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**TRANSPORT AND TELECOMMUNICATIONS INSTITUTE**

ANDREJS SOLOMENIKOVŠ

**SIMULATION MODELLING AND RESEARCH OF MARINE  
CONTAINER TERMINAL LOGISTICS CHAINS  
CASE STUDY OF BALTIC CONTAINER TERMINAL**

**SUMMARY OF DOCTORAL THESIS**

Riga, 2007



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**SUMMARY OF DOCTORAL THESIS**

for scientific degree of Telematics and Logistics

**SUPERVISOR:**

Dr. habil. sc. ing., professor  
Jurijs Merkurjevs, RTU

**CONSULTANT:**

Dr. habil. sc. ing., professor  
Igorš Kabaškins, TSI

Riga, 2007

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**SOLOMENIKOV, A.**

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**THE PROMOTION WORK PRESENTED AT THE TRANSPORT AND  
TELECOMMUNICATION INSTITUTE FOR THE SCIENTIFIC DOCTORAL IN  
TELEMATICS AND LOGISTICS**

**LIST OF OPPONENTS:**

- Dr. rer.nat. habil., Privatdozent **Jurijs Tolujevs**, Otto von Guericke  
Universität Magdeburg, Germany
- Dr. habil. sc. ing., professor **Jevgeņijs Kopitovs**, Transport and  
Telecommunication Institute, Latvia
- Dr. sc. ing., professor **Egils Ginters**, Vidzemes Augstskola, Latvia

The presentation and defence of the thesis will be held on April 17, 2007 at 16:00 at the Promotion Council of Transport and Telecommunication Institute Lomonosova 1, conference hall (auditorium 103), Riga, Latvia, phone: +371 7100617, fax: +371 7100535.

**AUTHOR'S STATEMENT**

Herewith I, Andrejs Solomenikovs, confirm that I have created the promotion work presented to the Transport and Telecommunication Institute for the doctoral degree in Telematics and Logistics. The promotion work has not been presented at any other university to obtain the scientific degree.

March 19, 2007

\_\_\_\_\_ Andrejs Solomenikovs

The doctoral thesis language is English; the thesis contains 172 pages, 5 chapters, 13 tables, 124 references to external sources, and 72 figures.

## ABSTRACT

The present summary represents an overview of doctoral thesis SIMULATION MODELLING AND RESEARCH OF MARINE CONTAINER TERMINAL LOGISTICS CHAINS. CASE STUDY OF BALTIC CONTAINER TERMINAL by Andrey Solomennikov in Logistics and Telematics. The promotional work has been supervised by RTU professor Dr. habil. sc. ing., corresponding member of Latvian Academy of Sciences Jurijs Merkurjevs and consulted by TSI professor Dr. habil. sc. ing., corresponding member of Latvian Academy of Sciences Igors Kabaškis.

The main results presented in the thesis are based on work performed over the time period of 2002-2003 under the Baltports-IT IST-2001-33030 project *Simulation and IT Solutions: Applications in the Baltic Port Areas of the Newly Associated States*. The results were presented in ten publications, and seven international conferences.

The thesis presents methodology and analysis for creation and practical application of simulation models of marine container terminals featuring trucks as horizontal means of container transportation.

The paper presents an original methodology based on parametric and non-parametric methods of mathematical statistics developed for creation of simulation model of marine container terminals, its verification and validation, as well as its subsequent application for practical purposes. The parameter simulation model adjustment has been presented as the task of Nelder and Mead direct optimization method of stochastic object function on a stochastic set of arguments. The object function has been defined as discrepancy of empirical functions of cumulative probability and tested for homogeneity using the Kolmogorov-Smirnov test statistic.

An important aspect of the developed model is its practical value, which has been illustrated in solving a series of tasks practical among which were determining the optimal size of truck workgroups, determining resource operational cycle times basing on BCT historical net productivity data, and economic analysis and optimal choice of resources in terms of cost efficiency.

The methodology presented in the paper allowed creation of a flexible simulation model easily adjustable also for other logistic systems such as airports, freight train hub terminals, mining facilities of natural resources, etc.

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# 1. SIGNIFICANCE OF RESEARCH

## 1.1. GLOBAL TRENDS

Today over 60% of the world's deep-sea general cargo is transported in containers, whereas some routes, especially between economically strong and stable countries, are containerized up to 100%.

FIGURE 1 shows the containerization trend with high increasing rates compared with the rates of world trade, seaborne trade and the gross domestic product (GDP) of the world.

The increasing number of container shipments causes higher demands on the seaport container terminals, container logistics, and management, as well as on technical equipment. An increased competition between seaports, especially between geographically close ones, is a result of this development.

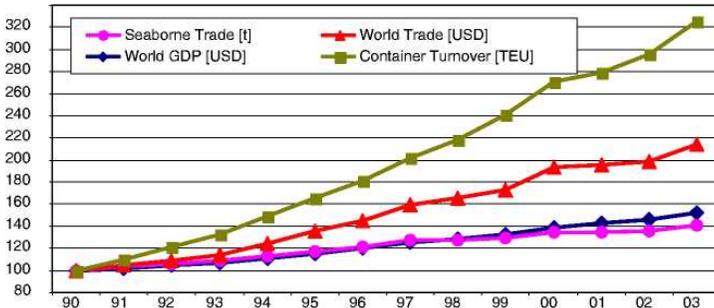


FIGURE 1. Containerization trend: high growth of container turnover

Due to increasing seaborne trade and container cargo flow, increasing marine container terminal throughput will be becoming a critical issue. The results of the thesis contribute to the contemporary issue of increasing performance of marine container terminals by offering a general methodology for simulation modelling and practical application.

## 1.2. SIGNIFICANCE OF SIMULATION MODELLING AS ANALYSIS TOOL

The role of simulation to evaluate alternative management policies is fundamental, especially when the policies are computer-generated and the human decision-makers have not a complete understanding of all their details. Moreover, computer generated policies are obtained from modelling assumptions that can often seem too restrictive in comparison to the complexity and the stochasticity of real world operations. A well-designed simulation tool can be the middle ground where the decision-makers compare their own experience with the decision support system-generated management policies and validate them.

Due to its complexity and time and labor-expensive, the field simulation of marine container terminals remains much uncovered. The importance and topicality of the issue as well as scarcity of research in the field of marine container terminals simulation modelling in 2001 caused European Commission to initiate an international project on specific research in the field of applied simulation modelling Baltports-IT IST-2001-33030 project *Simulation and IT Solutions: Applications in the Baltic Port Areas of the Newly Associated States*.

The present thesis covers the contemporary issue of practical applicability of simulation modelling for marine container terminals for optimization and increasing overall container terminal productivity.

## 1.3. PREVIOUS RESEARCH

Marine container terminal modelling and optimization is a broad scientific field representing a complex modelling problem. Besides that, there comes a high degree of problem specificity to a given container terminal due to technological differences in marine container terminals. Thus, there has been performed research on different aspects of container terminal modelling resulting in a large number of publications in this and respective areas.

Previous scientific research on Baltic Container Terminal has been carried out under DAMAC-HP project starting 1993 by Y. Tolujew, L. Novitsky, Y. Merkurjev, and E. Bluemel.

Specifically, the issues of simulation related to container terminals can be attributed to one of the following classes of problems:

- Berth allocation
- Vessel loading and discharge

- Intra-terminal container transportation
- Container stacking optimization
- Inter-terminal transport and other modes of transportation
- Simulation modelling of complete container terminals

The list of researchers covering each of the issues outlined above is presented below.

### **1.3.1. Berth allocation**

The aspects of modelling vessel arrival and berth allocation to arriving vessels at marine container terminals have been covered in sufficient depth by Guan, Y., Cheung, R.K., Imai, A., Nagaiwa, K., Tat, C.W., Nishimura, E., Papadimitriou, S., Kim, K.H., Moon, K.C., Legato, P., and Mazza, R.M.

### **1.3.2. Vessel loading and discharge**

Vessel loading and discharge as well as container stowage planning were researched by Avriel, M., Penn, M., Shpirer, N., Witteboon, S., Daganzo, C.F., Kim, K.H., Park, Y.M., Peterkofsky, Wilson, I.D., and Roach, P.A. Most of the works deal with quay crane scheduling methods and stowage optimization problem.

### **1.3.3. Intra-terminal container transportation**

For reference on optimization of container movement from quay cranes to storage locations and vice versa the works by the following authors are worthwhile: Baker, C., Bish, E.K., Leong, T.Y., Li, C.L., Simchi-Levi, D., Böse, J., Reiners, T., Steenken, D., Voss, S., Chen, Y., Leong, Demir, E.K., Nelson, Evers, J.J.M., Koppers, S.A.J., Grunow, M., Günther, H.O., Lehmann, M., Kim, K.H., Bae, J.W. Steenken, D., Henning A., Freigang, S., Voss, S., Van der Meer, J.R., De Koster, R., Roodbergen, K.J., Peeters, L.W.P. Savelsbergh, M.W.P. Vis, I.F.A., and Harika, I. Most of the works

### **1.3.4. Container stacking optimization**

The issues of storage space allocation and optimization of container stacking on storage yards have been covered by Chen, T., Chao, S.L., Hsieh, T.W., Cheung, R.K., Li, C.-L., Lin, W., Chung, Y.G., Randhawa, De Castilho, B., Daganzo, C.F., Holguin-Veras, J., Jara-Diaz, S., Kim, K.H., Bae, J.W., Kim, H.B., Kim,

K.Y., Kang, J.S., Ryu, K.R., Lee, K.M., Hwang, H., Park, Y.M., Kozan, E., Preston, P., Ng, W.C., Zhang, C., Wan, Y.W., Liu, J., Linn, R.J.

### **1.3.5. Inter-terminal transport and other modes of transportation**

Intermodal transportation of containers from container terminal to other means of transportation has been researched by Ballis, A., Abacoumkin, C., Bostel, N., Dejax, P., Duinkerken, M.B., Ottjes, J.A., Evers, J.J.M., Kurstjens, S.T.G.L., Dekker, R., Dellaert, N.P., Kozan, E., Newman, A.M., Yano, C.A., Van Horsen, W.

### **1.3.6. Simulation modelling of complete container terminals**

Complete container terminal operations have been modelled and documented by Abacoumkin, C., Ballis, A., Bish, E.K., Gambardella, L.M., Rizzoli, A.E., Zaffalon, M., Hartmann, S., Kia, M., Shayan, E., Ghotb, F., Kozan, E., Meersmans, P.J.M., Vis, I.F.A., De Koster, M.B.M., Dekker, R., Wagelmans, A.P.M., Merkuryev, Y., Tolujew, Bardachenko, V., J., Blümer, E., Novitsky, L., Ginters, E., Vitorova, E., Merkuryeva, G., Pronins, J., Shabayek, A.A., Yeung, W.W., Van der Meer, Van Hee, K.M., Huitink, B., Leegwater, D.K., Wijbrands, R.J., Yun, W.Y., Choi, Y.S., Henesey, L.

Taking into consideration increasing goods flow and growing importance of container terminals, there have been several international projects funded by EU covering issues of marine container terminal simulation modelling such as projects such as AMCAI, DAMAC-HP, SPHERE and BALTPORTS-IT. The resulting works covered general issues related to marine container terminals outlined above.

## 2. GENERAL INFORMATION ON RESEARCH

### 2.1. AIM OF THE RESEARCH

The subject of the research is logistics chains and multimodal processes at marine container terminals. The case study was performed on facilities of Baltic Container Terminal serving as a sample of marine container terminal logistics systems featuring trucks as horizontal transport of containers.

The general aim of the research is increasing marine container terminal efficiency by means of application of simulation modelling. Technically, it is required to build a simulation model that would be capable of ‘*what if?...*’ scenario testing for application of diverse combinations of resources at a required level of realism.

The complexity of the research has been caused by the requirements imposed by the management of terminal. In order to insure model realism, the model had to be based on the real inputs of the container terminal. On the contrary, many of the simulation described above in paragraph 1.3. PREVIOUS RESEARCH deal with approximated inputs which does not allow application of the model for real needs of terminal management (see illustration in FIGURE 2 below).

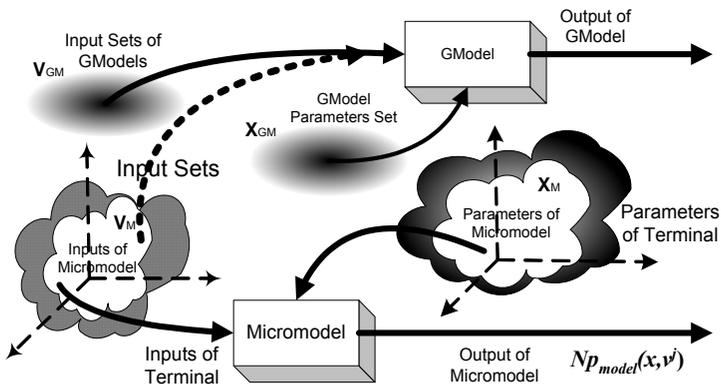


FIGURE 2. Illustrated comparison of sets of parameters and inputs of general models and those used in micro-simulation modelling.

Thus, the specific aim of research was solving several practical tasks outlined in part 3.7. PRACTICAL APPLICATIONS OF SIMULATION MODEL.

The challenging complexity of the research task called for a thorough methodology which resulted in a creating a general approach to creation of simulation models of such class of objects.

## 2.2. METHODOLOGY AND TOOLS

In order to complete the goal set out in the research, the modelling approach was adjusted for the specificity of the task. Thus, the methodology featured the following steps specific for the task in focus:

- *Arriving at a rational level of detailing by constructing hierarchically integrated models* until the acceptable level of model details elaboration is reached. Reaching an acceptable level of micro-operations of the technological chain. Reaching an acceptable level of elaboration of parameter modelling and resource logics and rules (e.g. with two and more quay or yard cranes simultaneously involved, the truck logics might employ different rules such as choosing the server basing on minimal quay length). The next step is verification of resource overlap logics adequacy and correction of visualized structural models. Once it has been verified that the model properly depicts the logics of technological chains at accepted level of elaboration, we proceed to the next step.
- *Parameterization* of the model consists of creating an interface for inputting control parameters and monitoring and visualization of internal variables of the model.
- *Adjusting control parameters* of the models.
- *Modelling and adjusting inputs of the model*, i.e. creating sub-model blocks for scenario modelling (analyzing situations ‘*what if input statistics change?*’)
- *Application for solving practical problems*. Section 3.7. PRACTICAL APPLICATIONS OF SIMULATION MODEL of the present paper presents utilization of the model for choosing an appropriate set of resources subject to several constraints.

The logical model which consequently served as the basis for the simulation model represented in the research was created in co-operation with BCT operational personnel and management of the BCT. The final logical model later implemented as the basis for the simulation model was verified by the management of BCT.

The structure of the logical model (structure of resource cycles, operation logics, durations of resource micro-operations) was developed on-field through measurement and observations as well as from management of Baltic Container terminal. The input data used both for simulation model parameter adjustment and model verification were BCT database container statistics basing on 142 vessel observations over a period of several months of container terminal operations. The statistics included the following parameters for each of the 142 vessels: number of 20ft import and export containers, 40ft import and export containers, hatch covers, containers and net productivity data as container moves per hour.

The logical model verified by the BCT management was implemented in several simulation models created in micro-simulation software environment *Arena* of Rockwell Software.

The task of parameter adjustment of the simulation model was solved by application of the developed two-tier methodology combining both parametrical and non-parametrical methods of statistical analysis. The main underlying mathematical algorithm is based on Kolmogorov-Smirnov test for two empirical cumulative distribution function statistical identity.

### 2.3. SCIENTIFIC INNOVATION OF RESEARCH

The paper presents an original developed methodology for simulation modelling of marine container terminals. Specifically, the following major points of the research represent scientific innovation:

- there has been created a simulation model of Baltic Container Terminal at predefined level of detailing. The created simulation model represents an original marine container terminal micro-simulation in terms of depth of detailing and visualization.
- there has been developed an original two-tier algorithm for simulation model parameter adjustment using productivity cumulative empirical distribution functions. The algorithm is based on combination of parametrical and non-parametrical methods of statistical analysis. The algorithm is covered in more detail in section **3.4.1. Two-tier parameter adjustment algorithm** on page 19 of the present review.

- the paper represents an efficient approach for choosing a rational level of simulation model detailing through top-to-bottom hierarchically integrated simulation models. The approach is presented in paragraph 3.2. CHOOSING LEVEL OF SIMULATION MODEL DETAILING on page 11.
- practical application of the developed simulation model represents a new approach developed in the research for choosing an optimal combination of resources which yields more reliable results than the traditional method. The approach is presented in 3.7. PRACTICAL APPLICATIONS OF SIMULATION MODEL on page 31.

The methodology and simulation model presented in the thesis are original in respective class of models which is confirmed by a series of publications featured in project proceedings of “Applications of Simulation and IT Solutions in the Baltic Port Areas of the Associated Candidate Countries project BALTPORTS-IT (2001-2003)” funded by the 5<sup>th</sup> IST Programme of the European Commission as well as in other publications.

#### 2.4. PRACTICAL VALUE AND APPLICATION OF THE RESEARCH

The developed simulation model was applied by the management of the terminal for solving the following practical tasks:

- determining the optimal size of truck workgroups for the Baltic Container Terminal and number of trucks on net productivity
- determining resource operational cycle times basing on BCT historical net productivity data for workgroups consisting of three, four, and five trucks respectively.
- there was solved the problem of choosing the most cost-efficient set of resources among available ones using the simulation model. Thus with the help of the simulation model, there was chosen a combination of one of the three available quay cranes, one of the three available yard cranes, and one of three truck brigades of either four, five, or six trucks.

There have been illustrated and compared two approaches to the economic task of choice of cost-efficient equipment for the Baltic Container Terminal: the traditional slowest link approach and simulation-based analysis. It has been discovered that despite the attractive simplicity of the slowest link method it shows unsatisfactory degree of solution precision for the economic analysis.

The necessary degree of precision which is important for logistic systems like BCT calls for more precise tools like stochastic modelling methods which nowadays gain on popularity in estimation of business projects.

The work has demonstrated that a thoroughly developed simulation model of specific operations affected by random fluctuations allows determination of basic technological and economic data as well as allows quantitative estimation of the associated economic and technological uncertainty of the modelled operations.

## 2.5. OVERVIEW OF THESIS STRUCTURE

The doctoral thesis contains 172 pages, 5 chapters, 13 tables, 124 references to external sources, and 72 figures.

### 3. MAIN RESULTS OF THE RESEARCH

#### 3.1. INTRODUCTION TO BALTIC CONTAINER TERMINAL

In the early eighties to meet constantly growing demand in container traffic, to and from the main industrial centers of the ex-Soviet Union, the Port of Riga was the exclusive port in the Baltics designated as ideal for the development of a specialized container terminal. The decision was made after having considered the favorable geographical location, developed rail and road networks to Moscow, Pskov, Novograd, St. Petersburg, Minsk, Kiev, Vilnius, Tallinn, Alma-Ata Tashkent and other major destinations.

The infrastructure available includes much more than a normal feeder port would normally require and BCT has a capacity of handling in excess of 325,000 TEU per annum in its present state.

Baltic Container Terminal complete pool of quayside and landside transport includes the following units: 3 quay cranes, 6 yard cranes, 10 tractor (truck) units, 2 reachstackers (capable of transporting 40ft containers), and over 30 forklifts. The breakdown by resource type and manufacturer is represented in TABLE 1 below.

TABLE 1. Breakdown of quayside and landside transport of Baltic Container Terminal by quantity, type, and manufacturer.

<b>Quayside Cranes</b>				
<b>Manufacturer</b>	<b>Quantity</b>	<b>Capacity</b>	<b>Outreach</b>	<b>Backreach</b>
Kone	1	30.5T	32m	12.5
Kone	2	35.0T	32m	12.5
<b>Yard Cranes</b>				
<b>Manufacturer</b>	<b>Quantity</b>	<b>Capacity</b>	<b>Stacking Capabilities</b>	<b>Type</b>
Kone	4	30.5T	19 accross 1 over 4	Rail Mounted Yard
Kone	2	30.5T	Railway Track	Rail Mounted Yard
<b>Tractor Units</b>				
<b>Manufacturer</b>	<b>Quantity</b>			
SISU	8			
Terberg	2			

TABLE 1. Breakdown of quayside and landside transport of Baltic Container Terminal by quantity, type, and manufacturer (continued from page 10).

<b>Reach Stackers</b>		
<b>Manufacturer</b>	<b>Quantity</b>	<b>Capacity</b>
Kalmar	2	41T
<b>Forklifts</b>		
<b>Manufacturer</b>	<b>Quantity</b>	<b>Capacity</b>
Kalmar	5	25T
Kalmar	1	13T
TCM	2	5.25T
Linde	1	3.5T
Toyota	1	3T
Hyster	4	2T
Toyota	8	1.5T
TCM	4	1.5T
Nissan	2	1.8T
Nissan	1	4T
Toyota	2	2T

### 3.2. CHOOSING LEVEL OF SIMULATION MODEL DETAILING

In the process of modelling an important and challenging task is choosing a reasonable level of detail abstraction of the logistic model so that the model remains comprehensible for the end-user without losing its explanatory power. While choosing an appropriate depth of detailing an important factor to consider is not to overcomplicate the model since the end-user (in the case of BCT simulation model it is largely the management of the terminal) should be capable of verifying (and if necessary modifying) model's logical structure.

The structure and depth of detailing should contribute to the ultimate goal of the research which is creation of an adequate flexible simulation model of logistics chains of operational elements of the Baltic Container Terminal. Such a model should rapidly address diverse '*what if...?*' situations and assist the management in decision-making with regard to the optimal resource allocation and workload in the everyday dynamic set-up.

The logic of the BCT simulation system assumes consequent rational detailed elaboration of processes, from general overview models down to more detailed ones with a developed hierarchical structure of embedded sub-models.

As a result of this approach, there has been created a framework of four models, namely:

- Model 1:* a general model of BCT integrated in the logical structure of agencies and other terminals (1st level of detailing)
- Model 2:* a model of service processes of every single vessel entering the port on up to three berths. This model portrays the logics of simultaneous servicing of several vessels (up to three at a given time) and allows user changes in workload schedules as well as changes in productivity of each individual resource.
- Model 3:* a detailed model of every separate berth portraying in detail loading and discharge of every single move (container unit and restow containers) for a single vessel.
- Model 4:* a detailed model of loading and discharge processes (included hatch covers) with underlying resource allocations and their monitoring with accuracy up to one second.

While the first three models will be briefly described below, the 4th model will be considered in more details. This consideration will first refer to verification and validation of the lowest-level model. Its verification was performed by several traditional approaches including a walkthrough and involving independent as well as terminal specialists, at both operational and managerial levels. As a result, the program logic was refined and approved by terminal management.

It should be pointed out that *Model 1* leads us to an important conclusion as for modelling of BCT activities. Independently of number of moves to be done on each single vessel, the container terminal tends to minimize the estimated servicing duration. Thus, one of the most unwanted cases from the point of view of operational workload would be if a vessel of a high-priority line entered the terminal with a substantial delay. In order to compensate for this delay, the terminal would try to employ all of its available resources and line up their

activity in the most time-efficient way. Therefore, optimal resource allocation is important for the core business of BCT, and will be given substantial attention in this project.

*Model 2* attempts to estimate the influence of diverse algorithms of work teams on the vessel servicing times and thus a theoretical throughput of the terminal. A further consideration of the model revealed the necessity for considering a lower level model that would depict the underlying processes in detail.

*Model 3* allows further analysis of loading and discharge processes of a vessel on one berth. Further insight into *Model 3* revealed the need for ability of addressing each single resource unit and their flexibility in allocation on several berths (servicing several vessels). As a result, the technical modelling became even more complicated; this, however, considerably improved the reality and flexibility of the model.

These possibilities are provided in *Model 4* that represents the next level of detailing. This is a lowest-level model of terminal operation. A further level of detailing seems to be unnecessary, as it would involve a large number of additional variables that could hardly be measured in reality and the time elapsed for modelling would be inappropriate for quick-enough decisions.

### 3.3. DESCRIPTION OF MICRO-SIMULATION MODEL

Let us consider micro-simulation *Model 4* that realizes the lowest level of BCT operations. FIGURE 3 portrays the structural scheme of resource types necessary for vessel loading and discharge processes.

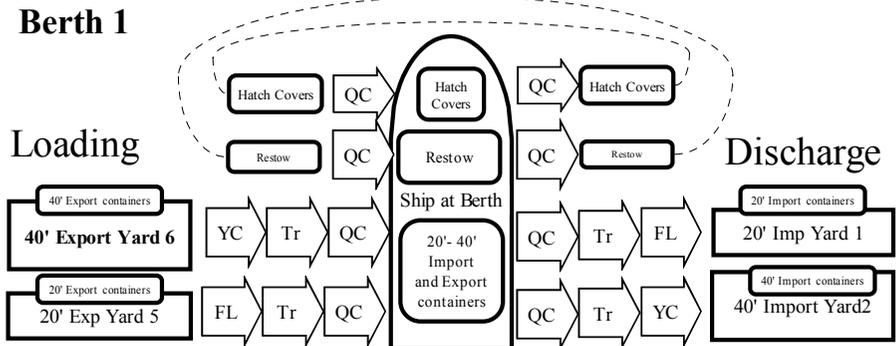


FIGURE 3. Resource allocation map within Model 4

Notations: YC -Yard Crane, Tr -Trucks, QC - Quay Crane, FL - ForkLift.

The right-hand side of the scheme labeled Discharge depicts the sequence of processes involved in discharging containers off a vessel. The main element of the discharge sequence is the technological chain of delivery of 20ft and 40ft incoming (import) containers. Consequently, the left-hand sub-scheme of the figure above illustrates the process sequence of loading containers on board. The additional two cycles of loading and discharging are dictated by the necessity of modelling operations with hatch covers and restow containers.

The logical framework for resources employed in BCT micro-simulation model is illustrated in FIGURE 4.

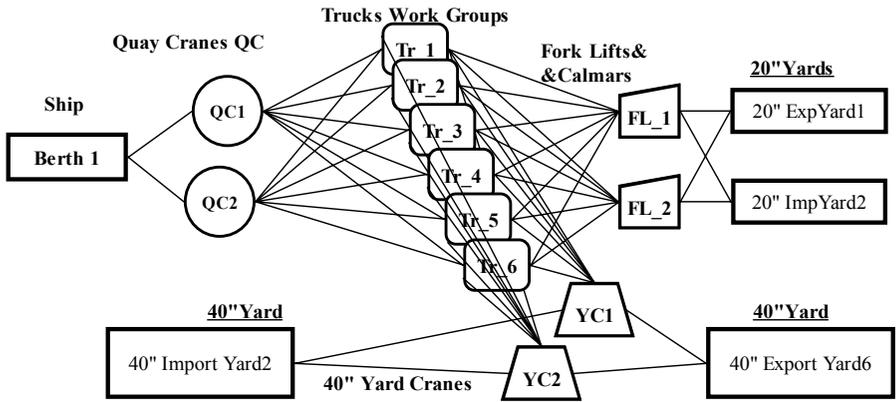


FIGURE 4. Logical structure of allocating different types of resources in BCT micro-simulation model

**3.3.1. Simulation model variables**

There are special reserved variables for each vessel that contain information on vessel and shipping line name, vessel arrival/departure schedule, as well as additional information necessary for terminal proceedings.

By the present moment, there has been modelled one berth of BCT which in deep detail depicts loading and discharging of one vessel. Since the model allows adjusting parameters at every model run, which to a tremendous affect model performance, let us consider the adjustment variables of the model.

There can be distinguished six groups of variables involved in the simulation model:

1. **INPUT** variables
2. **STATE (CONDITION)** variables
3. **CONTROL** variables
4. **MONITORING** variables
5. **VISUALIZATION** variables, and
6. **OUTPUT** variables

### 3.4. PARAMETER ADJUSTMENT

Model inputs  $\mathbf{v}^j \in \mathcal{V} \subset \mathcal{V}$  and model output  $Np_{model} \in \mathbf{R}^+$ , where  $\mathbf{R}^+$  is a set of positive numbers with the set of model parameters  $\mathbf{x} \in \mathcal{X}$  belonging to a feasible subset  $\mathcal{X} \subset \mathcal{X}$  represents an implicit function of several variables  $Np_{model}(\mathbf{x}, \mathbf{v}^j)$ . The input vector of the model  $\mathbf{v}^j \in \mathcal{V}$  can be described as a regularized sequence of discrete values of number of containers and hatch covers carried by a  $j^{\text{th}}$  vessel.

$$\mathbf{v}^j = (\mathbf{v}^j_{20Import}, \mathbf{v}^j_{40Import}, \mathbf{v}^j_{hatches}, \mathbf{v}^j_{restow}, \mathbf{v}^j_{20Export}, \mathbf{v}^j_{40Export}) \quad (1)$$

where

- $\mathbf{v}^j_{20Import}, \mathbf{v}^j_{40Import}$  - number of import (inbound) 20ft and 40ft containers,
- $\mathbf{v}^j_{hatches}$  – number of hatch covers to be processed for freeing up necessary containers,
- $\mathbf{v}^j_{restow}$  - number of restow containers (containers to be temporarily moved ashore to free up access to other containers),
- $\mathbf{v}^j_{20Export}, \mathbf{v}^j_{40Export}$  - number of export (outbound) 20ft and 40ft containers,
- $j=1, 2, \dots, N_v$ , where  $N_v$  – set of feasible combinations (1) for the vessels to be processed by the terminal.

The formal task of the parameter adjustment is as follows: it is required to map values of  $Np_{model}(x, v_j)$  of random inputs  $v_j \in \mathcal{V} \subset \mathcal{V}$  and randomly distributed parameters  $\mathbf{x} \in \mathcal{X}$  into output  $Np(x, v_j) \in \mathbf{R}^+$  whereas the parameters of the model  $\mathbf{x} \in \mathcal{X}$  and its output  $Np$  belong to the given feasible sets  $\mathcal{X}^+$  and  $\mathbf{R}^+$  (set of positive rational numbers). The formalized task of the research is illustrated in FIGURE 5 below.

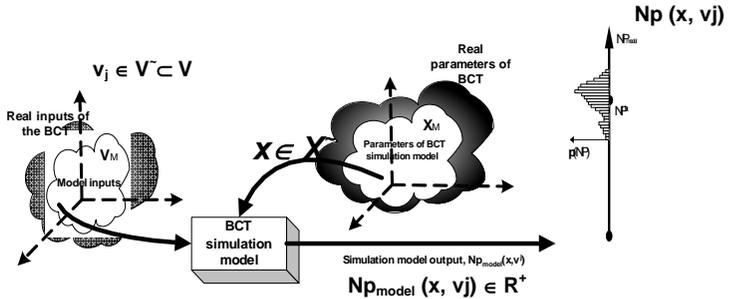


FIGURE 5. Illustration of the formal aim of the research.

Any vessel modelled belongs to a definite set of vessels, since the tonnage and belonging to a shipping line cannot be of random nature. Generally speaking, vessel sequence is a discrete, almost non-stationary flow. This vessel flow is almost regular over time since vessels fall into time window schedules; however, reality shows constant delays caused by weather conditions and other technical reasons. Since we are not interested in the statistics of input vector component distribution with regard to vessel flow, vessel distribution as such remains beyond the scope of the present research.

The vector of the parameters of the model  $x \in X$  represents durations of resource micro-operations in technological chains of moving containers and hatch covers. Probability distributions of vector co-ordinates  $x_i$  is approximated by asymmetric triangular distributions, each defined by three parameters, namely the lower boundary  $xmin_i$ , mode  $xmod_i$ , and upper boundary  $xmax_i$ . The feasible scope of  $x_i$  vector values is subject to technological constraints which define the set  $X$ .

$$a_i \leq xmin_i, xmax_i \leq b_i, xmin_i < x_i < xmax_i, i = 1, 2, \dots, N_x \quad (2)$$

where  $a_i, b_i$  - lower and upper restraining boundaries for parameter  $x_i$ ,  $N_x$  - dimension of model parameter space.

Let us define the expression

$$\{Np^j_{terminal}, v^j\} \quad (3)$$

where  $Np^j_{terminal} \in R^+, v^j \in V$

as a test sample of  $N_t$  observations, basing on which the model adequacy with regard to real-life data should be verified.

Let us define by  $f(\cdot)$  the statistic underlying some criterion of significance  $CR(\cdot)$ . Here  $CR(\cdot)$  is a criterion that defines the degree of adequacy of terminal sample data  $\{Np_{terminal}^j, v^j\}$  to the sample data of model output  $\{Np_{model}(x, v^j)\}$  along the same set of inputs  $v^j$ . Then comparing the criterion value

$$CR[\{Np_{terminal}^j, v^j\}, \{Np_{model}(x, v^j)\}]$$

with the calculated value  $CR(N_t)$  allows making a conclusion regarding coincidence of the real and model sample data.

Function  $f[Np_{terminal}^j, v^j, Np_{model}(x, v^j)]$  represents the object function when adjusting model parameters with sensitivity threshold:

$$f[Np_{terminal}^j, v^j, Np_{model}(x, v^j)] \leq CR(N_t) = \varepsilon_t \quad (4)$$

Now the general task of the research is as follows. Using simulation modelling it is required to construct a model (function)

$$Np_{model}(x, v^j), Np_{model} \in R^+, x \in X^-, v^j \in V^- \quad (5)$$

that would depict input vectors  $v_j$  of a feasible set of inputs  $v^j \in V^-$  into a scalar function  $Np_{model} \in R^+$  defined on the set of parameters  $x \in X^-$  as long as condition (4) holds.

The logical structure of such a model must correspond to the structure of logistical processes of the terminal so that visualization and animation of the processes facilitates process recognition and logical adequacy verification. The order of operations implemented in the model must realistically depict the order of operations of the terminal. Resource interaction at the micro-level (e.g. operations like quay crane placing container onto truck) must be well illustrated by the model.

Micro-level modelling casts a shaft of light onto queuing resulting at the points of container movement from one to another resource type. To illustrate this, let us consider the following situation: if the truck arrives at the quay crane, which is busy at the moment lifting container off the vessel then the truck is waiting for the quay crane, or conversely, if the quay crane is ready with its current job before the truck is there, it should stay in place awaiting the truck to arrive. Since

these micro-level operations arising across resource types in the logistics chain are not modelled directly but rather follow pre-modelled sets of rules, it is important to monitor these by introducing special monitoring variables to be used by report data arrays. The waiting periods should be clearly shown when visualizing, whereas the idle/active status of each resource unit should be displayed. Technically, it is the queues and respective characteristics that bring the degree of uncertainty which simulation models are best suited for.

In order to get down to calculations and model verification using real-life numerical data, it is first required to determine the feasible set of parameters  $X$ , i.e. to find more precise boundaries for vectors  $a$ ,  $b$  as per (2). The next step would be estimating parameters of triangular distributions ( $xmin_i$ ,  $xmod_i$ ,  $xmax_i$ ),  $i = 1, 2, \dots, N_x$ , where  $xmin_i$  is the lower boundary  $xmin_i$ ,  $xmod_i$  – the mode, and  $xmax_i$  standing for the upper boundary. The primary estimations are performed via direct measurement, expert opinions, and indirect methods.

Now let us formalize the most difficult task of the research, namely creating and implementing an approach for model parameter adjustment. The model output  $NP_{model}$  represents a random function, depending on a number of variables  $x_i$ , most of which are also random. Probability distributions of these variables in the model are approximated by asymmetric triangular distributions. Queuing at the quay and yard cranes is also of a random character which leads to non-linear dependence of model outputs on the parameters.

Another reason of non-linearity is the calculation of  $NP_{terminal}$  of the terminal as value inverse to the average time of container move from vessel to the truck. Since  $NP_{terminal}$  data in the terminal database are stored as average values relying on the number of loaded, discharged, and restow containers as well as hatch covers for each vessel, it leads us to a conclusion that we are dealing with a non-linear random object function. It should be noted that such an object function represents no analytical function, since it is given implicitly through simulation modelling. Therefore a methodology for parameter adjustment should be searched among methods of non-linear programming and non-differentiable functions with given constraints to functions arguments.

Usually parameter adjustment is performed via minimization of difference of model outputs and those of the research object (which is the terminal statistics in our case)

$$\|NP_{model} - NP_{terminal}\| = f(x) \rightarrow \min \quad (6)$$

where  $f(x)$  – is the object function, and  $x$  stands for the vector of the parameters of the model.

However, in the case considered both the function  $f(x)$  and the parameters  $x$  are random values, whose distribution characteristic is not normal.

Having this in mind, let us apply special statistical procedures for hypothesis testing for random values by introducing corresponding statistics (functions) similar to that of (5):

$$f[Np^j_{terminal}, Np^j_{model}] - CR(N) \leq \epsilon_f \tag{7}$$

### 3.4.1. Two-tier parameter adjustment algorithm

In order to put theoretical considerations on parameter adjustment into practice, we need to find the minimum discrepancy of BCT observed data histograms and those of the model through changing the model parameter values. Taking the task in focus, an appropriate criterion of estimating degree of such histogram discrepancy would be the Kolmogorov-Smirnov test of respective cumulative functions of empirical distribution. The methodology is illustrated in FIGURE 6.

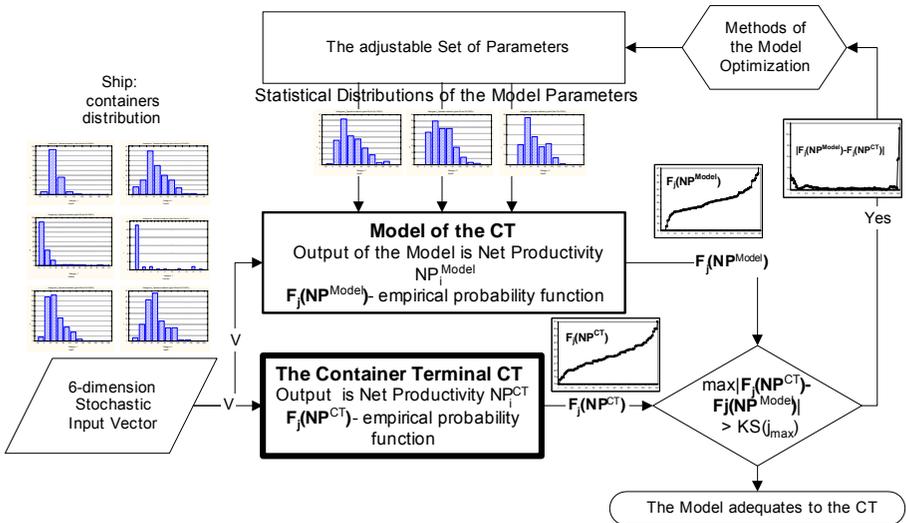


FIGURE 6. Illustration of parameter adjustment methodology

However, a straightforward application of Kolmogorov-Smirnov test on the subset of feasible parameters has a severe disadvantage: since the test in itself yields the maximum absolute discrepancy value of cumulative probability functions, for non-overlapping histograms the Kolmogorov-Smirnov test would yield one and the same value equal to one.

Once the iteration procedure reaches the mentioned threshold value, the object function is replaced with Kolmogorov-Smirnov criterion and the iteration procedure of parameter adjustment continues. As the threshold value for the new object function is reached, the process of parameter adjustment is finished. With this new threshold value reached, the output of the model corresponds to the output of the object (the BCT observed data) at given level of statistical significance. If the above-mentioned threshold value is not reached, the procedure stops at originally determined number of iterations. At this point we have to make decision to either modify the feasible subset of model parameters, or increasing the level of significance of Kolmogorov-Smirnov test, or revising and modifying the model itself.

### 3.4.2. Algorithm description

Let us describe the algorithm of adjustment of aggregated model parameters or resource cycles  $\mathbf{Tq}$ ,  $\mathbf{Tt}$ ,  $\mathbf{T}_y=\mathbf{Tf}$ .

In order the Nelder-Mead extremum search procedure to start we have to input the four points of the initial simplex.

STEP 1 Heuristically we choose co-ordinates of four initial points, the vertices of the simplex  $\mathbf{X}^{(1)}=[\mathbf{T}_q^{(1)}, \mathbf{T}_t^{(1)}, \mathbf{T}_y^{(1)}]$ ,  $\mathbf{X}^{(2)}=[\mathbf{T}_q^{(2)}, \mathbf{T}_t^{(2)}, \mathbf{T}_y^{(2)}]$ ,  $\mathbf{X}^{(3)}=[\mathbf{T}_q^{(3)}, \mathbf{T}_t^{(3)}, \mathbf{T}_y^{(3)}]$ ,  $\mathbf{X}^{(4)}=[\mathbf{T}_q^{(4)}, \mathbf{T}_t^{(4)}, \mathbf{T}_y^{(4)}]$ . The maximum number of iterations  $i_{\max}$  is chosen.

STEP 2 The co-ordinates of each point of  $\mathbf{X}^{(1)}$ ,  $\mathbf{X}^{(2)}$ ,  $\mathbf{X}^{(3)}$ ,  $\mathbf{X}^{(4)}$  are step-by-step input in the model. For each point there are performed calculations of  $\mathbf{k}$  values of net productivity  $[\mathbf{Np}_k^{(1)}]$ ,  $[\mathbf{Np}_k^{(2)}]$ ,  $[\mathbf{Np}_k^{(3)}]$ ,  $[\mathbf{Np}_k^{(4)}]$ , for  $\mathbf{k}=142$ .

STEP 3 The obtained  $4*\mathbf{k}$  values of net productivity  $[\mathbf{Np}_k^{(1)}]$ ,  $[\mathbf{Np}_k^{(2)}]$ ,  $[\mathbf{Np}_k^{(3)}]$ ,  $[\mathbf{Np}_k^{(4)}]$ ,  $\mathbf{k}=1,2,\dots, 142$ , are input in the database and are used for calculations fo the four values of the object function  $\mathbf{f}_t^{(i)}=$

$= 11.91638 * [\text{mean}(\mathbf{Np}_{\text{BCT}}) - \text{mean}(\mathbf{Np}^{(i)})] / s^{(i)}$ ,  $i=1,2,3,4$ ,  $11.91638 =$   
 $= (142)^{(1/2)}$  – standardizing coefficient  
 $s^{(i)}$  – square root of sample dispersion of observations  $[\mathbf{Np}_k^{(i)}]$ ,  $k=1,2,\dots,142$ .  
 $\mathbf{f}_t^{(i)}$  – values of the  $\mathbf{t}$ -statistic (Student distribution statistic),  $i=1,2,3,4$ .

**STEP 4** Launching Nelder and Mead algorithm. It is assumed  $i=i+1$ . The  $[\mathbf{Np}_k^{(i)}]$  vector parameters and object function  $\mathbf{f}_t^{(i)}$  (see below) values are calculated and stored in the database.

$$\mathbf{f}_t^{(i)} = 11.916 * [\text{mean}(\mathbf{Np}_{\text{BCT}}) - \text{mean}(\mathbf{Np}^{(i)})] / s^{(i)}.$$

**STEP 5** Testing if inequality below holds:

$$\mathbf{i} > \mathbf{i}_{\text{max}} \quad (\text{i})$$

where  $\mathbf{i}_{\text{max}}$  is the maximum number of iterations.

If inequality (i) does hold, the procedure stops, analysis of behaviour of object function basing on monitoring database data excerpt and the procedure leaps back to STEP 1.

If inequality (i) does not hold, the following inequality is tested:

$$\mathbf{f}_t^{(i)} \geq \mathbf{t}^{(*)} \quad (\text{ii})$$

where  $\mathbf{t}^{(*)}$  – cut-off of  $\mathbf{t}$ -statistic at **5%** level of significance for two-sided criterion with 142 degrees of freedom.

If the inequality (ii) is false, we move on to step 4.

On the contrary, if the inequality (ii) does hold, then we might conclude that at the first stage the necessary tolerance of solution has been reached and the procedure continues to stage two of parameter adjustment with the new object function and Kolmogorov-Smirnov test statistic.

**STEP 6** The final  $4 * k$  values of productivities  $[\mathbf{Np}_k^{(i-3)}]$ ,  $[\mathbf{Np}_k^{(i-2)}]$ ,  $[\mathbf{Np}_k^{(i-1)}]$ ,  $[\mathbf{Np}_k^{(i)}]$ ,  $k=1,2,\dots,142$ , are called from the procedure monitoring data base and are used for calculations of four values for the new object function.

$$\mathbf{f}_{\text{KS}}^{(i)} = \max[\mathbf{F}(\mathbf{Np}_{\text{BCT}}) - \mathbf{F}(\mathbf{Np}^{(i)})], \mathbf{j} = \mathbf{i}, \mathbf{i}-1, \mathbf{i}-2, \mathbf{i}-3,$$

$f_{KS}^{(j)}$  – statistic of the Kolmogorov-Smirnov test

STEP 7 Launching Nelder and Mead algorithm. It is assumed  $\mathbf{j} = \mathbf{j} + 1$ .. The  $[\mathbf{Np}_k^{(j)}]$  vector parameters and object function  $f_{KS}^{(j)}$  (see below) values are calculated and stored in the database:

$$f_{KS}^{(j)} = \max[F(\mathbf{Np}_{BCT}) - F(\mathbf{Np}^{(j)})], j = j+1, i, i-1, i-2, i-3$$

STEP 8 The following inequality is tested:

$$\mathbf{i} > \mathbf{i}_{\max} \quad (\text{i})$$

where  $\mathbf{i}_{\max}$  – is the maximum number of iterations

If inequality (i) does hold, the procedure stops, analysis of behaviour of object function basing on monitoring database data excerpt and the procedure leaps back to STEP 1.

In case the inequality (i) does not hold, the following inequality is tested:

$$f_{KS}^{(j)} \geq f_{KS}^{(*)} \quad (\text{ii})$$

where  $f_{KS}^{(*)}$  – Kolmogorov-Smirnov test statistic value at 5% level of significance for two-sided criterion with 142 degrees of freedom.

If the inequality (ii) proves false, the procedure leaps to STEP 7.

If the inequality (ii) does hold, then we might conclude that at the second stage the necessary degree of solution sensitivity has been finally reached.

The logics of the algorithm is summarized in FIGURE 7 on the next page.

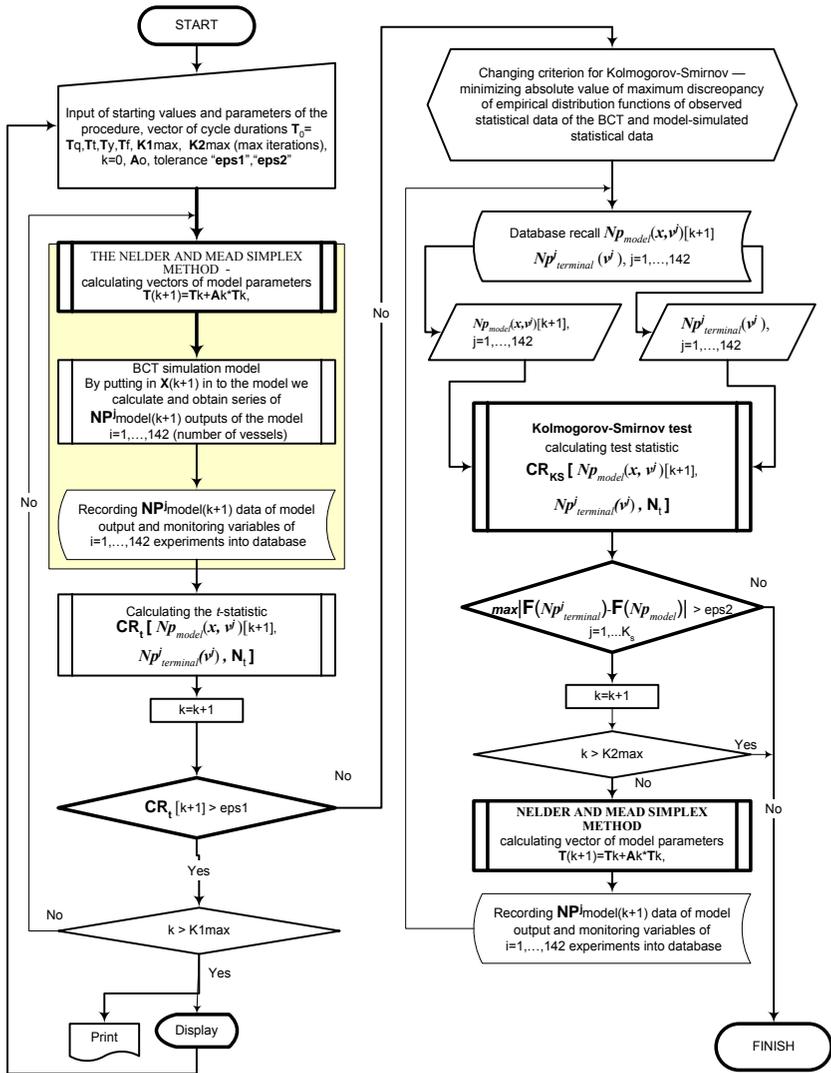


FIGURE 7. Graphical representation of parameter adjustment algorithm

### 3.5. OVERVIEW OF MICRO-SIMULATION MODEL

#### 3.5.1. Integrated resource models

This section presents the structure of the micro-simulation model of the *Baltic Container Terminal*.

The figure below presents a fragment of logic model of discharge (import) operations at Baltic Container Terminal (right-hand side of the FIGURE 8 below), depicting the following processes: 20ft container import, 40ft container import, hatch cover removal and replacement, and restow container processing.

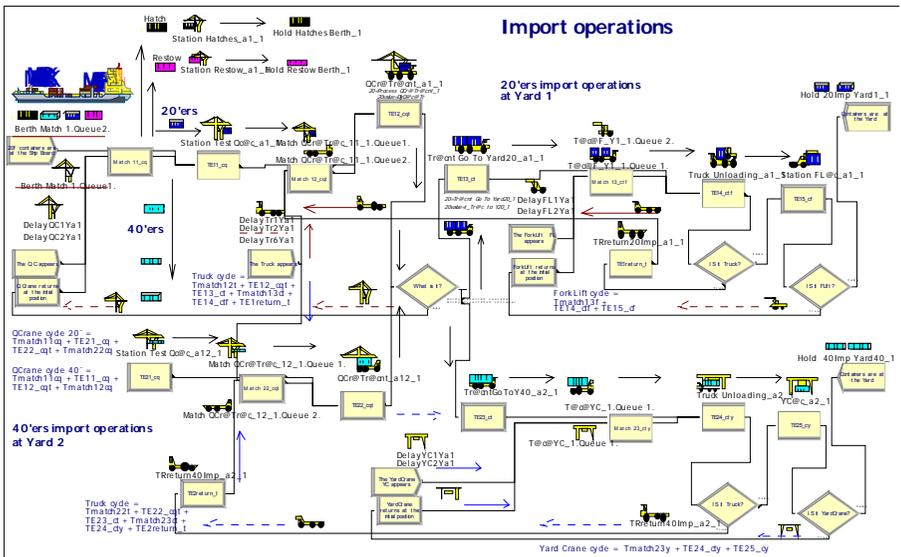


FIGURE 8. Model of logistic operations for import (discharge) operations

The next level of detailing outlines operational cycles of resource units.

#### 3.5.2. Quay and yard crane operational cycle

The necessary conditions for the quay crane to start working are the following events:

- test for current working time is positive
- test of container availability in the loading queue is also positive

The first condition allows taking regard in the model for lunch breaks, shift change breaks, and work stops due to equipment malfunction.

Testing for loading container availability is applied for the quay crane not to make unnecessary moves as well as not to remain in meaningless waiting for the container if the container queue is empty.

The quay crane work cycle is represented in FIGURE 9 below. Let us denote **T<sub>q</sub>** cycle the fastest no-delay work cycle.

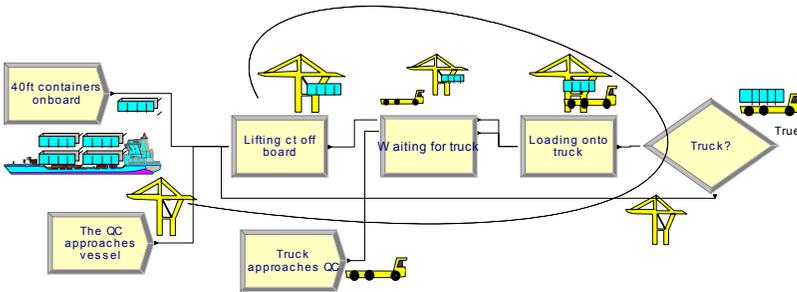


FIGURE 9. Quay crane operational cycle

The yard crane is modelled similarly to the quay crane with other parameters

### 3.5.3. Truck operational cycle

Modelling logics of truck operational cycle is more complicated than that of the crane operational cycles (see FIGURE 10). If we leave time losses in queues for loading at quay crane and respective time losses at discharge queues at the yard crane, the net cycle time would be referred to as the **T<sub>t</sub>** cycle.

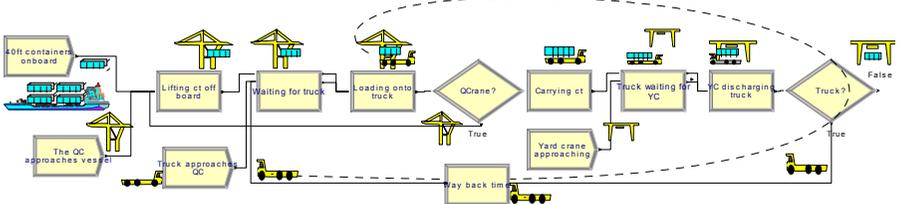


FIGURE 10. Truck operational cycle

Yet, at the lowest operation level each resource unit is controlled separately. The resource unit logics is in its turn implemented through a separate sub-model, e.g. as per illustration of quay crane below.

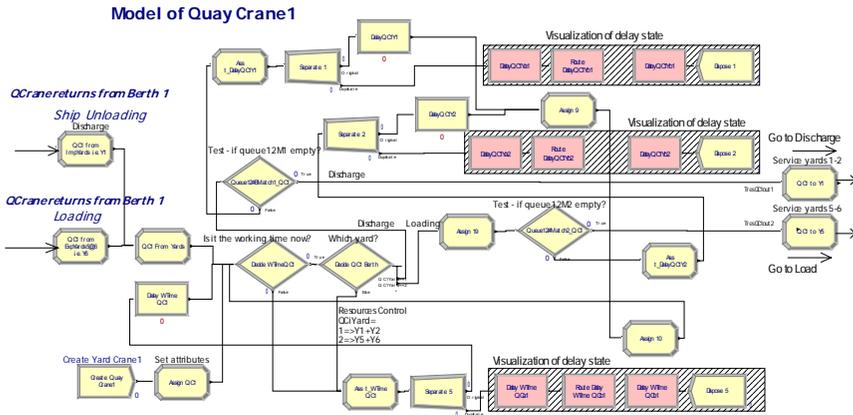


FIGURE 11. Quay crane logical model implemented in Arena package

Other resource units are modelled in a similar approach. The resource models represent integrated structure, illustrating a top-to-down level of abstraction approach.

### 3.5.4. Visualization and variable monitoring

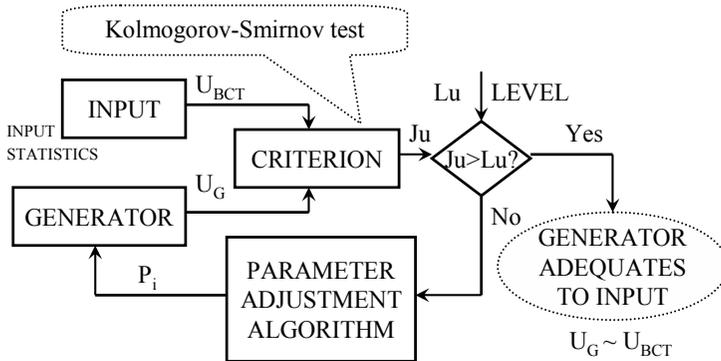
Another important aspect for the user of the model is to be able to associate the model processes with the real-life objects and operations. Thus, visualization represents a useful tool, by giving an understandable overview of the container terminal processes enabling the end-user to control the status of model variables, parameters, and output in real-time mode.

A sample screenshot in the simulation running mode featuring real-time monitoring of several variables and processes is presented in FIGURE 12.



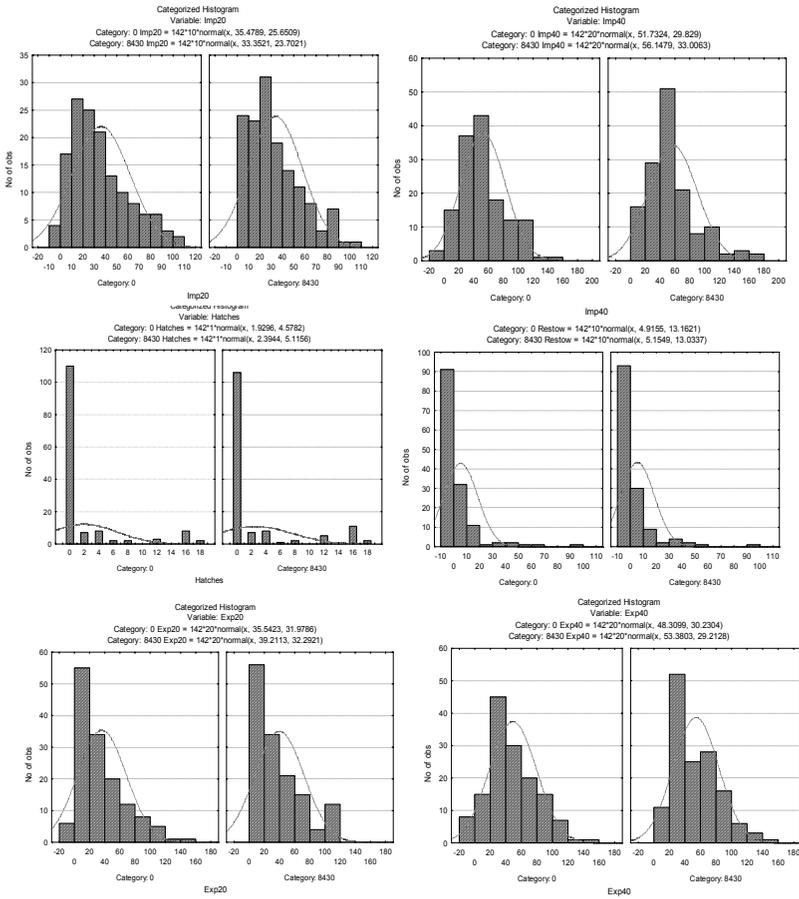
### 3.6.1. Calibration of input generators

The logic of implementation methodology developed to adjust distributions parameters of the input generators is depicted on FIGURE 13.



**FIGURE 13.** General methodology for calibration of input generators of the model output using Kolmogorov-Smirnov test.

The results of input generator validation (40ft import, 20ft import, 40ft export, 40 ft import, hatches, and restow containers) is represented in FIGURE 14 on the next page.



**FIGURE 14.** Visual representation of histograms of BCT observed real statistical data (left) with the model-generated values (right-hand side pane), positively verified by the Kolmogorov-Smirnov test

### 3.6.2. Calibration of model parameters

The adjustment of parameters was performed following the same general methodology based on Kolmogorov-Smirnov test outlined in the section above.

The graphical representation of the algorithm is portrayed in FIGURE 15.

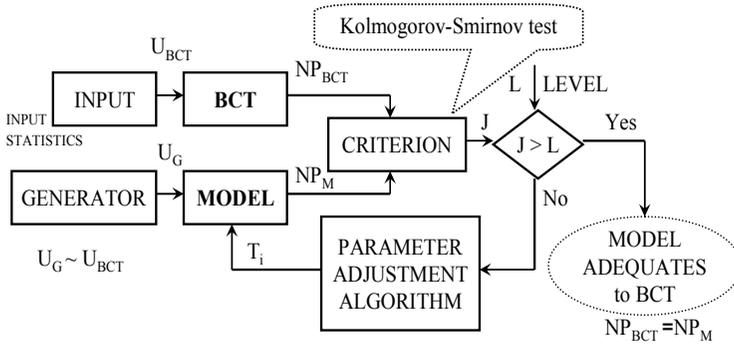


FIGURE 15. General methodology for adjustment of model parameters and validation of the model output using Kolmogorov-Smirnov test.

The model realism was validated against BCT database observed statistics of 142 vessel processing.

A comparative model-simulated and observed data output (net productivity) histogram chart is represented in FIGURE 16.

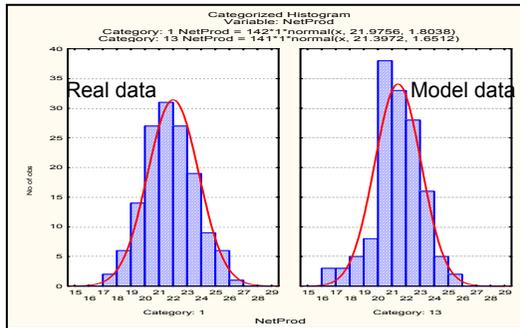


FIGURE 16. Comparing modeled and BCT observed output NP data: tested positive by Kolmogorov-Smirnov test

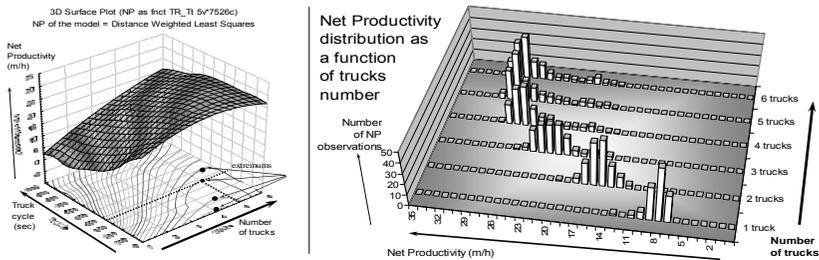
As the model output was tested statistically identical to the observed real data of the BCT terminal by the Kolmogorov-Smirnov test, with the inputs being also identical, the model can be considered successfully validated representing a statistically reliable simulation tool for practical applications.

### 3.7. PRACTICAL APPLICATIONS OF SIMULATION MODEL

The practical application includes three tasks approached with the help of the model: analyzing dependence of net productivity of the terminal on number of trucks, and economically efficient choice of resources.

#### 3.7.1. Dependence of net productivity on number of trucks

One of the described application tasks for the model was to define an optimal truck workgroup size for BCT operations. The dependence of net productivity on number of trucks was determined through a set of statistical experiments. The



**FIGURE 17.** It might be noted that the values of net productivity are near the maximum when using 4 trucks. The right-hand side pane portrays histograms of net productivity of the model, obtained with different number of trucks (Z-scale represents number of observations, Y-scale is net productivity (moves/hour), X-scale is number of trucks).

number of available trucks adversely affects the average time for moving each container, and consequently affects net productivity depending on the new average cycle time of a truck denoted **Tt**.

In order to discover the dependence of **NPm(TR)** [where **NPm** denotes **Net Productivity** of the **model**, moves/hour, and **TR**—the number of trucks available to the model], there were completed 142 vessel model cycle runs with 1-6 trucks accordingly. Thus, each number of trucks was tested in processing of 142 vessels. **FIGURE 17** portrays distribution of probability density **NPm(TR)** in experimental histograms and gives a rather full representation of the probabilistic nature of the dependency being studied.

It follows from the results of the modelling that marginal increase in net productivity drops with number of trucks exceeding four.

### 3.7.2. Economic analysis: choice of resources

The management of marine container terminals eventually face the problem of choosing an optimal set of resources among the available supply. Thus, following task was brought forward for the simulation model: among three available options of quay crane (for the sake of simplicity referred to as QC1, QC2, and QC3), three yard cranes (Y1, Y2, and Y3), and three available truck

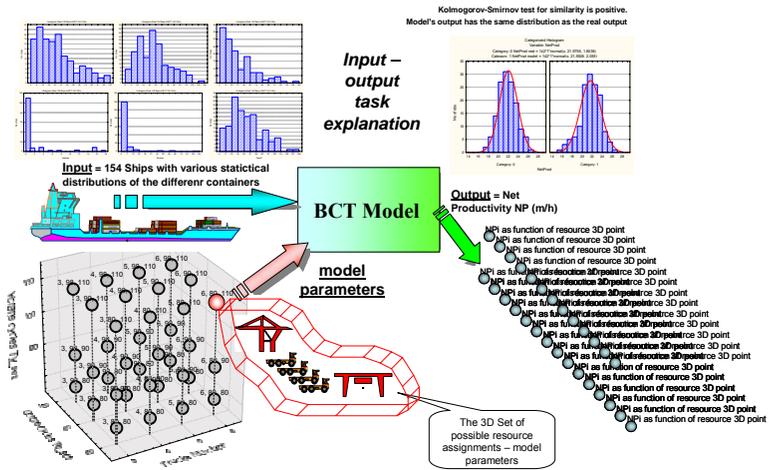


FIGURE 18. Illustration of methodology for economic analysis

workgroups of three to six trucks (Tr\_3, Tr\_4, Tr\_5, and Tr\_6) a logistic chain had to be made consisting of *quay crane-yard crane-truck workgroup*. The economic effect has to be given due attention since each resource unit has its unique performance and cost characteristics.

In order to complete this task, the performance statistics generated by the simulation model and develop a separate economic model incorporating the cost/efficiency data of the resources involved (see FIGURE 18).

The scope of possible combinations and set of relationships between terminal resources to be considered when addressing the problem studied is illustrated in FIGURE 19.

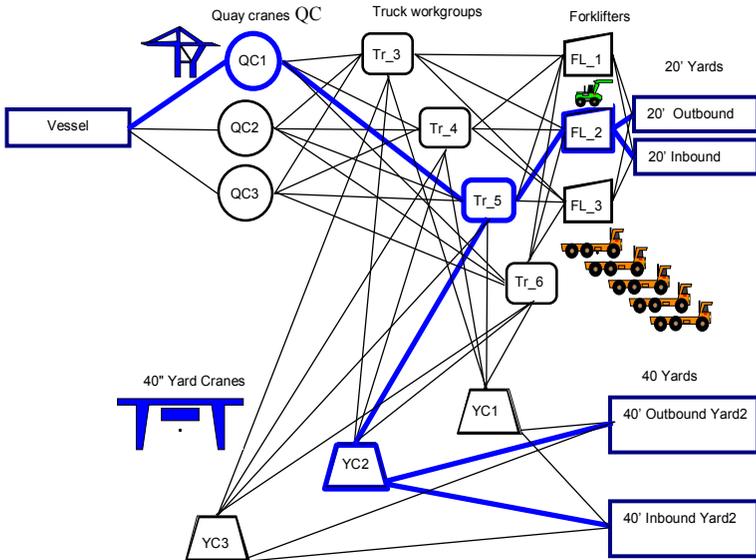


FIGURE 19. Scope of possible combinations of resources

The task in focus considers the following pool of resources:

- Three quay cranes, QC1, QC2, and QC3 having different initial cost  $Pq_1$ ,  $Pq_2$ , and  $Pq_3$ , and nominal maximal productivity of  $Nq_1$ ,  $Nq_2$ , and  $Nq_3$  (which are the average values of the work cycle  $Tq_{1\_set}$ ,  $Tq_{2\_set}$ ,  $Tq_{3\_set}$ ) and complete depreciation duration of  $Lq_1$ ,  $Lq_2$ ,  $Lq_3$ .
- Four sets of identical tug-masters 3Tr, 4Tr, 5Tr, 6Tr in work-teams of 3, 4, 5, and 6 machines per team. The tug-master sets have the initial cost of  $Pt_1$ ,  $Pt_2$ ,  $Pt_3$ ,  $Pt_4$ , average full work cycle time  $Tt1\_set = Tt2\_set = Tt3\_set = Tt4\_set = 430$  seconds  $\pm 10\%$  and identical service duration  $Lt_1 = Lt_2 = Lt_3 = Lt_4$ .
- Three types of yard cranes YC1, YC2, and YC3 having different initial cost,  $Py_1$ ,  $Py_2$ , and  $Py_3$ , nominal maximal productivity  $Ny_1$ ,  $Ny_2$ , and  $Ny_3$  (average cycle duration  $Ty1\_set$ ,  $Ty2\_set$ ,  $Ty3\_set$ ) and expected service durations of  $Ly_1$ ,  $Ly_2$ ,  $Ly_3$ .

The data mentioned above are wrapped up in a tabular form in TABLE 2.

TABLE 2. Technical characteristics and costs of resources

Resource type	Operational cycle, sec.	Nmax	Initial cost	Resource life time	Depreciation cost per operational hour
<b>QC1</b>	80	45	1000000	20	19.61
<b>QC2</b>	90	40	920000	20	18.04
<b>QC3</b>	98	37	870000	20	17.06
<b>YC1</b>	80	45	875000	20	17.16
<b>YC2</b>	90	40	820000	20	16.08
<b>YC3</b>	110	33	770000	20	15.10
<b>3Tr</b>	143	25	125000	7	12.25
<b>4Tr</b>	108	33	166700	7	16.34
<b>5Tr</b>	86	42	208000	7	20.42
<b>6Tr</b>	72	50	250000	7	24.51

It has to be noted that financial information (such as resource cost, terminal income per operational hour etc.) represents confidential information. For this reason, in this part of economic research were used estimates differing from the real data keeping the aspect ratio.

In order to formulate the mathematical description, we define the following:

**STqci**, **STyci**, **STtri** - depreciation costs of respective resource per working hour,

**SSqc** – quay crane personnel flat-rate salary per operational hour  $QC_i$ ,  $i=1,2,3$ .

**SSyc** – yard crane personnel flat-rate salary per operational hour  $YC_i$ ,  $i=1,2,3$ .

**SStri** – truck driver flat-rate salary per operational hour,  $Tri$ ,  $i=1,2,3,4$ .

**SENqc** – electricity costs of quay crane per operational hour,  $QC_i$ ,  $i=1,2,3$ .

**SENYc** – electricity costs of yard crane per operational hour  $YC_i$ ,  $i=1,2,3$ .

**SENtr** – fuel costs of truck workgroup per operational hour  $Tri$ ,  $i=1,2,3,4$ .

**SRMqc** – quay crane repair and maintenance costs under normal workload due to wear and tear (linear depreciation costs proportional to number of moves)  $QC_i$ ,  $i=1,2,3$

**SRMYc** – yard crane repair and maintenance costs under normal workload due to wear and tear (linear depreciation costs proportional to number of moves),  $YC$ ,  $i=1,2,3$ .

**SRMtr** – truck workgroup repair and maintenance costs under normal workload due to wear and tear per operational hour (linear depreciation costs proportional to number of quay crane moves),  $Tri, i=1,2,3,4$ .

**SRTqc** – quay crane eventual repair and increased maintenance costs under overload due to more intense wear and tear per operational hour. These costs arise due to increase in performance at more intense operational workload above average recommended values.

**SRTyc** – yard crane eventual repair and increased maintenance costs under overload due to more intense wear and tear per operational hour. These costs arise due to increase in performance at more intense operational workload above average recommended values.  $YCi, i=1,2,3$ .

**SRTtr** – truck workgroup eventual repair and increased maintenance costs under overload due to more intense wear and tear per operational hour. These costs arise due to increase in performance at more intense operational workload above average recommended values.

**Sother** – other fixed costs related to container movement (cost of capital, rent, office expenses, indirect labor costs, etc.)

The total costs  $SSSijk(NP)$  per operational hour for each type of resource  $i(i=1,2,3.)$ ,  $j(j=1,2,3.)$ ,  $k(k=1,2,3,4.)$  non-linearly depend on net productivity  $NP$ (moves per hour) of the whole logistics chain:

$$\begin{aligned} SSSijk(NP) = & STqci + SSqci + SENqci(NP) + RMqci(NP) \\ & + SRTqcj(NP) + STycj + SSycj + SENycj(NP) + \\ & + RMycj(NP) + SRTycj(NP) + STtrk + SStrk + \\ & + SENtrk(NP) + SRMtrk(NP) + SRTtrk(NP) \end{aligned} \quad (8)$$

For each considered combination of resources the economic efficiency can be represented as difference between the net operational income per hour  $P(NP)$  and the total costs:

$$CRITERION_{ijk} (NP) = P(NP) - SSSijk(NP) - Sother \quad (9)$$

Now the formal task is finding a set of resources which would bring the criterion (9) to a maximum value, namely

$$\begin{aligned} \textit{Maximum} [ CRITERION_{ijk} (NP) ] = \mathbf{Cmax}_{u,v,w} \quad (10) \\ i=1,2,3; j=1,2,3; k=1,2,3,4 \text{ and } u, v, w - \text{indices of specific resources} \\ \text{bringing the criterion (9) to a maximum.} \end{aligned}$$

The task in itself is not the search of the maximum as such, but rather finding the set of resources bringing to it.

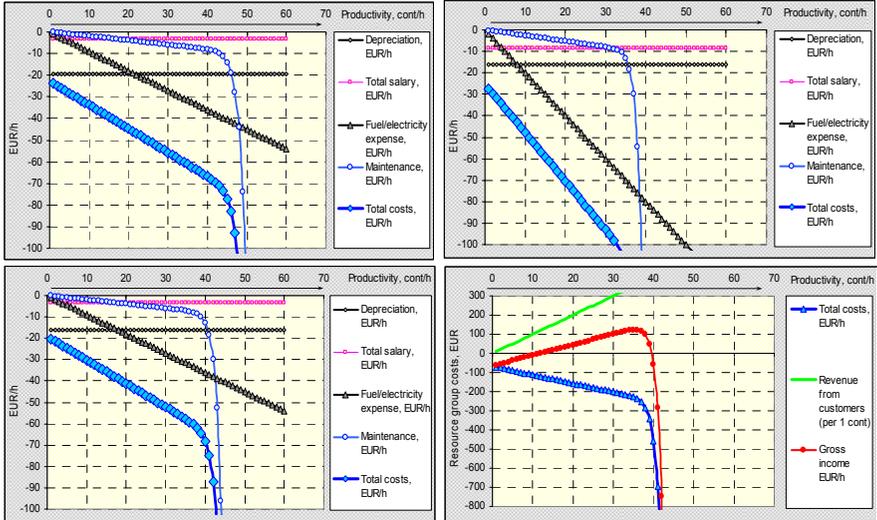
Let us concentrate on analysis of dependencies between the parameters of the models (number of trucks and cycles of resources, left-hand side pane of TABLE 3) and the net productivity output data, costs, and the criterion of economic efficiency as per modelled results.

TABLE 3. Sample of modelling resulting modelling table

Parameters						Outputs				
Trucks	Tt_set	Ty_set	Tq_set	Tq_out	Ty_out	NP	QC_cost	Trucks_cost	YC_cost	Criterion
4	430	110	80	88	104	<b>29.0</b>	54.6	90.9	50.2	<b>94.4</b>
6	430	90	80	84	85	<b>36.7</b>	63.1	162.3	59.6	<b>81.6</b>
5	430	110	90	91	109	<b>28.5</b>	52.5	112.0	49.6	<b>70.5</b>
3	430	90	80	110	91	<b>25.5</b>	50.8	63.9	47.3	<b>93.4</b>
4	430	80	80	94	80	<b>28.0</b>	53.5	88.5	51.1	<b>86.7</b>
3	430	80	90	89	79	<b>22.1</b>	45.5	56.5	44.6	<b>74.8</b>
4	430	110	90	97	114	<b>27.4</b>	51.3	87.2	48.5	<b>87.2</b>
5	430	110	80	99	106	<b>27.0</b>	52.5	108.0	48.0	<b>62.0</b>
6	430	110	98	98	111	<b>26.9</b>	49.7	128.9	47.8	<b>42.1</b>
5	430	90	80	81	89	<b>34.6</b>	60.8	129.3	57.3	<b>98.4</b>
3	430	90	98	107	90	<b>23.6</b>	46.2	59.1	45.2	<b>85.7</b>

This table compactly presents the basic technical and economical information obtained through simulation modelling. The number of rows of the table is equal to the number of possible combinations, in this case  $3 \times 4 \times 3 = 36$  combinations times 154 vessels (where for each the net productivity was calculated). Thus, the number of total observations made up  $36$  (resource combinations)  $\times$   $154$  (vessels modelled)  $= 5\,544$  rows of values with several dozens of parameters (columns). The examples of dependencies (as per TABLE 3), as well as the criterion (9) behaviour at different net productivity (NP) levels is represented in FIGURE 18.

The depreciation costs and salary do not depend on changes in speed of moves within +/- 15% boundaries and therefore assumed to be constant for each type of resource. The fuel and electricity costs are proportional to number of container moves.



**FIGURE 20.** Example of costs analysis for separate resource units and the set of resources SSS122 (QC1+4Trucks+YC2). The maximum efficiency is reached at NP=37

The repair and maintenance costs were broken down into two components: linear and exponential components. The former is proportional to the number of resources and describes normal resource workload operation. The exponential component depicts increased resource depreciation due to intensive exploitation above the normal level of productivity. This, in turn, leads not only to resource shorter lifecycle but might eventually cause unpredictable breakdowns finally resulting in economic losses.

As per FIGURE 20 the sum of these two components illustrate a drop in economic efficiency at overload performance apparently caused by increased wear and tear.

The tables below present mathematical expectations of efficiency criterion values for different combinations of resources.

**TABLE 4.** Mathematical expectations of economic efficiency (EUR) for workgroups consisting of 3, 4, 5 and 6 trucks.

<b>Trucks 3</b>				
Average of Criterion		YC1	YC2	YC3
<b>Tq_set \ Ty_set</b>		<b>80</b>	<b>90</b>	<b>110</b>
<b>QC1</b>	<b>80</b>	77	78	76
<b>QC2</b>	<b>90</b>	78	78	77
<b>QC3</b>	<b>98</b>	78	78	<b>83</b>

<b>Trucks 4</b>				
Average of Criterion		YC1	YC2	YC3
<b>Tq_set \ Ty_set</b>		<b>80</b>	<b>90</b>	<b>110</b>
<b>QC1</b>	<b>80</b>	<b>88</b>	85	77
<b>QC2</b>	<b>90</b>	87	86	78
<b>QC3</b>	<b>98</b>	85	85	87

<b>Trucks 5</b>				
Average of Criterion		YC1	YC2	YC3
<b>Tq_set \ Ty_set</b>		<b>80</b>	<b>90</b>	<b>110</b>
<b>QC1</b>	<b>80</b>	<b>82</b>	78	62
<b>QC2</b>	<b>90</b>	80	78	64
<b>QC3</b>	<b>98</b>	75	75	64

<b>Trucks 6</b>				
Average of Criterion		YC1	YC2	YC3
<b>Tq_set \ Ty_set</b>		<b>80</b>	<b>90</b>	<b>110</b>
<b>QC1</b>	<b>80</b>	<b>67</b>	59	43
<b>QC2</b>	<b>90</b>	60	59	44
<b>QC3</b>	<b>98</b>	52	53	44

For workgroup of three trucks the highest average economic efficiency value reached ca. EUR 83 per hour for the least productive cranes QC3 and YC3. This is an expected result if we remember that the workgroup of three trucks is also the least productive of the three available options.

The workgroup of four trucks yields the average value of EUR 88 per hour, which is a 6% increase compared to the previous case. In contrast to the three-truck brigade, in this case the maximum is achieved with the most productive cranes QC1 and YC1.

Adding another truck to the four-truck brigade does not affect the crane productivity requirements. The maximum average value of EUR 82 still falls on the most productive cranes QC1 and YC1, which is 7% below the previous combination.

Finally, a brigade consisting of six trucks cannot show any marginal efficiency even with the most productive cranes with efficiency criterion freezing at EUR 67, a drastic 18% fall from the level of the previous case.

Thus, a global optimum was reached for the brigade of four trucks where the highest average value of economic efficiency made up EUR 88 per hour with the most productive cranes QC3, YC3.

FIGURE 21 presents a comparative graph of dependence of economic efficiency on the number of trucks in brigade (3,4,5,6), quay cranes QC1, QC2, QC3 and yard cranes YC1, YC2, YC3 and respective 95% confidence interval of criterion of economic efficiency for all considered combinations of resources.

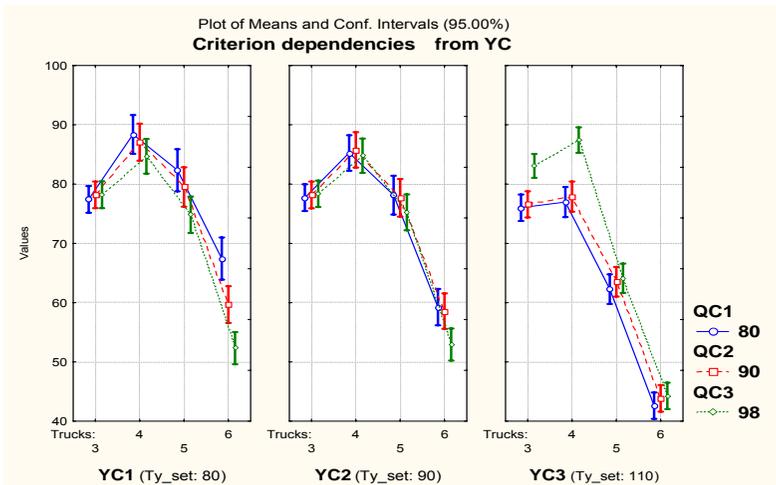


FIGURE 21. Analysis data of average values of economic efficiency and respective 95% significance intervals for the considered combinations of resources.

### 3.7.3. Comparing with traditional approach

Let us consider taking the apparently more complicated and costly way of simulation modelling for relatively simple logistics chains consisting of three elements: loading cargo, moving cargo, and discharging cargo. Why should we necessary solve this task through simulation modelling?

In order to see the reasons let find the solution to choice of equipment without the BCT simulation model and compare the both results.

In a simplistic case, the productivity of the logistics chain of elements  $QC_i + Tr_j + YC_k$  cannot exceed productivity of the slowest link, i.e. the lowest of (NP<sub>tr</sub>, NP<sub>qc</sub>, NP<sub>yc</sub>):

$$NP_{min}(i,j,k) = \min(NP_{qci}, NP_{trj}, NP_{yck}) \quad (11)$$

Here indices  $i,j,k$  stand for different types of resources involved in the logistics chain.

Now in order to calculate economic efficiency (9) we have to use the minimum productivity value  $NP_{min}(i,j,k)$  to sum up all associated resource costs at given productivity level  $SSS_{ijk}(NP_{min}(i,j,k))$ .

Choosing the highest value among the found values will thus determine the best choice of resources in our logistics chain.

However, any increase in productivity will obviously result in increased wear and tear of the equipment and associated financial losses, especially for the slowest link of the logistics chain.

The key condition of this approach is the assumption on equal productivity of the whole logistics chain at the productivity of the slowest link. Since the working productivity of each piece of equipment lies within +/- 10% boundaries of initial given level, let us consider influence of statistical performance fluctuation in each resource net productivity statistics on performance statistics of the whole logistics chain. For example, let us consider the chain  $QC_2 + Tr_5 + YC_2$ , where  $NP(QC_2)=40$ ,  $NP(Tr_5) = 41.9$ ,  $NP(YC_2)=40$ . Since the least productive are the first and the last elements, it follows that the productivity of the whole chain has to be close to  $NP(QC_2)=NP(YC_2)=40$  (as per TABLE 4 featuring the productivity of the least productive element of the whole chain, in this case 40).

We might conclude that the slowest chain algorithm would work well also in conditions of statistical fluctuations of the elements of logistic chain. Let us test this statement using the detailed statistical model of the container terminal.

Let us start by analyzing the productivities values of all the feasible resource combinations and comparing them to the productivity values observed for the same combinations arising from the simulation model runs (see table below).

TABLE 5. Net productivity values of feasible combinations of resources

Min (NP <sub>tr</sub> , NP <sub>qc</sub> , NP <sub>yc</sub> )		YC1	YC2	YC3	YC1	YC2	YC3	YC1	YC2	YC3
NP of Resource	NP	45	40	32.7	45	40	32.7	45	40	32.7
<b>Trucks = 3</b>	<b>25.1</b>	Min (NP <sub>tr</sub> , NP <sub>qc</sub> , NP <sub>yc</sub> )			NP average from model			(NP <sub>min</sub> -NP <sub>aver</sub> )/NP <sub>aver</sub> , %		
QC1	45.0	25.1	25.1	25.1	23.0	22.8	22.3	9%	10%	13%
QC2	40.0	25.1	25.1	25.1	22.8	22.6	22.1	10%	11%	14%
QC3	36.7	25.1	25.1	25.1	22.6	22.5	23.3	11%	12%	8%
Min (NP <sub>tr</sub> , NP <sub>qc</sub> , NP <sub>yc</sub> )	NP	45	40	32.7	45	40	32.7	45	40	32.7
<b>Trucks = 4</b>	<b>33.5</b>	Min (NP <sub>tr</sub> , NP <sub>qc</sub> , NP <sub>yc</sub> )			NP average from model			(NP <sub>min</sub> -NP <sub>aver</sub> )/NP <sub>aver</sub> , %		
QC1	45.0	33.5	33.5	32.7	28.3	27.5	25.9	18%	22%	26%
QC2	40.0	33.5	33.5	32.7	27.8	27.3	25.7	20%	23%	27%
QC3	36.7	33.5	33.5	32.7	27.2	27.0	27.3	23%	24%	20%
Min (NP <sub>tr</sub> , NP <sub>qc</sub> , NP <sub>yc</sub> )	NP	45	40	32.7	45	40	32.7	45	40	32.7
<b>Trucks = 5</b>	<b>41.9</b>	Min (NP <sub>tr</sub> , NP <sub>qc</sub> , NP <sub>yc</sub> )			NP average from model			(NP <sub>min</sub> -NP <sub>aver</sub> )/NP <sub>aver</sub> , %		
QC1	45.0	41.9	40.0	32.7	31.6	30.5	27.1	32%	31%	21%
QC2	40.0	40.0	40.0	32.7	30.7	30.1	27.1	30%	33%	21%
QC3	36.7	36.7	36.7	32.7	29.5	29.4	27.0	25%	25%	21%
Min (NP <sub>tr</sub> , NP <sub>qc</sub> , NP <sub>yc</sub> )	NP	45	40	32.7	45	40	32.7	45	40	32.7
<b>Trucks = 6</b>	<b>50.2</b>	Min (NP <sub>tr</sub> , NP <sub>qc</sub> , NP <sub>yc</sub> )			NP average from model			(NP <sub>min</sub> -NP <sub>aver</sub> )/NP <sub>aver</sub> , %		
QC1	45.0	45.0	40.0	32.7	33.7	31.6	27.6	34%	27%	19%
QC2	40.0	40.0	40.0	32.7	31.5	31.1	27.5	27%	29%	19%
QC3	36.7	36.7	36.7	32.7	29.7	29.6	27.4	24%	24%	19%

Let us plot the results, with values of expression (11)  $\min(NP_{qci}, NP_{trj}, NP_{yck})$  along the X-scale and the average values of net productivity data of the respective combinations of resources along the Y-scale.

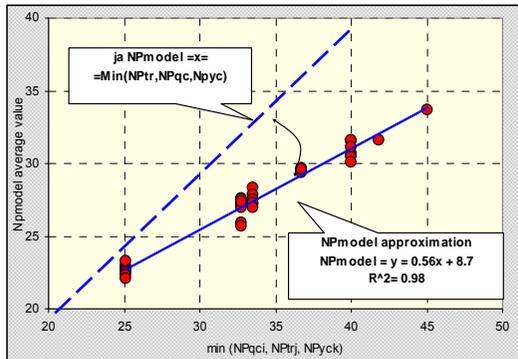


FIGURE 22. Dependence of the resource net productivities in the stochastic simulation model (Y-scale) and slowest link method assuming  $NP_{min}(i,j,k) = \min(NP_{qci}, NP_{trj}, NP_{yck})$  along Y-scale.

From the graph above it follows that the assumption of the logistics chain performance equal to the performance of the slowest element does not hold. The error increases proportionally to the productivity increase and in the considered productivity range from NP=20 to NP=40 the error lies between 10-25% which is insufficient for determining a combination of resource whose own productivities deviate 15%-25%. Therefore the more precise method of simulation modelling is preferred.

#### 4. CONCLUSIONS AND FURTHER RESEARCH

The world trade has shown a stable increase over the previous years and this trend still continues. With a growing container turnover, increasing container terminal performance is a critical issue for the container terminals. At the same time, high operating costs for ships and container terminals and also high capitalization of ships, containers and port equipment demand a reduction of unproductive times at port. Therefore, the potential for cost savings is high and importance of performance analysis tools is becoming more acute with increasing container flows.

For increasing efficiency there exist different methods of modelling and simulation models. A general disadvantage of these models is insufficient detailing of micro-operations and involved resources which limits possibility of estimating effect of a specific resource unit on the overall productivity of the logistics chain of the terminal.

Therefore, the problem of estimating efficiency of specific resources in conditions of random resource interaction still largely remains unaddressed.

Filling in this gap, the promotional work presents an original developed methodology for simulation modelling of marine container terminals. Specifically, the following major points of the research represent scientific innovation:

- there has been created a micro-simulation model of Baltic Container Terminal at predefined level of detailing (up to single resource unit with second-wise monitoring possibilities). The created model represents a unique marine container terminal micro-simulation model in terms of depth of detailing and visualization.
- the paper represents an efficient approach for choosing a rational level of detailing through top-to-bottom hierarchically integrated simulation models. The outlined methodology allows multiple levels of detailing.

- there has been developed and implemented two-tier algorithm for simulation model parameter adjustment which was presented as the task of optimization of stochastic object function on a set of stochastic arguments. The algorithm is based on combination of parametrical and non-parametrical methods of statistical analysis aimed at minimizing stochastic object function. Such an approach ensures high degree of precision of parameter adjustment at a relatively small number of iterations. The first stage of the algorithm utilizes the t-criterion and Nelder and Mead simplex method in order to search the local minimum of expected value discrepancy of the model and the BCT observed net productivity data. At this stage the analysis based solely on the mean values of probability distributions of the parameters. At the second stage of the algorithm the object function is defined as discrepancy of empirical functions of cumulative probability and tested for homogeneity using the Kolmogorov-Smirnov algorithm.
- the model features input adjustable input generators (generators of container flow). The easily adjustable generators are important for ‘*what if...?*’ scenario analysis for analyzing potential bottlenecks in terminal performance for container flow characteristics differing from the historical data. For the aims set out in this work, the input generators were adjusted for the historical data of BCT.
- practical application of the developed simulation model represents a new approach developed in the research for choosing an optimal combination of resources which yields more reliable results than the traditional method.

One of the important aspects of the described simulation is its wide range of applications for performance and cost-efficiency analysis. Namely, there have been addressed the following issues:

- determining the optimal size of truck workgroups for the Baltic Container Terminal,
- researching effect of yard location proximity to the berths and the number of trucks on net productivity
- determining historical resource operational cycle times basing on BCT database data. There has been performed a sensitivity analysis of the solutions obtained which revealed reasonable model stability with regard to input variations in productivity values.

- among combinations of three available quay cranes, three yard cranes, and brigade of three to six trucks with unique performance and costs there was chosen a single optimal cost/performance combination of resources using the simulation model.

It has been demonstrated that the thoroughly developed logistical model of specific operations affected by random fluctuations allows determination of basic technological and economic data as well as allows quantitative estimation of the associated economic and technological risks of the modelled operations

Finally, thanks to the logical block-based structure of the model, it was revealed that the underlying principles and methodology can easily be transferred to general terminal and warehousing systems modelling (such as industrial or passenger airport, marine, or railway terminals) and natural resource mining facilities. The flexibility of the methodology represents solid foundation for future research and application of modelling methodology for the mentioned types of objects.

## 5. PUBLICATIONS

The results of the doctoral thesis have been published in the following sources:

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9. Ю.А. Меркурьев, В.В. Бардаченко, А.В. Соломенников, Ф. Камперман. Выбор оптимального набора ресурсов на Балтийском контейнерном терминале с помощью имитационного моделирования. *Transport and Telecommunication.* Riga: Institute of Transport of Telecommunication, Vol. 6, No. 4, 2005, pp. 4–29.
10. Yuri Merkuryev, Vladimir Bardachenko, Andrey Solomennikov, and Fred Kamperman. Simulation system of BCT. IST4Balt. Proceedings of the International Workshop “IST 16th Framework Programme – Great Opportunity for Cooperation and Collaboration”, Riga, Latvia, 6–7 April 2005. Riga: RTU, 2005, pp. 91–95.