervals. Besides, the current execution characteristics of flows (e.g., cross-docking processing) should be considered. The next peculiarity is the necessity to take decisions on operative reconfiguration in case of emergency.

A significant practical challenge is partial information

Proceedings 26th European Conference on Modelling and Simulation ©ECMS Klaus G. Troitzsch, Michael Möhring, Ulf Lotzmann (Editors)
ISBN: 978-0-9564944-4-3 / ISBN: 978-0-9564944-5-0 (CD)

unavailability at the zero point of time as well as information updates during the execution. Finally, some other peculiarities such as return flows, many varying parameters, and multi-objective problem formulation may represent barriers in applying graph-theoretical methods.

Another possibility to model the considered problem can be the mathematical programming (MP)-based implementation (*Melo et al. 2010*). However, due to the above-mentioned peculiarities, the number of variables and constraints became very large and would force us to make some unrealistic assumptions regarding dynamic changes in control and structural parameters.

MATHEMATICAL MODEL

Distribution planning model

We propose to apply an original concept called structure dynamics control (SDC). SDC is a process of producing control inputs and implementing the SC transition from the current macro-state to a planned one (in the planning mode) or any other feasible state (in the disruption-recovery mode) in which the SC adaptation can be performed and the desired performance can be achieved over the given period of time (*Ivanov et al., 2010, Ivanov and Sokolov, 2012*).

The main idea of the SDC-based models is the dynamic interpretation of SC planning and control in accordance with the natural logic of time and the corresponding execution processes (e.g., transportation) with the help of optimal program control (OPC). However, the solution procedure is transferred to other methods (e.g., MP). In this setting, the solution procedure becomes undependable from the continuous optimization and can be of discrete nature, e.g., a linear programming, transportation problem, or integer allocation problem. The planning model has been presented in details in the study by *Ivanov et al. (2011)* and is not included in this paper.

Scenario-oriented analysis

Optimal distribution plans are calculated for optimistic and pessimistic scenarios. The DN is considered as a dynamic non-stationary system. The changes of DN structure (e.g., because of changes in transportation costs, contracts with suppliers, unplanned transportation resource unavailability) are referred as SC structure dynamics (*Ivanov et al. 2010*). With DN structure dynamics, the scenarios of SC execution are set up.

The distinguishing feature of the proposed approach is that the execution scenarios are generated nor randomly, but on the basis of an original approach to network structure reliability assessment developed by authors (*Kopytov et al. 2010*). Based on this method, the nodes 1, 4, and 7 (see Figure 1) have been revealed as critical operations in the considered DN. In Figure 1 corresponding execution scenarios are presented.

In Figure 1, structure dynamics scenarios are depicted. $St_{i_1,i_2,...,i_k}$ denotes the structural state where $i_1,i_2,...,i_k$ are numbers of missing or disrupted operations (nodes) in the network shown in Figure 1.

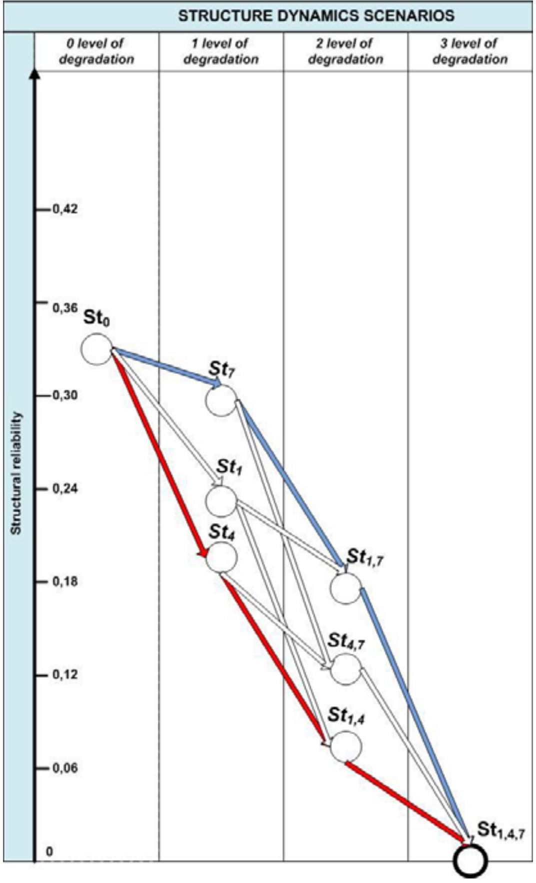


Figure 1. Structural reliability and structure dynamics scenarios

The blue line depicts the optimistic and the red one – the pessimistic scenario.

In order to formalize the above-mentioned dynamic changes, let us introduce a dynamic alternative multi-graph (DAMG):

$$G_\chi(t)=\left\langle X_\chi(t),E_\chi(t),W_\chi(t)\right\rangle, \qquad (1)$$

where the subscript χ is the number of an execution scenario, the time point t belongs to a given set T, $X_\chi(t)=\{A_{xi}(t), i\in N_\chi\}$ is a set of nodes on the DN, $E_\chi(t)=\{e_{xij}(t),\ i,j\in N_\chi\}$ is a set of arcs in the DN, and $W_\chi(t)=\{w_{\chi ij}(t),\ i,j\in N_\chi\}$ is a set of operation characteristics for the transportation (if $i\neq j$) or processing at warehouse (if $i=j$).

The elements of the time-spatial matrix function $e(t)$ define the links between A_{xi} and A_{xj}, and $e_{xij}(t)$ is equal to 1, if a transportation from A_{xi} to A_{xj} is possible, 0 – otherwise. In the DN, different products $\rho \in P = \{1,2,...,p\}$ of different importance may be served.

Let us define elements of the set $W_\chi(t) = \{w_{\chi ij}(t),\ i,j \in N_\chi\}$ which describe transportation, processing, and warehouse operations:

- $V_{\chi i}(t)$ is maximal warehouse capacity of the node $A_{\chi l}$;
- $\psi_{\chi i\rho}(t)$ is maximal inbound processing intensity of the product ρ in $A_{\chi l}$;
- $\omega_{\chi ij\rho}(t)$ is maximal transportation intensity of the product ρ between $A_{\chi i}$ and $A_{\chi j}$;
- $\varphi_{\chi i\rho}(t)$ is maximal outbound processing intensity of the product ρ from $A_{\chi i}$.

We assume that each network element within the subintervals (structure constancy intervals) is characterized by these characteristics which do not change within this interval.

CASE STUDY

A DN of an enterprise in the FMCG (fast moving consumer goods) branch is considered. The DN is composed of two mega-hubs (nodes 1 and 6), a central distribution hub (node 4), two intermediate terminals (nodes 2 and 3), an outsourcing terminal (node 7), and a regional distribution center (node 5). The execution in each of the nodes and transportation arcs is limited by maximal warehouse capacity, processing intensity, and transportation intensity correspondingly, see Figure 2.

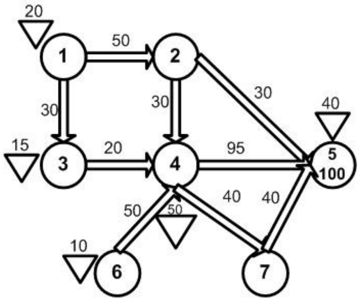


Figure 2. Distribution network structure

In Figure 2, triangles refer to the warehouse capacity and numbers on the arcs refer to maximal transportation intensity. The suppliers first deliver goods to the mega-hubs 1 and 6. Then, the goods shall be processed in the central distribution hub 4 via cross-docking. The goods from the hub 1 should be additionally processed at intermediate terminals 2 and 3. From the hub 4, the goods are moved to the regional distribution center 5 that has a certain demand in each of the periods (i.e., 100 units). In order to take into account possible problems with the channel 4-5, an outsourcing terminal is used as an alternative way for deliveries to the distribution center 5. Besides, it is possible to move small quantities (maximal 30 units) directly from the terminal 2 to the center 5.

The transportation volumes are constraint by maximal transportation intensity (as noted on the arcs in Fig. 1). The stocking volume is constraint by maximal warehouse capacities as shown by triangles in Fig. 2. The processing at terminals and hubs is constrained subject to maximal in- and outbound processing intensities. The suppliers deliver certain order quantities to the nodes 1 and 6 at the beginning of each period, and many periods are involved into the planning horizon. The adaptive planning procedure is applied, i.e., the demand and order quantities become known only shortly before the beginning of the next period, and are known only for this period.

It is assumed, that:

- transportation/processing intensities and warehouse capacities may change in each period,
- the demand of the regional distribution center may change in each period,
- any node or arc in the network may be temporarily unavailable,
- order quantities may vary in each period,
- inventory of the previous periods may be used in the next periods,
- if the processing intensity and warehouse capacity are exceed by the delivered quantity, the unprocessed and unstored goods are sent back to an additional warehouse (not in the main network) subject to additional costs,
- sourcing, transportation and inventory costs are assumed to be a linear function from the quantities,
- inventory costs are count in each of the periods,
- fixed costs are related to both nodes and arcs and are proportionally distributed between them.

The problem consists of the DN optimal plan sensitivity analysis subject to disturbance impact on SC and interconnection with the decisions in capacity and sourcing planning.

EXPERIMENTAL RESULTS

Planning results

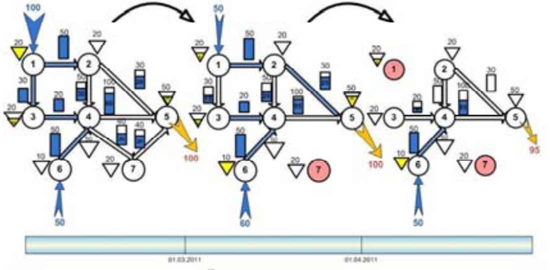
Let us consider the optimistic and pessimistic scenarios. We consider three intervals of the structural constancy. The problem is to maximize the service level under the assumption of the demand of 300 units for the planned period of three months (i.e., 100 units each month) whilst minimizing the costs as composed of the storage, transportation, return, sourcing, and fix costs.

In the *optimistic trajectory*, the events for the transition to the second interval are the changes in sourcing volumes at nodes 1 and 6 as well as a failure in the operation of the terminal 7. Analogously, the transition to the third interval of the structural constancy is launched by the failure in the operation of the mega-hub 1 and terminal 7 along with the change in the sourcing volume in the node 6.

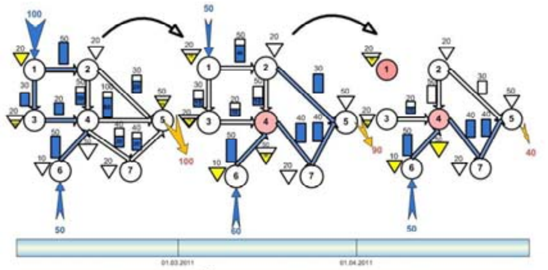
In the *pessimistic trajectory*, the events for the transition to the second interval are the changes in sourcing volumes at nodes 1 and 6 as well as unavailability of the link from the central distribution hub 4 to the regional distribution center 5. Analogously, the transition to the third interval of the structural constancy is launched by the failure in the operation of the mega-hub 1 and further unavailability of the link from the central distribution hub 4 to the regional distribution center 5 along with the change in the sourcing volume in the node 6.

Therefore, the SC structure dynamics considers both the adaptive planning (i.e., changes in the sourcing volumes) and disturbances (i.e., node failures). Note that the demand and supply quantities for the next months become known only shortly before the beginning of this new period and only for this period.

In Figure 3, results of optimal planning subject to the highest priority of the service level component in the goal function for the optimistic and pessimistic scenarios are presented.



a) Optimistic scenario



b) Pessimistic scenario

Figure 3. Distribution plans for optimistic (top) and pessimistic (buttom) scenarios

The yellow triangles show the warehouse capacities and their actual utilization. The blue quadrangles represent the transportation channel capacities and the actual transportation quantities.

Through the running of the planning model under the assumption of the high priority of the service level component in the goal function, optimal solution for the optimistic scenario allows to deliver 295 units which is equal to the service level of 98,3% subject to the planned demand of 300 units. Total inventory in all the periods is 125 units with a distribution among periods as 50 units in the first period (caused by excessive sourcing quantities at the nodes 1 and 6), 60 units in the second period, and 15 units in the third period.

Total cost and revenue have been calculated under the following assumptions: transportation cost per unit = 0.1, inventory cost per unit = 0.07, sourcing cost per unit = 0.4, return cost = 0.2, fixed cost for the DN = 90, and selling price = 1. It can be observed that in the optimistic scenario, a profit of 42.75$ can be achieved.

Optimal solution for the pessimistic scenario allows to deliver 230 units which is equal to the service level of 76,7%. Total inventory in all the periods is 200 units with a distribution among periods as 50 units in the first period (caused by excessive sourcing quantities at the nodes 1 and 6), 70 units in the second and 80 units in the third period (caused mainly by the break in deliveries from 4 to 5). The operative reconfiguration in the second period is suggested to increase transportation intensities on the arcs 4-7-5 and 2-5. The operative reconfiguration in the third period is suggested to increase transportation intensities on the arc 4-7-5. It can be observed that in the pessimistic scenario, the selling volume decreases significantly and no profit can be achieved. The losses amount to 21$.

Obviously, if the decision-maker is a pessimistic psychological type, SC design and sourcing decisions should be reconsidered. For example, an alternative link from the node 4 to the node 5 may be introduced along with an additional node on sourcing subject to the mega-hub 1. Warehouse capacities can also be increased. In the optimistic scenario, the failure of the node 7 does practically not influence the flow volume. That is why it can be suggested to analyse a DN structure without this node subject to possible reduction of fixed costs. Subsequently, in both of the scenarios, sourcing decisions may be reconsidered, especially in the first period.

For answering these and many other interesting questions, an analysis of different possible DN structures and execution scenarios is needed.

Scenario-oriented analysis

The further analysis may include two basic decision groups: (1) analysis of DN plans in different scenarios of the SC structure dynamics subject to different disturbances and (2) analysis of SC design excessiveness and flexibility subject to capacity and sourcing planning decisions. In particular, the following questions can be addressed:

- What elements are critical for the SC design and what elements are excessive and can be removed without decreasing the service level?
- Do additional costs in SC design elements pay off

by the increase in the service level subject to mitigating the negative effects of possible operation failures or a large delivery flow volume?

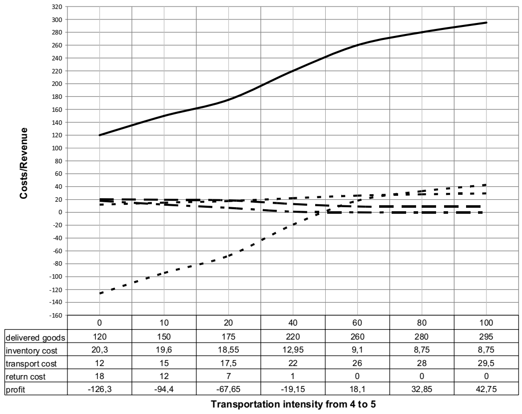
- What are the bottlenecks of the SC structure and where additional elements are needed?
- How sensitive are the SC structures and optimal solutions (i.e., the DN plans) to different execution scenarios?

Disturbance analysis

Let us analyse the plans ($\delta_{optimistic}, \delta_{pessimistic}$) subject to the following disturbances:

- *variant 1* – decrease in transportation intensity on the way $4 \rightarrow 7 \rightarrow 5$,
- *variant 2* – decrease in warehouse capacity at the node 4,
- *variant 3* – decrease in transportation intensity on the way $4 \rightarrow 5$, and
- *variant 4* – influence of all the variants simultaneously.

Plan $\delta_{optimistic}$ turned out to be stable subject to the disturbances of variants 1 and 2. In Figure 4 the analysis of the *optimistic plan* sensitivity to the disturbance of the variant 3 is presented.



	0	10	20	40	60	80	100
delivered goods	120	150	175	220	260	280	295
inventory cost	20,3	19,6	18,55	12,95	9,1	8,75	8,75
transport cost	12	15	17,5	22	26	28	29,5
return cost	18	12	7	1	0	0	0
profit	-126,3	-94,4	-67,65	-19,15	18,1	32,85	42,75

Figure 3. Analysis of the optimistic plan sensitivity to the disturbance of the variant 3

From the Figure 3 it can be observed that the positive profits may be achieved by the transportation capacity decrease to up to the 50 units. After this point, the number of the delivered goods and, as follows, the revenue fall significantly while the costs increase.

In Figure 4, results of sensitivity analysis for the *pessimistic scenario* plan subject to the disturbances 1-4 are presented.

Corresponding cost- and revenue-based analysis can be performed analogously to the optimistic scenario as shown in Figure 3. An example of such an analysis for the disturbance 3 is presented in Figure 5.

From the Figures 3-5 it can be, e.g., observed that:

o decrease in transportation intensity on the way $4 \rightarrow 5$ (disturbance no. 3) does not significantly influence the cost, but considerably impact the volume of delivered goods in optimistic plan. On the contrary, the volume of delivered goods in pessimistic plan is influenced by disturbance no. 3 only to a small extent.

o disturbance no. 1 influences the volume of the delivered goods only in the pessimistic scenario.

o decrease in warehouse capacity at the node 4 (disturbance no. 2) does not influence the volume of the delivered goods neither in the pessimistic not in the optimistic scenario. This is due to reserve warehouse capacities at the other nodes in the DN,

o disturbances of the variants 1 and 2 increase the volume of return flows to 15 and 20 units correspondingly. But their mutual impact (disturbance no.4) increases the volume of return flows to 60 units (see Figure 5).

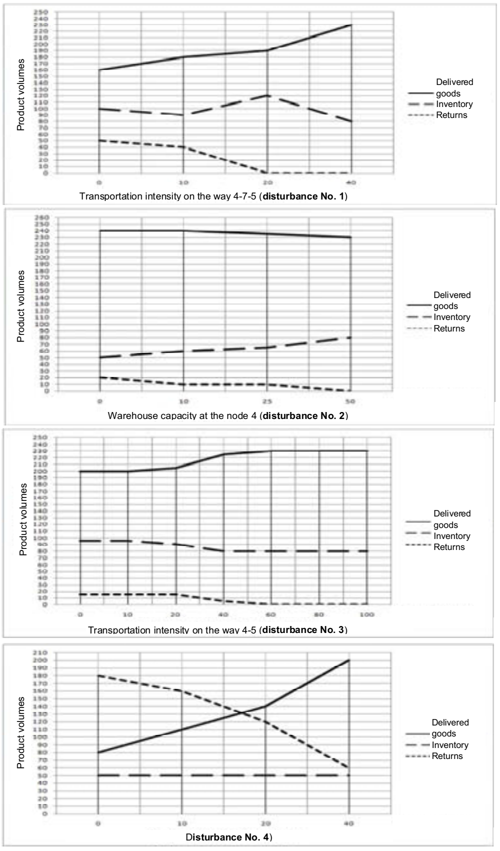
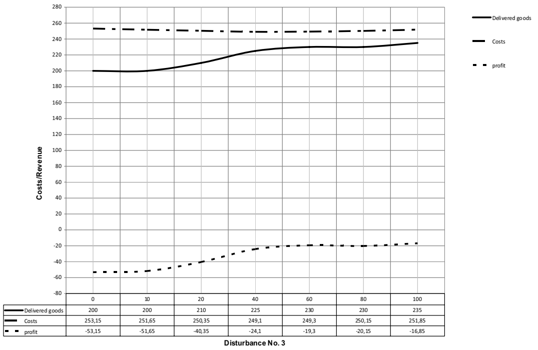


Figure 4. Quantity-based analysis of the pessimistic plan sensitivity to the disturbances of the variants 1-4



	0	10	20	40	60	80	100
Delivered goods	200	200	210	225	230	230	235
Costs	253,15	251,65	250,35	249,1	249,3	250,15	251,85
profit	-53,15	-51,65	-40,35	-24,1	-19,3	-20,15	-16,85

Figure 5. Cost-based analysis of the pessimistic plan sensitivity to the disturbances of the variant 3

Structural analysis

In this part, in particular, the following questions have be addressed:

- What elements are critical for the SC design and what elements are excessive and can be removed without decreasing the service level?
- Do additional costs in SC design elements pay off by the increase in the service level subject to mitigating the negative effects of possible operation failures or a large delivery flow volume?
- What sourcing quantities can be recommended for different scenarios?

To answer the *first* question, in Figure 6, a re-designed DN structure is presented subject to smaller warehouse capacities at the nodes 3, 7, 2 and 5 as well as smaller intensity of transportation channels 2→4 and 4→5.

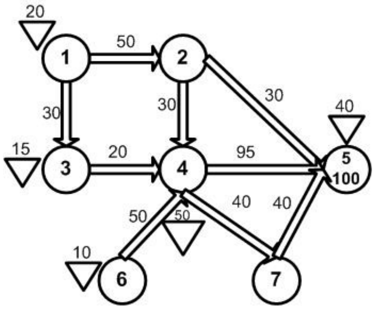


Figure 6. Re-designed DN structure

The smaller capacities result in a decrease of fixed cost of 12$. Both for the optimistic and pessimistic scenarios, the same volume of the delivered goods as in the initial DN structure can be realized. Total cost in the optimistic scenario will be reduced from 252.25 to 240.25$, and the profit increases from 42.75$ to 54.75$. In the pessimistic scenario, total cost will be 239.5 instead of 251.5 and the losses will be reduced from 16.5$ to 4.5$.

CONCLUSIONS

In this study, we extended the planning and control frameworks for supply chains by taking into account the integrated consideration of distribution network planning and analysis. A real case study of distribution planning has been considered. An original approach to analysis of multi-stage, multi-commodity distribution network in the multi-period mode with adaptive update of demand, capacity, and supply information is proposed. Optimal distribution plans are calculated for optimistic and pessimistic scenarios. Subsequently, these plans are analyzed subject to different disturbances and regarding distribution network design and sourcing planning decisions. The performed sensitivity and structural analysis reveals some interesting managerial insights into building robust distribution plans and interconnecting decisions on distribution network design, planning, and sourcing.

ACKNOWLEDGMENTS

This research described in this paper is partially supported by grants of Russian Foundation for Basic Research (RFBR) (10-07-00311, 11-08-01016, 11-08-00767), Saint-Petersburg Scientific Center RAS (SPII RAS project 2011), and the program of fundamental investigation of the department of Nano Technologies and Information Technologies RAS (project 2.3).

REFERENCES

Akkerman R., Farahani, P., Grunow, M. 2010. Quality, safety and sustainability in food distribution: a review of quantitative operations management approaches and challenges. OR Spectrum, 32:863–904.

Amiri A. (2006). Designing a distribution network in a supply chain system: Formulation and efficient solution procedure European Journal of Operational Research, 171, 2, 567-576.

Bertsimas, D., Sim, M. 2004. Price of Robustness. Operations Research, 52(1) 35-53.

Chou, M.C., Chua, G.A., Teo, C.-P., Zheng, H. (2011) Process flexibility revisited: The graph expander and its applications. Operations Research 59 (5), pp. 1090-1105.

Craighead, C., Blackhurst, J., Rungtusanatham, M., & Handfield, R. (2007). The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities. Decision Sciences, 38 (1), 131-156.

Ivanov, D., Sokolov B., Käschel J., 2011. Integrated supply chain planning based on a combined application of operations research and optimal control, Central European Journal of Operations Research, 19(3), 219-317.

Ivanov, D., Sokolov, B. (2010), Adaptive Supply Chain Management, Springer, London et al.

Ivanov, D., Sokolov, B. (2012). Dynamic supply chain scheduling. *Journal of Scheduling*, DOI: 10.1007/s10951-010-0189-6.

Ivanov, D., Sokolov, B., Kaeschel, J. (2010). A multi-structural framework for adaptive supply chain planning and operations with structure dynamics considerations. *European Journal of Operational Research*, 200(2), 409-420.

Kopytov E.A., Pavlov A.N., Zelentsov V.A. New methods of calculating the Genome of structure and the failure criticality of the complex objects' elements. In: Transport and Telecommunication, Vol. 11, No 4, 2010, pp. 4-13. (in Russian)

Lin, YK. (2001). A simple algorithm for reliability evaluation of a stochastic-flow network with node failure. Computers & Operations Research 28, 1271-1285

Mula, J., Peidro, D., Díaz-Madroñero, M., Vicens, E. (2010). Mathematical programming models for supply chain production and transport planning European Journal of Operational Research, 204, 3, 377-390.

Peng, P., Snyder, LV., Lim, A., Liu Z. (2011). Reliable logistics networks design with facility disruptions Transportation Research Part B: Methodological, 45, 8, 1190-1211.

Santoso, T., Ahmed, S., Goetschalckx, G. and Shapiro, A. (2005), "A stochastic programming approach for supply chain network design under uncertainty. European Journal of Operational Research, Vol. 167, pp. 96-115.

Tayur, S., R. Ganeshan and M. Magazine (Eds.). Quantitative Models for Supply Chain Management, Kluwer Academic Publishers, 1999.

AUTHOR BIOGRAPHIES

BORIS V. SOKOLOV is a deputy director at the Russian Academy of Science, Saint Petersburg Institute of Informatics and Automation. Professor Sokolov is the author of a new scientific lead: optimal control theory for structure dynamics of complex systems. Research interests: basic and applied research in mathematical modeling and mathematical methods in scientific research, optimal control theory, mathematical models and methods of support and decision making in complex organization-technical systems under uncertainties and multi- criteria. He is the author and co-author of five books on systems and control theory and of more than 270 scientific papers. Professor B. Sokolov supervised more over 50 research and engineering projects. *Homepage: www.spiiras-grom.ru.*

DMITRY IVANOV is full professor for international supply chain management at Berlin School of Economics and Law, Germany. He is the (co)-author of more than 170 scientific works, including the monograph Adaptive Supply Chain Management. His research interests lie in the area of adaptive supply chains, applied optimal control theory, operations research and business information systems. Member of the IFAC Technical Committee 5.2. His works have been published in various academic journals, including International Journal of Production Research, European Journal of Operational Research, Annual Reviews in Control, Journal of Scheduling, etc. *Homepage: www.ivanov-scm.com*

ALEXANDER N. PAVLOV is a senior researcher at the Russian Academy of Science, Saint Petersburg Institute of Informatics and Automation. Associate Professor Pavlov is the author and co-author of more than 130 scientific papers. His research interests are related to the development of scientific bases of control theory of structural dynamics of complex organizational and technical system.

Homepage: www.spiiras-grom.ru