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Promotional work for scientific degree of Doctor of Engineering
in Telematics and Logistics

SIMULATION MODELLING AND RESEARCH OF MARINE CONTAINER TERMINAL LOGISTICS CHAINS

CASE STUDY OF BALTIC CONTAINER TERMINAL

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JŪRAS KONTEINERU TERMINĀLU LOĢISTIKAS ĶĒŽU IMITĀCIJAS MODEĻU IZPĒTE UN IZSTRĀDE

BALTIJAS KONTEINERU TERMINĀLA GADĪJUMA IZPĒTE

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ABSTRACT

The promotional work 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 methodology is developed basing on the case study of Baltic Container Terminal (seaport of Riga, Latvia).

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 an original methodology based on parametric and non-parametric methods of mathematical statistics developed for creation of simulation model of marine container terminals at a required level of realism, 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 practical tasks 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 is easily adjustable allowed creation of a flexible simulation model offers a wide scope of applications, including other logistic systems such as airports, freight train hub terminals, mining facilities of natural resources, etc.

ANOTĀCIJA

Promocijas darbā ir piedāvāta metodoloģija un analīze, kas apraksta jūras konteineru terminālu imitācijas modeļu izstrādi un praktisku pielietošanu. Metodoloģija tika izstrādāta izpētot Baltijas Konteineru Termināla loģistikas ķēdes.

Promocijas darba nozīmīgākie rezultāti tika sasniegti laika periodā no 2002.g. līdz 2006.g. Baltports-IT IST-2001-33030 *Simulation and IT Solutions: Applications in the Baltic Port Areas of the Newly Associated States* projekta ietvaros. Darba sasniegumi ir prezentēti septiņās starptautiskās konferencēs un ir aprakstīti desmit publikācijās.

Promocijas darbā ir izklāstīta jauna metodoloģija, kas pamatojas uz matemātiskās statistikas parametriskām un neparametriskām metodēm, tā apraksta jūras konteineru terminālu imitācijas modeļa izstrādi, verifikāciju, validāciju un modeļa turpmākās pielietošanas iespējas. Imitācijas modeļa parametru pielāgošana ir aprakstīts kā Neldera un Mida tiešās optimizācijas metodes uzdevums ar stohastisko mērķa funkciju pie stohastiskas argumentu kopas. Mērķa funkcija ir definēta kā empīrisko sadalījumu funkciju statistiskā starpība un to pārbaudei uz viendabību tika izmantots Kolmogorova-Smirnova tests.

Izstrādātā modeļa svarīgs aspekts ir tā praktiskais nozīmīgums, kas ir pierādīts, risinot virkni lietišķu uzdevumu, tādu kā vilcēju optimālā skaita noteikšana, resursu darba cikla laika noteikšana, pamatojoties uz BKT darbības vēsturiskajiem datiem un ekonomisko analīzi, un resursu optimālā izvēle izmaksu lietderības ziņā.

Promocijas darbā piedāvātā metodoloģija ļauj izstrādāt elastīgu imitācijas modeli, kuru var viegli pielāgot arī citām loģistikas sistēmām, tādām kā lidostas, kravas vilcienu centrālie termināli, dabas bagātību ieguves resursi utt.

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LIST OF ABBREVIATIONS

AGV – Automatic Guided Vehicle

ALV – Automated Lifting Vehicles

ASC – Automated Stacking Cranes

BCT – Baltic Container Terminal

DGPS – Differential Global Positioning System

ECT – European Container Terminal

EDI – Electronic Data Interchange

EDI – Electronic Data Interchange

EDIFACT – Electronic Data Interchange For Administration, Commerce and Transport

ES – Evolutionary Strategies

GA – Genetic Algorithm

GDP – Gross Domestic Product

GPS – Global Positioning System

HHLA – Hamburger Hafen und Lagerhaus

MCB – Multiple Comparisons with the Best

MCT – Marine Container Terminal

NMSM – Nelder and Mead Simplex Method

NP – Net Productivity

OBC – Overhead Bridge Crane

QC – Quay Crane

RMG – Rail Mounted Gantry crane

RSM – Response Surface Methodology

RTG – Rubber Tired Gantries

SA – Simulated Annealing

SC – Straddle Carrier

STS – Ship To Shore

TEU – Twenty feet Equivalent Units

TS – Tabu Search

YC – Yard Crane

1. INTRODUCTION TO RESEARCH TOPIC

The chapter presents some brief information on the research performed, its scientific innovation and methods developed as well as gives an overview to world trends of seaborne trade, container terminal operations, logistics processes, and types of resources used. Besides, the chapter introduces the simulation methods used in simulation modelling of marine container terminals.

1.1. GENERAL INFORMATION ON 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 below in paragraph 1.1.2. PREVIOUS RESEARCH deal with approximated inputs which does not allow application of the model for real needs of terminal management. Thus, the specific aim of research was solving several practical tasks outlined in CHAPTER 5. 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.

1.1.1. 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.

1.1.2. 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.

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.

1.1.2.1. 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.

1.1.2.2. 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.

1.1.2.3. 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

1.1.2.4. 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.

1.1.2.5. 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 Horssen, W.

1.1.2.6. 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.

1.1.3. 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. This stage is described in part 2.2. CHOOSING LEVEL OF DETAILING

- *Parameterization* of the model consists of creating an interface for inputting control parameters and monitoring and visualization of internal variables of the model. More about this stage can be found in 2.6. AGGREGATED PARAMETERS
- *Adjusting control parameters* of the models which is described in detail in 3. MODEL CALIBRATION METHODOLOGY
- *Modelling and adjusting inputs of the model*, i.e. creating sub-model blocks for scenario modelling (analyzing situations '*what if input statistics change?*'). More about input adjustment can be found in 4.2. ADJUSTING EXTERNAL PARAMETERS.
- *Application for solving practical problems*. CHAPTER 5. PRACTICAL APPLICATIONS OF SIMULATION MODEL of the thesis 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.

1.1.4. Scientific innovation of research

The thesis 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 3.2. Two-tier parameter adjustment algorithm on page 97 of the thesis.
- 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 2.2. Choosing level of detailing.
- 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 Chapter 5. Practical applications of simulation model.

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 Baltports-IT IST-2001-33030 project *Simulation and IT Solutions: Applications in the Baltic Port Areas of the Newly Associated States*. (2001-2003) funded by the 5th IST Programme of the European Commission as well as in other publications.

1.1.5. 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.

1.1.6. Overview of thesis structure

The thesis consists of 172 pages, 5 chapters, 13 tables, 124 references and 72 figures.

1.2. INTRODUCTION TO CONTAINER TERMINAL OPERATIONS

The marine container terminal is the place were containers arriving by ocean vessels are transferred to inland carriers, such as trucks, trains, or canal barges and visa versa. Every marine container terminal performs four basic functions: receiving, storage, staging, and loading for both import (entering the terminal by sea and usually leaving by land modes) and export (usually entering the terminal by land and leaving by sea modes) containers.

Receiving involves container arrival at the terminal, either as an import or export, recording its arrival, retrieving relevant logistics data and adding it to the current inventory. Storage is the function of placing the container in a known and recorded location so it may be retrieved when it is needed. Staging is the function of preparing a container to leave the terminal. In other words the containers that are to be exported are identified and organized so as to optimize the loading process. Import containers follow similar processes, although staging is not always performed. An exception is a group of containers leaving the terminal via rail. Finally, the loading function involves placing the correct container on the ship, truck, or other mode of transportation. In this work the emphasis will be put on internal logistics chain of container terminal (i.e. vessel-truck-yard and opposite direction respectively).

Containers came into the market for international conveyance of sea freight almost five decades ago. They may be regarded as well accepted and they continue to achieve even more acceptance due to the fact that containers are the foundation for a unit-load-concept. Containers are relatively uniform boxes whose contents do not have to be unpacked at each point of transfer. They have been designed for easy and fast handling of freight. Besides the advantages for the discharge and loading process, the standardization of metal boxes provides many advantages for the customers, as there are protections against weather and pilferage, and improved and simplified scheduling and controlling, resulting in a profitable physical flow of cargo.

The most common distinction refers to a so-called standard container as one which is twenty feet (20') long, describing the length of a short container. Other containers are measured by means of these containers, i.e., in Twenty feet Equivalent Units (TEU) (e.g., standard 40ft containers represent 2 TEU).

Additional properties of containers may be specified whenever appropriate (e.g., the weight or weight class of a container, the necessity of special handling for reefer containers or oversized containers).

According to Volk (2002), first regular sea container service began about 1961 with an international container service between the US East Coast and points in the Caribbean, Central and South America. The breakthrough after a slow start was achieved with large investments in specially designed ships, adapted seaport terminals with suitable equipment, and availability (purchase or leasing) of containers. A large number of container transshipments then led to economic efficiency and a rapidly growing market share. In this context, transshipment describes the transfer or change from one conveyance to another with a temporarily limited storage on the container yard.

As classified by Steenken et al. (2004), every marine container terminal performs four basic functions: receiving, storage, staging, and loading. The functions at every marine container terminal are performed using specialized equipment, which has high ownership and operating (annual maintenance, wear and tear) costs. Thus, it is generally perceived among terminal managers that a high utilization factor should be achieved to justify the investment. Obtaining information describing the daily demand for container moves is of significant importance in reaching this goal. An accurate prediction of the expected demand on a particular day would allow the terminal manager to make prudent allocations of the available handling equipment. These factors call for a thorough cost-revenue analysis in terms of choice of equipment and workload distribution.

Marine terminals are key nodes in the transportation network interface and it is their role to perform transfer activities in the most efficient way. Despite the unparalleled success in implementing technological innovations to improve operating performance at marine terminals, uncertainty and variation in the daily demand patterns still remain a challenge for port managers and inhibit the successful use of new innovations to their full potential. This paper presents a methodology and tools, which use the data available through a terminal's information system to predict day-to-day variations of demand in terms of the number of containers moving through the terminal. Results of the application indicate a significant potential in using the methodology developed in this paper as an operational planning tool, which is illustrated in part 5. PRACTICAL APPLICATIONS OF SIMULATION MODEL.

Container traffic has been growing steadily since its beginning in the 1960s. In recent years, a significant portion of this growth has been due to the increased demand for intermodal services, where containers are transported by ships, trains, and trucks. Since more than 80% of the international trade is moved by vessels, marine terminals are key nodes in the transportation network interface. Therefore, it is the role of the marine container terminal to perform transfer activities in the most efficient way (Voss, Bose, 200).

The last decade has been a period of revolutionary changes in technology including hardware and equipment, and improvement in information and logistics systems. From the operational perspective, deployment of these new advancements enables container terminals to better utilize their available capital and technological resources and meet the increasing requirements of the freight transportation industry (Volk, 2002).

1.3. CURRENT TRENDS IN MARINE CONTAINER TRANSPORTATION

According to Steenken et al. (2004), 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 %. An international containerization market analysis shows that in 1995 9.2 million TEU were in circulation; the container fleet had almost doubled in ten years from a size of 4.9 million TEU in 1985 (Hulten, 1997).

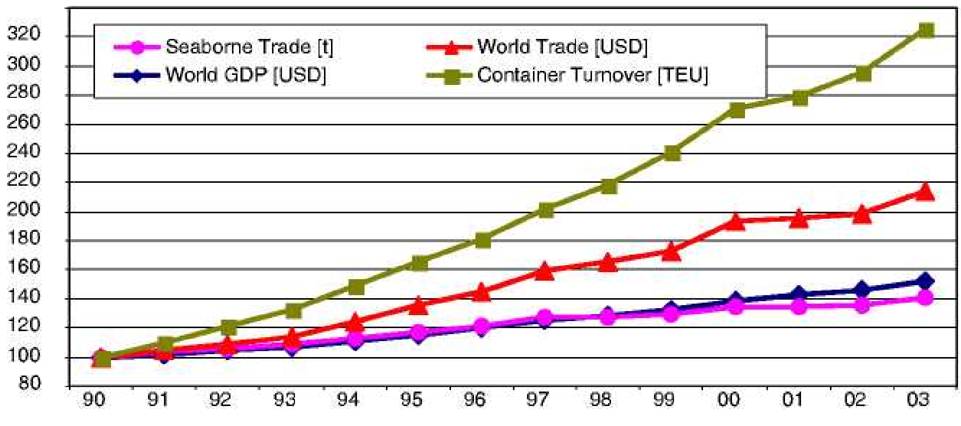


FIGURE 1.1. Containerization trend: high growth of container turnover. Source: Boyes (2000, 2003)

FIGURE 1.1, basing on reports by Boyes (2000, 2004) 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. Due to the positive forecast for container freight transportation, a similar development can be expected in the future.

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. As per Volk (2002), the seaports mainly compete for ocean carrier patronage and short sea operators (feeders) as well as for the land-based truck and railroad services. Muller (1995) and Hulten (1997) argue that the competitiveness of a container seaport is marked by different success factors, particularly the time in port for ships (transshipment time) combined with low rates for loading and discharging. Therefore, a crucial competitive advantage is the rapid turnover of the containers, which corresponds to a reduction of the time in port of the container ships, and of the costs of the transshipment process itself. That is, as a rule of thumb one may refer to the minimization of the time a ship is at the berth as an overall objective with respect to terminal operations.

1.4. CONTAINER TERMINAL LOGISTICS PROCESSES

Operations are nowadays unthinkable without effective and efficient use of information technology as well as appropriate operations research methods. This section represents a short introduction to main logistics processes and operations in container terminals as well as presents a survey of optimization methods.

1.4.1. CONTAINER TERMINAL STRUCTURE

In general logistics terms, container terminals can be described as open systems of material flow with two external interfaces. These interfaces are the quayside with loading and unloading of ships, and the landside where containers are loaded and unloaded on/off trucks and trains. Containers are stored in stacks thus facilitating the decoupling of quayside and landside operation.

After arrival at the port, a container vessel is assigned to a berth equipped with quay cranes to load and unload containers. Unloaded import containers are transported to yard positions near to the place where they will be transshipped next. Containers arriving by road or railway (the outbound logistics chains are not considered in the present paper) at the terminal are handled within the truck and train operation areas. They are picked up by the internal equipment and distributed to the respective stocks in the yard.

Additional moves are performed if sheds and/or empty depots exist within a terminal; these moves encompass the transports between empty stock, packing centre, and import and export container stocks (see FIGURE 1.2.).

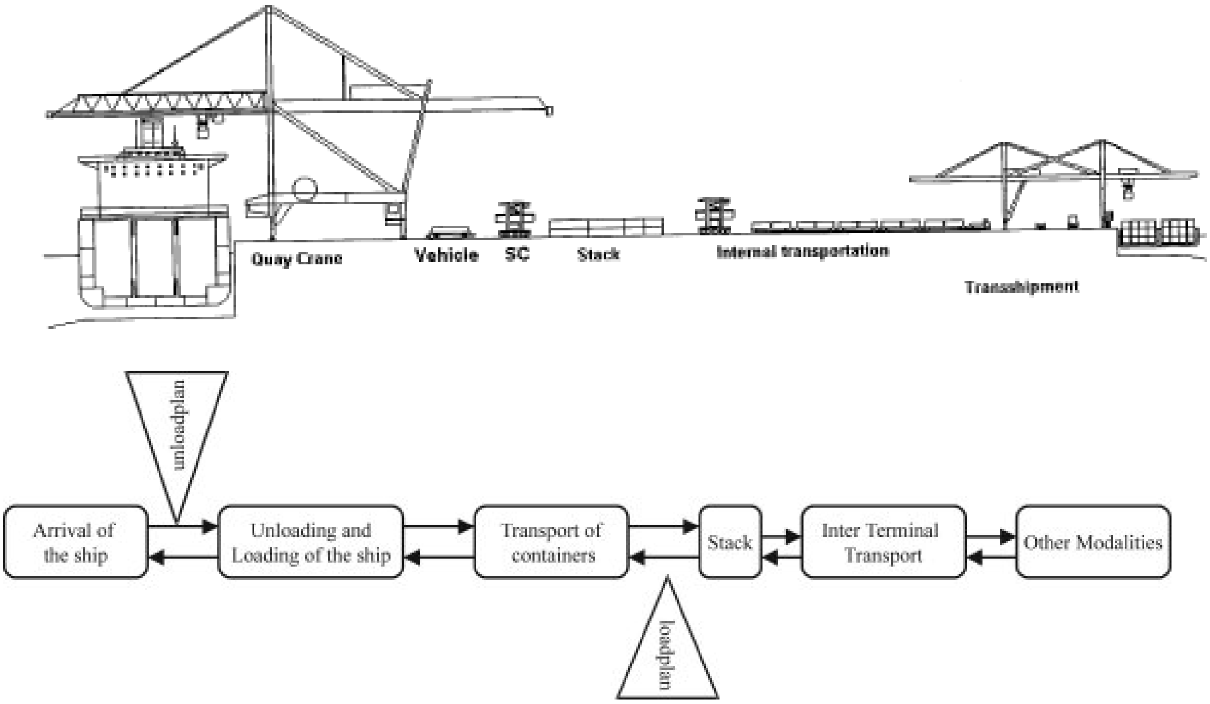


FIGURE 1.2. Container terminal system and respective logistics processes. Source: Vis, de Koster (2002)

The associated transport flow is reflected in FIGURE 1.3. The container storage area is usually separated into different stacks (or blocks) which are differentiated into rows, bays and tiers. Some stack areas are reserved for special containers like reefers which need electrical connection, dangerous goods, or overheight/overwidth containers which do not allow for normal stacking. Often stacks are separated into areas for export, import, special, and empty containers. Besides, in these general functions some terminals differ also in their operational units. For example, if railway stations do not exist inside the terminal, containers have to be transported by trucks or other landside transportation means between the external station and the terminal. This results in additional logistic demands.

Other differences occur if sheds exist within the terminal area. At sheds containers are stuffed and stripped, and goods are stored. Additional movements have to be performed connecting the yard stacks with the sheds. The same applies to empty depots where empty containers are stored according to the needs of shipping lines.

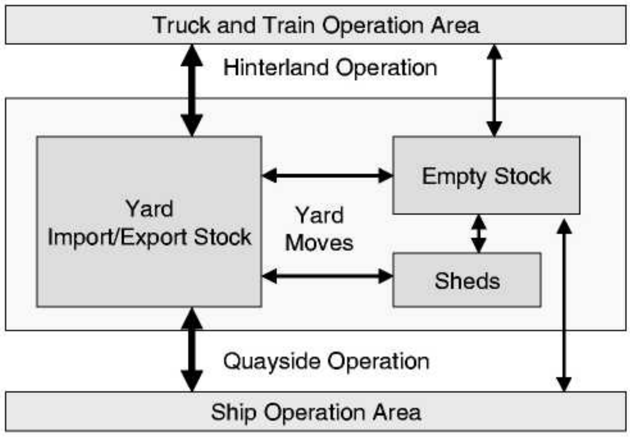


FIGURE 1.3. Operation areas of a seaport container terminal and flow of transports. Source: Steenken et al. (2004)

Different types of ships have to be served at the quayside. The most important ones are deep-sea vessels with a loading capacity of up to 8’000 container units (TEU) which serve the main ports of different countries and continents. Such vessels are about 320m long with a breadth of 43m and a draught of 13m; on deck containers can be stowed 8 tiers high and 17 rows wide, in the hold 9 high and 15 wide (Vis and de Koster, 2003). The vessel sizes call for respective dimensions of the cranes’ height and jib length. Loading of about 2’000 containers is common in large ports; the same is valid for unloading. Speaking of the Baltic Container Terminal, its most common customers are feeder vessels with a capacity of 100 to 1’200 TEU link smaller regional ports with the overseas ports delivering containers for deep-sea vessels (Baltic Container Terminal website).

In general, trucks have a capacity of up to three TEU, the tugmasters featured in the BCT model have the capacity of 2 TEUs (i.e. two 20ft containers or one 40ft container). At container terminals the trucks directed to transfer points where they are loaded and unloaded. To serve trains, railway stations with several tracks may be part of container terminals, where the capacity of one train is about 120 TEU (Lemper, 2003). Shuttle trains connecting a terminal with one specific hinterland destination obtain increased importance.

The modal split of hinterland transportation is very specific for different ports which has a direct impact on the terminal layout and type of equipment (Muller, 1995).

A great variety of container terminals exists mainly depending on which type of handling equipment is combined to form a terminal system. All terminals use gantry cranes, either single-or dual-trolley, manual or semi-automatic. The transport between quay and stack can be performed either by trucks with trailers, multi-trailers, AGVs (Automatic Guided Vehicles) or straddle carriers. These vehicles can also serve the landside operation except AGVs which nowadays are exclusively engaged at the quayside (Saanen et al., 2003). Container stacking is either performed by gantry cranes or by straddle carriers.

Despite the variety of equipment combinations, two principal categories of terminals can be distinguished: pure straddle carrier (see FIGURE 1.7. b) for straddle carriers) systems and systems using gantry cranes for container storage (Steenken, 2003). Terminals with gantry cranes for container storage apply any kind of transport vehicles mentioned above. According to Mahoney (1985), even mixed systems of transport vehicles occur; e.g., multi-trailers for the quayside and straddle carriers for the landside operation. AGV terminals only exist in combination with automatic gantry cranes. Trains are normally loaded and unloaded by gantry cranes even in case of straddle carrier terminals, although in some cases straddle carriers are also used for this purpose (see FIGURE 1.4. below).

The decision on which equipment is used at container terminals depends on several factors. Space restrictions, economical and historical reasons play an important role. A basic factor is the dimension of the space which can be used for a terminal (Koch, 1997). Some considerations can be the following: if space is restricted, gantry cranes to store containers are preferred. A decision for AGVs and automated gantry cranes can be made in case of high labour costs and new terminal construction. Because space is becoming a scarce resource, a trend for higher storage is to be foreseen.

Besides the mentioned two main categories, common in Europe and Asia, a third type, quite often in North America, is an on-chassis system, in which containers are stored on chassis instead of being stacked on top of each other. This system lacks of special stacking cranes, has simpler stacking logistics and is more space demanding (Ioannou et al., 2003).

1.4.2. HANDLING EQUIPMENT

Usually, container terminals are described very specifically with respect to their equipment and stacking facilities. Steenken et al. (2004) point out that from a logistic point of view terminals only consist of two components: stocks and transport vehicles.

The yard stacks, ships, trains, and trucks belong to the '*stock'* category. Stocks are statically defined by their ability to store containers while from a dynamic point of view a stowage (or loading) instruction is necessary defining the rules how and where containers have to be stored. There is no principal difference between these different types of stocks but only a difference in capacity and complexity. Routing and scheduling of ships, trains and trucks do not belong to container terminal operation. Therefore, they can be considered statically as storage entities whereas a stowage instruction exists in any case even for trucks where at least the position of the containers to be loaded has to be defined. For specific stowage, ships and trains need instructions defining the position for every container. Transport means either transport containers in two or three dimensions. Cranes and vehicles for horizontal transport belong to this category. Their logistical specifics are that transport jobs have to be allocated to the means of transport and sequences of jobs have to be performed. The calculation of sequences is typical for the transportation means and defines a principal difference to the stocks categorized above. As mentioned by Leaving aside these identities but being fixed on the specifics of each component and equipment applied at container terminals results in a variety of operations research approaches and solutions.

The following sections present a short introduction to equipment types used at container terminals: types of cranes, horizontal transport means, and assisting systems.

1.4.2.7. Quay and yard cranes

There exist different types of cranes that are used at container terminals. The *quay* (also referred to as *gantry*) cranes (FIGURE 1.4.) for loading and unloading ships play a major role. Two types of quay cranes can be distinguished: single-trolley cranes (featured at BCT) and dual-trolley cranes (NKM Noell Special Cranes website, 2006). The trolleys travel along the arm of a crane and are equipped with spreaders, which are specific devices to pick up containers. Modern spreaders allow to move two 20' containers simultaneously (twin-lift mode).

Conventionally single-trolley cranes are engaged at container terminals. They move the containers from the ship to the shore either putting them on the quay or on a vehicle (and vice versa for the loading cycle). Single-trolley cranes are man-driven. Dual-trolley cranes represent a new development only applied at very few terminals. The main trolley moves the container from the ship to a platform while a second trolley picks up the container from the platform and moves it to the shore. The main trolley is man-driven while the second trolley is automatic. At modern cranes, the crane driver is supported by a semi-automatic steering system; this is both the case for one and two-trolley cranes. The maximum performance of quay cranes depends on the crane type. The technical performance of cranes is in the range of 50-60 container moves/hour, while in operation the performance is in the range of 22-30 container moves/hour (Steenken, 2003).

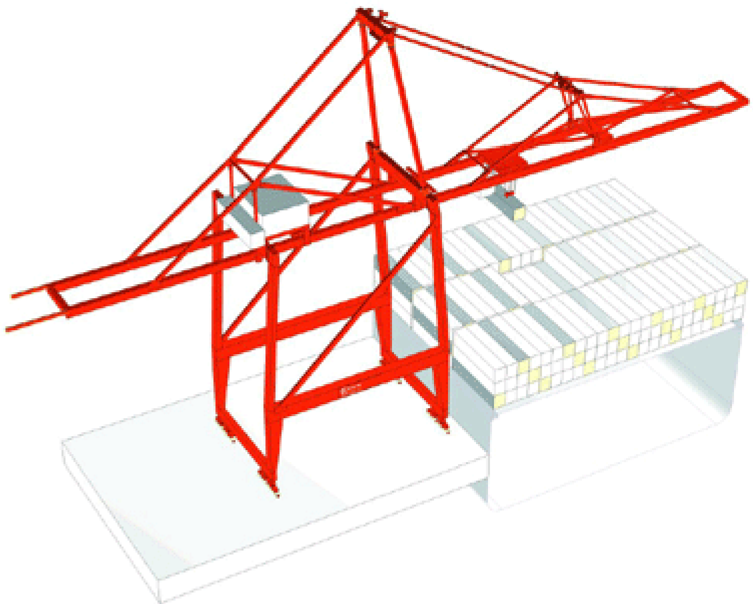
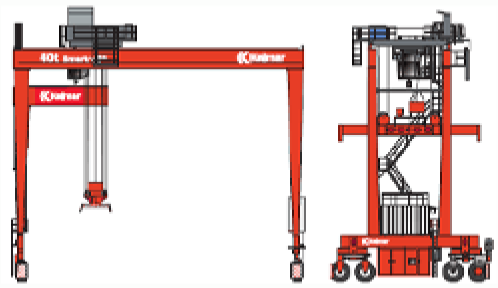


FIGURE 1.4. Quay crane (here: single-trolley crane). Source: Kalmar Industries website

A second category of cranes is applied to movement of stacks at container storage yards. At present there exist three types of yard cranes (see FIGURE 1.5.): *Rail Mounted Gantry* cranes (RMG), *Rubber Tired Gantries* (RTG), and *Overhead Bridge Cranes* (OBC). Rubber tired gantries are more flexible in operation while rail mounted gantries are more stable and overhead bridge cranes are mounted on concrete or steel pillars. Commonly gantry cranes span up 8-12 rows and allow for stacking containers 4-10 high. To avoid operational interruption in case of technical failures and to increase productivity and reliability, two RMGs are often employed at one yard stack area, also referred to as block. Containers which have to be transported from one side of the block to the other then have to be buffered in a transition area of the block. Double-RMG systems represent a new development. They consist of two RMGs of different height and width able to pass each other thus avoiding a handshake area. This results in a slightly higher productivity of the system. Although most of the gantry cranes are man-driven, the tendency is for automatic driverless gantry cranes which are in use at some terminals (e.g. Thamesport, Rotterdam, Hamburg). The technical performance of gantry cranes is approximately 20 moves/hour (Mattfeld, 2003).

a)



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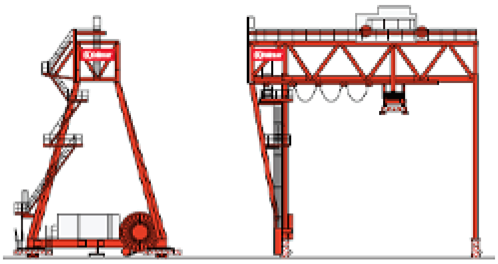


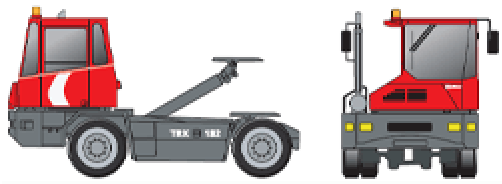
FIGURE 1.5. Different types of yard cranes: a) RTG crane and b) RMG crane. Source: Kalmar Industries website

Similar cranes are used for loading and unloading trains. They span several rail tracks (about six). Containers to be transferred from/to trains are pre-stowed in a buffer area alongside the tracks.

1.4.2.8. Horizontal transport means

A variety of vehicles is employed for the horizontal transport both for the ship-to-shore transportation and the landside operation. The transport vehicles can be classified into two different types. (Koch, 1997). Vehicles of the first class are 'passive' vehicles in a sense that they are not able to lift containers by themselves. Loading and unloading of these vehicles is done by cranes, either quay cranes or gantry cranes. Trucks with trailers (also referred to as tractors or tugmasters), multi-trailers and Automated Guided Vehicles (FIGURE 1.6.) belong to this class. AGVs are robotics able to drive on a road network which consists of electric wires or transponders in the ground to control the position of the AGVs. AGVs can either load one 40ft or 45ft container or two 20ft containers – in the latter case multiple load operation is possible. Since AGV systems demand for high investment, they are only operated where labour costs are high; they are now in operation at ECT/Rotterdam and at the HHLA/Hamburg in combination with automatic gantry cranes (Gademann and van de Velde, 2000).

a)



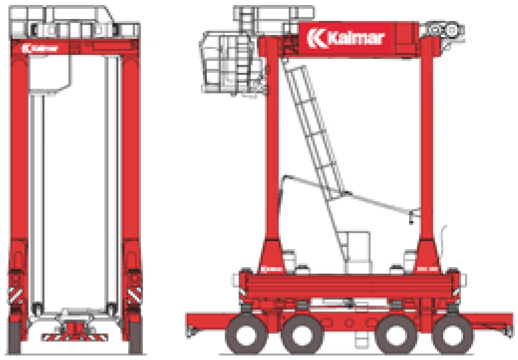
b)

FIGURE 1.6. Passive horizontal transport means: a) tractor (truck) and b) AGV. Source: Kalmar Industries website

Transport vehicles of the second class are able to lift containers by themselves. *Straddle Carriers* (SC), forklifts, and reachstackers belong to this class (see FIGURE 1.7.). There exist a large number of forklift and reachstacker variations suited for handling both empty containers as well as loaded ones. Straddle carriers (however, not featured at BCT) not only transport containers but are also able to stack containers in the yard. Therefore, they can be regarded as cranes not locally bound, with free access to containers independent of their position in the yard. The straddle carriers' spreader allows to transport either 20ft or 40ft containers; twin mode to transport/stack two 20ft containers simultaneously is becoming available. Straddle carriers exist in numerous variations, these are usually man-driven and able to stack 3 or 4 containers high, i.e., they are able to move one container over 2 or 3 other containers, respectively.

a)

b)



c)

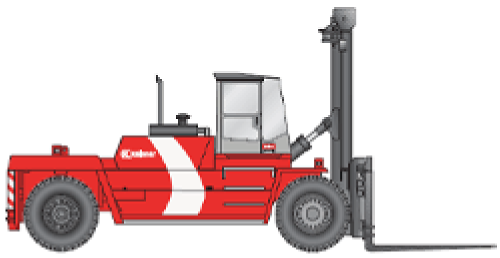


FIGURE 1.7. Container-lifting horizontal transport means: a) Reachstacker, b) Straddle carrier, c) Forklift truck. Source: Kalmar Industries website

1.4.2.9. Assisting systems

Besides cranes and transport vehicles, assisting systems play an eminent role for the organization and optimization of the work flow at container terminals. This is valid especially for communication and positioning systems (Murty et al., 2003).

Container terminal operators support a very intense communication with external parties like shipping lines, agents, forwarders, truck and rail companies, governmental authorities like customs, waterway police and others. The electronic communication is based on international standards (EDIFACT; Electronic Data Interchange For Administration, Commerce and Transport). Every change of container status is communicated between the respective parties (Bruzzone and Signorile, 1998). From the point of view of the terminal operator the most important messages are: the container loading and discharging lists which specify every container to be loaded or unloaded to/from a ship with specific data; the 'bayplan' which contains all containers of a ship with their precise data and position within the ship (it is communicated before arrival in the port); the 'stowage instruction' which describes the positions where export containers have to be located in a ship and which is the base for the stowage plan of the terminal; container pre-advices for delivery by train and truck, and the schedule and loading instruction for trains - only to name a few (Hartmann, 2004). Although only some of these messages – especially the stowage instruction for ships and trains – interfere directly with the operational activities of the terminal, they are very important because they serve for completeness and correctness of container data which is necessary to optimize the work flow.

Besides the communication with external partners, the internal communication systems play a major role in optimizing the terminal operation. The radio data communication, which was installed at container terminals since the middle of the 1980s, plays a key role because it is the main medium to transmit job data from the computer to cranes and transport vehicles. The radio data communication was the technical base for the implementation of operations research methods to optimize job sequences (Kim and Kim, 2003).

Since the middle of the 1990s Global Positioning Systems (GPS) were installed at container terminals. Initially they were used to automatically identify the position of the containers in the yard guaranteeing that the container yard position in the terminals' computer system is accurate. According to Li and Vairaktarakis (2001), because of the size of containers and the yard layout, differential GPS (DGPS) is necessary. DGPS components are not installed at containers but on top of the transport and stacking equipment. The position is measured, translated into yard coordinates and transmitted to the computer whenever a container is lifted or dropped. Alternatives to DGPS are optical based systems, especially Laser Radar (van der Heijden, et al., 2002). Sometimes both systems are integrated to assure a higher reliability.

Container positioning systems like DGPS, dead-reckoning or Laser Radar constitute the technical base for the improvement of yard and stacking logistics.

Transponder and electrical circuits are used to route gantry cranes and automatic vehicles like AGVs whereas DGPS is used for the steering of automatic straddle carriers and other equipment (Gademann and van de Velde, 2000).

1.5. TERMINAL LOGISTICS OPTIMIZATION METHODS

The need for optimization using methods of operations research in container terminal operation has become more and more important in recent years. This is explained by the fact that the logistics especially of large container terminals has already reached a degree of complexity that further improvements require scientific methods. The impact of concurrent methods of logistics and optimization can no longer be judged by operations experts alone. Objective methods are necessary to support decisions. Different logistic concepts, decision rules and optimization algorithms have to be compared by simulation before they are implemented into real systems (Desrochers et al., 1990).

The characteristics of container terminal operation demands online real-time optimization and decision. This is because most of the processes occurring at container terminals cannot be foreseen for a longer time span - in general the planning horizon for optimization is very short. Some examples shall illustrate it: although data of containers to be delivered to terminals by trucks may be pre-advised by EDI (Electronic Data Interchange), the exact time when the containers arrive at the terminal is not known (Gambardella et al., 1998). On arrival, containers have to be checked for damages, and pre-advised data may be wrong; both data influence the target stack location. As trucks have to travel to transition points where the containers are picked up by straddle carriers or cranes, the truck sequences at the gate and at the transition points need not be the same. Thus only those container jobs can be sequenced which are already released for transportation by internal terminal equipment – in general only a few. As trucks permanently arrive, recalculation has to be performed periodically or event driven. Analogous arguments hold for train operation (Gutenschwager et al., 2004).

A similar situation occurs for ship loading and unloading. As Toth and Vigo (2002) point out, although in general data of containers and their positions within the ship are precisely known in advance and the preplanning process (see below) allows the calculation of job sequences, they often have to be changed because of operational disturbances. As vessels are not static and move permanently (because of tide, weather, stability), containers which are next in the sequence cannot be accessed by the crane's spreader. Crane drivers make their own decisions and may alter the pre-calculated loading or unloading sequence by themselves.

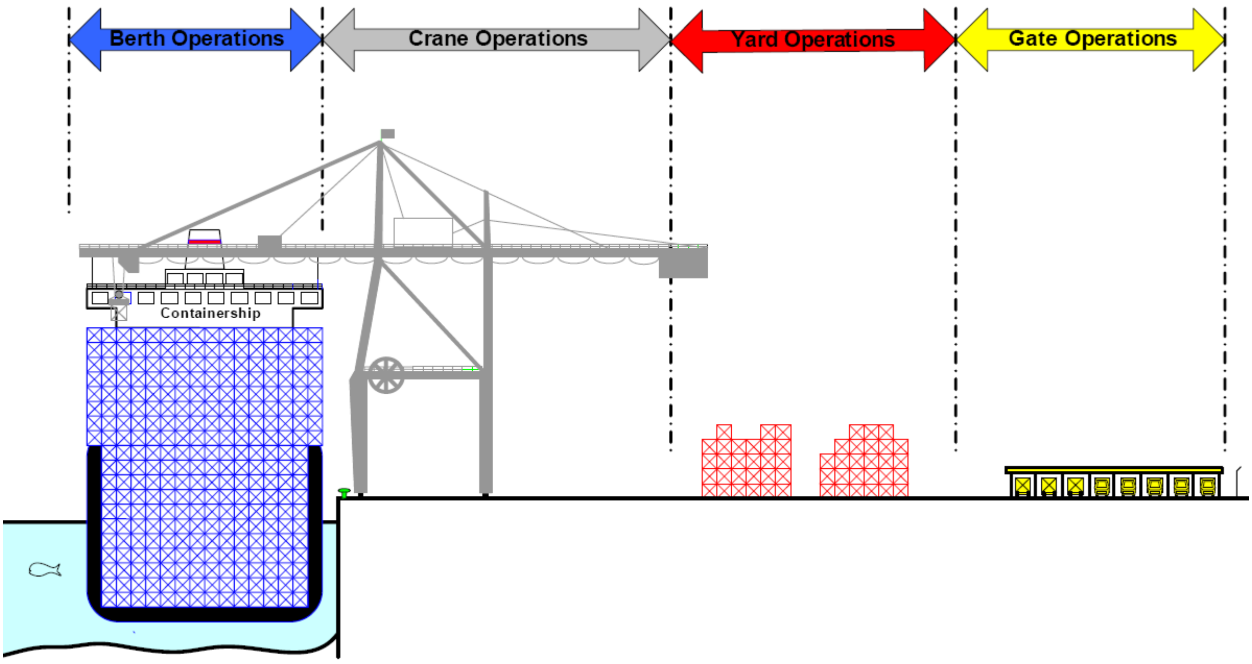


FIGURE 1.8. Classification of logistics processes at a container terminal. Source: Steenken et al. (2004)

According to Steenken et al. (2004), there can be distinguished several classes of logistics processes basing on container terminal topography: berth operations, crane operations, yard operations, and gate operations (see FIGURE 1.8. above). The underlying optimization area is constituted of the following factors influencing overall performance: vessel planning, storage and stacking logistics, and transport logistics. According to the classification above, the following sections describe the most important processes at container terminals that can be optimized by means of operations research methods.

1.5.1. THE VESSEL PLANNING PROCESS

Bruzzone and Signorile identify three partial processes in vessel planning: 1) the berth planning, 2) the stowage planning, and 3) the crane split. Let us consider these points in more detail below.

1.5.1.1. Berth planning

Before arrival of a ship, a berth has to be allocated to the ship. The schedules of large oversea vessels are known about one year in advance. They are transferred from the shipping lines to the terminal operator by means of EDI. Berth allocation ideally begins before the arrival of the first containers dedicated to this ship - on average two to three weeks before the ship's arrival (Hoffarth, 1994). Besides technical data of ships and quay cranes – not all quay cranes can be operated at all ships - other criteria like the ship's length and the length of the crane jib have to be considered. All ships to be moored during the respective time period have to be reflected in berth allocation systems. Several objectives of optimized berth allocation exist. From a practical point of view the total sum of shore to yard distances for all containers to be loaded and unloaded should be minimized. This corresponds to maximum productivity of ship operation. Automatic and optimized berth allocation is especially important in case of ship delays because then a new berthing place has to be allocated to the ship whereas containers are already stacked in the yard (Lim, 1998).

1.5.1.2. Stowage planning

Stowage planning is the core of ship planning. Planning a ship's stowage is a two-step process. The first step is executed by the shipping line. The shipping line's stowage plan has to be designed for all ports of a vessel's rotation. The positions for all containers and all ports of a rotation have to be selected within the ship. Avriel, et al. (2000) argue that stowage planning of a shipping line usually does not act with specific containers identified by numbers, but on categories of containers. These categories or attributes are: the length or type of a container, the discharge port and the weight or weight-class of containers. Containers of these attributes are assigned to specific positions within the ship. The objective of optimization from the shipping line's point of view is to minimize the number of shifts during port operation (ship to ship or ship to shore shifts) and to maximize the ship's utilization. Constraints to be satisfied mainly result from the stability of the ship (Wilson and Roach, 2000).

The stowage plan of the shipping line is transferred to the terminal operator by EDI. The stowage instruction of the shipping line is filed into the terminal's system and serves as a working instruction or pre-plan for the terminal's ship planner. The stowage instruction of the shipping line is characterized by the assignment of containers of special attribute sets to ship slots. Based on this instruction the terminal planner then assigns dedicated containers identified by numbers to the respective slots (Haghani and Kaisar, 2001). The attribute set of the slot and the container selected in the yard have to match. The stowage planning systems of a container terminal, therefore, display both the ship's sections to be planned and the yard situation. Some of the systems allow for automatic assignment and optimization. Different objectives of optimization are possible, e.g., maximization of crane productivity, cost minimization, or minimization of yard reshuffles. From a practical point of view the minimization of yard reshuffles plays an important role. Restows (or reshuffles) occur when a container has to be accessed while others on top of it have to be removed first. Restowing consumes time which is an offset to the transportation time between stack and shore reducing the productivity of ship operation (Dubrovsky et al., 2002).

1.5.1.3. Crane split

To achieve a high productivity for the crane operation containers have to arrive at the quay in the right time and in the order of the loading sequence; i.e., loading sequence and sequence of horizontal transport have to correspond with each other. Otherwise crane waiting times and/or queuing of transport vehicles occur. Both reduce crane productivity and extend the ship's berthing time (Kim et al., 2003). As a common feature, containers are more or less spread in the yard and have different distances to the crane; special containers like overheight containers need special equipment which has to be mounted before they can be transported, reefer containers have to be disconnected from the electrical circuit, and yard restows occur to a respective percentage. All this consumes additional transportation time. In manually driven systems the performance additionally depends on the driver's skill and decision which path he travels. Even technical or operational disturbances of the crane operation occur which enforce to change the loading sequence. Therefore, transportation times cannot be calculated exactly even if automated equipment is in use (Liu et al., 2002).

1.5.2. Storage and stacking logistics

Stacking logistics has become a field of increasing importance because more and more containers have to be stored in ports as container traffic grows continuously and space is becoming a scarce resource. Generally containers are stacked on the ground in several levels or tiers and the whole storage area is separated into blocks. A container’s position in the storage area (or yard) is then addressed by the block, the bay, the row and the tier. The maximum number of tiers depends on the stacking equipment, either straddle carriers or gantry cranes (Liu et al., 2002). According to operational needs the storage area is commonly separated into different areas. There are different areas for import and export containers, special areas for reefer, dangerous goods or damaged containers. The average daily yard utilization of large container terminals in Europe is about 15’000-20’000 containers resulting in about 15’000 movements per day, which about ten times more than in Baltic Container Terminal (UNCTAD, 2003). The average dwell time of containers in the yard as estimated by Preston and Kozan (2001), lies in the range of 3-5 days.

A storage planning or stacking decision system has to decide which block and slot has to be selected for a container to be stored. Because containers are piled up, not every one is in direct access to the stacking equipment. Containers that are placed on top of the required one have to be removed first. Reshuffles (or rehandles) may occur due to several reasons; the most important ones result if data of containers to be stacked are wrong or incomplete. At As per Kim et al (2000), at European terminals up to 30% of the export containers arrive at the terminal lacking accurate data for the respective vessel, the discharge port, or container weight – data which are necessary to make a good storage decision. Even after arrival, vessel and discharge port can be changed by the shipping line. For import containers unloaded from ships the situation is even worse: the landside transport mode is known in at most 10-15% of all cases at the time of unloading a ship, e.g., when a location has to be selected in the yard (Steenken, 1992).

Because pre-stowage needs extra transportation, it is cost expensive and terminals normally try to avoid it by optimizing the yard stacking, but it is executed when ship loading has to be as fast as possible. Storage and stacking logistics are becoming more complex and sophisticated; they play an important role for the terminals’ overall performance.

As per Vis and de Koster (2002), two classes of storage logistics can be distinguished. In storage or yard planning systems, stack areas and storage capacities are allocated to a ship's arrival in advance according to the number of import and export containers expected. An appropriate number of slots in blocks and rows are reserved for a special ship. Depending on the planning strategy, the reservation for export containers can be split for discharge port, container type/length, and container weight. A common strategy for export planning is to reserve slots within a row for containers of the same type and discharge port while heavier containers are stacked on lighter ones assuming that they are loaded first because of the ship stability (Park and Kim, 2003). For import containers only a reservation of yard capacity of respective size is done without further differentiation. This is because data and transport means of delivery generally are unknown at the time of discharge. If the transport mode is known, import areas can be subdivided according to them. Common strategies for import containers are either selecting any location in the import area or piling containers of the same storage date.

Yard or storage planning seldom matches the real delivery because container delivery is a stochastic process not exactly to be foreseen. The quality of this yard concept mainly depends on the strategy how to determine a good stack configuration and a good forecast of the container delivery distribution. Both factors are hard to solve, the result is a comparatively high amount of yard reshuffles. In addition, the reservation of yard locations occupies stack capacity.

Because of these disadvantages some terminals installed an alternative stacking concept, called scattered stacking (Avriel et al, 1998). In scattered stacking, yard areas are no longer assigned to a specific ship's arrival but only once to a berthing place. On arrival of a container the computer system selects the berthing place of the ship from the ships schedule and automatically searches for a good stack location within the area assigned to the berth. A stack position is selected in real-time and containers with the same categories - ship, type/length, discharge port, and weight - are piled up one on top of the other. Containers for one ship are stochastically scattered over the respective stack area; reservation of yard slots is no longer necessary. This concept results in a higher yard utilization - because no slots are reserved - and a remarkable lower amount of reshuffles - because the stacking criteria merge the ship's stowage criteria (Dubrovsky et al., 2002).

Although the container attributes play a major role in yard stacking concepts, additional parameters have to be taken into account for improving logistic processes. Evidently, containers have to be stacked near to the future loading place, e.g., the transport distance should be minimal to ensure a high performance of the future operation. The performance of quay cranes is a multitude higher than the performance of stacking and transport equipment. Therefore, containers with the same categories have to be distributed over several blocks and rows to avoid congestions and unnecessary waiting times of vehicles. The actual workload of a gantry crane or other stacking equipment also has to be considered because allocating additional jobs to highly utilized equipment provokes waiting times. All these factors can be integrated into an algorithm while the weight of each factor is measured by parameters. The objective of yard optimization is to minimize the number of reshuffles and to maximize the storage utilization.

1.5.3. TRANSPORT LOGISTICS

As it was outlined above, two types of transport at a container terminal can be distinguished: the horizontal transport and the stacking transport carried out by gantry cranes. The horizontal transport itself subdivides into the quayside and the landside transport serving ships or trucks and trains, respectively. The section below deals with optimization issues related to the outlined classes of resources.

1.5.3.1. The quayside transport optimization

For ship loading and unloading containers have to be transported from stack to ship and vice versa. Transport optimization at the quayside not only means to reduce transport times but also to synchronize the transports with the loading and unloading activity of the quay cranes. A general aim is to enhance crane productivity. Crane productivity does not only depend on the technical data of the cranes, the real performance at operation is much lower. The reduction is caused by unproductive times like pauses and breaks during shifts, moves of hatch covers and lashing equipment, technical or operational disturbances and congestions occurring for the horizontal transport. Additionally, more transport vehicles provoke further costs and ship operation then is less economic.

Concerning logistics, a gain in ship productivity cannot be necessarily achieved by enhancing the number or the speed of transport vehicles operating at the quayside. This is because the possibility of congestions at the cranes and in the yard increases more than proportionally with the number of vehicles or their speed. Therefore, developing an optimization system also has to cope with the minimization of congestions.

As Li and Vairaktarakis (2001) point out, different modes of transport and strategies to allocate vehicles to cranes occur at the quayside. In single-cycle mode the vehicles serve only one crane. According to the crane's cycle they either transport discharged containers from the quay to the yard or export containers from the yard to the crane. In dual-cycle mode the transport vehicles serve several cranes which are in the loading or unloading cycle, respectively, thus combining the transports of export and import containers. Transport vehicles can either be allocated exclusively to one crane (gang structure) or to several cranes and ships (pooling).

Kim and Kim (2003) argue that in single-cycle mode no potential for the optimization of the import cycle exists. Optimization for discharged containers is restricted to the selection of optimal yard positions which is a task of the yard planning module. As import containers have to be transported to the pre-selected stack locations, empty travels cannot be reduced. Travel distances can only be reduced if locations near to the quay are selected. For export loading, however, there is a potential for optimization. In general the transport sequence is not identical to the loading sequence of the ship. The loading sequence is determined by the stowage plan, the crane split and the crane's loading strategy. The transport sequence, however, has to reflect different distances, yard reshuffles and special containers. The latter ones sometimes need special equipment which has to be provided before they can be transported. All effects result in additional transportation times. Therefore, the transport sequence has to be altered to ensure the right order of the loading sequence. Idle times of the cranes and vehicle congestions at cranes and stacks have to be avoided because both reduce productivity.

According to van der Heijden et al. (2002), the dual-cycle is more complex. The dual-cycle mode combines the transports of export and import containers to/from cranes operating at the same ship or at neighbouring ships. The fixed allocation of transport vehicles to cranes is given up, vehicles operate in a pool serving several cranes in alternative modes (loading or discharging). Empty distances and transportation times are reduced in dual-cycle mode. This mode is more efficient but harder to organize because of the higher complexity. The possibility of crane waiting times can be reduced if containers can be buffered under the crane's portal.

Ship operation in practice is dynamic and, therefore, demands online optimization. For import containers, e.g., the precise yard location cannot be selected before the container is unloaded and its data and condition is physically checked. Disturbances occurring during ship operation often force to alter the loading or unloading sequence immediately. Such disturbances are: interruption of crane operation because of operational or technical problems, change of (un)loading sequences decided by the crane driver because of ship stability reasons or problems occurring during the horizontal transport. Such reasons force (re)calculating sequences only for few containers. The objective of optimization in any case is to minimize the lateness of container deliveries for the cranes and the travel times of the transport vehicles (Kim and Park, 2003).

1.5.3.2. The landside transport optimization

The landside transport is split into the rail operation, the truck operation and the internal transports. As Hartmann (2004) claims, a common means of operation is to allocate a given number of vehicles to each sphere of operation appropriate to the workload expected. A more advanced strategy is to pool the vehicles for all these working areas.

Trains are commonly loaded and unloaded by gantry cranes while the transports between the stack and the railhead are performed by straddle carriers, trucks and trailers or similar equipment. Containers are then buffered alongside the railhead or directly on trailers. Sometimes pure straddle carrier operation exists where straddle carriers drive over the wagons to pick up and drop containers. Operation at the railhead is analogous to the quayside operation. A loading plan describes on which wagon a container has to be placed. The wagon position of a container depends on its destination, type and weight, the maximum load of the wagon and the wagon's position in the train sequence. A loading plan is either produced by the railway company and sent by EDI to the terminal operator or by the terminal operator himself. The aim of the rail operator is to minimize shunting activities during train transport while the aim of the terminal operator is to minimize the number of yard reshuffles, to minimize the crane waiting times and the empty transport distances of cranes and transport vehicles. Optimization at the railhead is facilitated if only a stowage instruction is sent to the terminal operator which indicates the wagon position for container attributes instead of specific positions for each container. The yard situation then can be reflected. Transport and crane activities have to be synchronized to avoid unnecessary crane waiting times or movements. Single- and dual-cycle mode exist depending on whether one or several trains are loaded and unloaded in parallel (Kim et al., 2003).

Trucks arrive at the terminal's in-gate where the data of the containers have to be checked and filed into the computer system or actualized in case of pre-advice. Trucks then drive to transition points where the containers are loaded or unloaded by internal equipment. Large container terminals serve some thousand trucks a day. Transition points are located either at the stack crane or inside the yard in case of straddle carrier operation. A truck driving schedule prescribes which points have to be accessed in which sequence. The arrival time of the trucks at the transition points cannot be precisely foreseen, i.e., transport jobs for the internal equipment cannot be released until the truck arrives at the transition point. Because of the permanently changing traffic volume, optimization has to be very flexible and fast. Online optimization is demanded for. Minimizing empty distances and travel times are the objectives of optimization at the truck operation area. Empty distances can be minimized if transports of export containers from the transition point to the yard are combined with transports of import containers from the yard to the interchange point (Steenken, 1992).

According to Chen (1999), internal movements occur because of different reasons. If sheds or depots for empty containers exist at a terminal additional transports have to be performed: Import containers to be stripped have to be driven to the respective shed while packed containers have to be driven to the export stock. Empty containers are needed at the sheds for stuffing purposes while unpacked containers have to be stored in the empty depot or in the yard. Because of imbalances, empty containers are needed for ship, train and truck loading and have to be transported to the respective yard or transition area. Additional transports occur when containers assigned for a ship's departure are left back because of ship's overbooking. A reorganization of the yard then has to be performed. Characteristic for these types of transports is that sequences of jobs have to be performed. Sometimes time-windows have to be kept. In general these kinds of transports are not as time critical as those for the ship or truck operation. Therefore, terminals try to execute them at times of less workload. The objective is to minimize empty and loaded travel times.

1.5.3.3. Crane transport optimization

Another field of application of optimization methods are the transports of quay and yard cranes operating in stacks. The transport requirements do not differ from those of the horizontal transport described above. Sequences of jobs have to be calculated and jobs have to be assigned to the respective crane. Commonly the location of a container to be positioned in the stack is calculated by the yard module (Preston and Kozan, 2001).

Therefore, as Kim et al. (2000) claim, transport optimization for stack cranes reduces to the same requirements as for the horizontal transport and comparative algorithms can be applied. Priority of jobs have to be taken into account - as is the case for the horizontal transport. The objective of optimization is to minimize the waiting times of the transport vehicles at the stack interfaces and the travel times of the stacking cranes. Because the traffic at the interfaces changes rapidly, online optimization is demanded for and job sequences have to be recalculated whenever a new job arises.

1.6. Baltic Container Terminal

According to Baltic Container Terminal website, BCT is a privately owned container terminal operating within the Freeport Area of the Riga Commercial Port. Hili Company Limited of Malta have acquired the full shareholding interests in BCT in January 1999, after having held a minority shareholding interest since the commencement of the terminal's privatization programme in May 1996.

Figure 1.9. Quayside view of BCT. Source: Baltic Container Terminal website

BCT is positioning itself as the gateway via Latvia to act as a main distribution center in the Baltic Region and the CIS. The western style of management being adopted is safeguarding against corruption and security issues besides ensuring the highest productivity levels in the region. Being a Free Trade Zone there are no customs interventions, nor any duties levied or taxes and clients deal directly with BCT on all issues. This ensures smooth running of operations guaranteeing cost effectiveness. Moreover, BCT enjoys a very harmonious relationship with its workforce and no industrial disruptions are experienced.

Constantly improved standards of efficiency and service call for high investments in computerisation systems and to ensure that we are always at the forefront of technology, Baltic Container Terminal Ltd is equipped with an advanced terminal computerisation control system – the NAVIS SPARCS System – which helps to guarantee improved quality services. This system substantiates the efficient real-time management of all operations and is strengthening the container terminal's position to realize its goals of improving productivity thus guaranteeing a more efficient service to our clients.

1.6.1. Facilities

In the early eighties to meet constantly growing demand in container traffic, to and from the main industrial centres 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 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. According to Baltic Container Terminal website, the list of facilities currently available at the terminal are as follows:

- **Ro-Ro Facilities:** a 25 meter ro-ro ramp is available at the west end of the quay making a ro-ro, lo-lo operation possible simultaneously. Ample open storage space is available for ro-ro cargo.
- **Rail Facilities:** the terminal is directly linked to the main rail routes with access from the terminal in place at quay side, at the warehouses and container freight station facilities.
- **Warehousing Facilities:** a total of 11,500 sqm of covered storage space is available.
- **Container Freight Station:** extensive facilities and equipment are available for the stuffing and stripping of containers with operations carried out to/from warehouses, truck or rail wagons.

- **Container Repair:** the terminal has its own engineering set up which also caters for minor repairs on damaged containers.

- **Refrigerated Containers:** there are 174 reefer points on the terminal which are monitored 24 hours a day 7 days a week. Emergency repair services are also available, as are container cleaning, washing, pre-tripping etc.

- **Terminal Computerization:** Baltic Container Terminal features Navis LLC of the U.S. to install a graphical terminal management software. With the demands of the future in mind, BCT has invested in state of the art technology to ensure improved quality services. The system includes yard planning, ship planning and equipment control modules. The terminal has invested in radio data terminals, installed on all yard equipment and a number of handheld terminals to enable efficient data transmission online. The new integrated system ensures the efficient real-time management of the entire container handling cycle. It is possible to anticipate in detail a ship's arrival and plan the operations needed at the terminal right through the entire process from unloading and stacking to the re-loading of containers.

The next section deals with the resources available at the BCT.

1.6.2. RESOURCES: QUAYSIDE AND LANDSIDE TRANSPORT

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 1.1. below.

TABLE 1.1. Breakdown of quayside and landside transport of Baltic Container Terminal by quantity, type, and manufacturer (Source: Baltic Container Terminal website).

Quayside Cranes				
Manufacturer	**Quantity**	**Capacity**	**Outreach**	**Backreach**
Kone	1	30.5T	32m	12.5
Kone	2	35.0T	32m	12.5
Yard Cranes				
Manufacturer	**Quantity**	**Capacity**	**Stacking Capabilities**	**Type**
Kone	4	30.5T	19 accross 1 over 4	Rail Mounted Yard
Kone	2	30.5T	Railway Track	Rail Mounted Yard

TABLE 1.1 (continued). Breakdown of quayside and landside transport of Baltic Container Terminal by quantity, type, and manufacturer (Source: Baltic Container Terminal website).

Tractor Units		
Manufacturer	**Quanity**	
SISU	8	
Terberg	2	
Reach Stackers		
Manufacturer	**Quantity**	**Capacity**
Kalmar	2	41T
Fork Lifts		
Manufacturer	**Quantity**	**Capacity**
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

1.7. CONTAINER TERMINAL SIMULATION MODELLING

According to Akbay (1996), simulation modelling is defined as studying mathematical model of a system using simulation. The objective of simulation optimization is to minimize the resources spent while maximizing the information obtained in a simulation experiment. System behavior at specific values of input variables is evaluated by running the simulation model for a fixed period of time. A simulation experiment can be defined as a test or a series of tests in which meaningful changes are made to the input variables of a simulation model so that we may observe and identify the reasons for changes in the output variable(s). When the number of input variables is large and the simulation model is complex, the simulation experiment may become computationally prohibitive. Besides the high computational cost, an even higher cost is incurred when sub-optimal input variable values are selected. The process of finding the best input variable values from among all possibilities without explicitly evaluating each possibility is simulation optimization. The objective of simulation optimization is minimizing the resources spent while maximizing the information obtained in a simulation experiment.

In recent years, simulation has become an important tool to improve terminal operation and performance. According to Gambardella et al. (1996), three types of simulation can be distinguished: 1) *strategic*, 2) *operational*, and 3) *tactical* simulation.

- *Strategic* simulation is applied to study and compare different types of terminal layout and handling equipment in respect to efficiency and costs expected. It is mainly used if new terminals are planned or the layout or the equipment of existing terminals has to be altered. Strategic simulation systems allow for easy design of different terminal layouts and employment of different types of handling equipment. The chief goal of strategic simulation is to decide on terminal layout and handling equipment which promises high performance and low costs. To match reality, simulation systems allow to design realistic scenarios or to import data of existing terminals.

- *Operational* simulation is applied to test different kinds of terminal logistics and optimization methods. It has achieved growing acceptance at least at large terminals. Terminal operation and logistics at large terminals are already very complex and the effect of alternative logistics or optimization methods has to be tested with objective methods. Therefore, optimization methods are tested in a simulation environment before they are implemented in real terminal control and steering systems.

- *Tactical* simulation means integration of simulation systems into the terminal's operation system. Variants of operation shall be simulated parallel to the operation and advices for handling alternatives shall be given especially if disturbances occur in real operation. Real data of operation then have to be imported and analyzed synchronously to the operation. Because of this ambitious requirement, tactical simulation is seldom or only partially installed at container terminals.

The section that follows represents basic approach and methods for simulation optimization.

1.7.1. General approach to simulation modelling

A general simulation model comprises *n* input variables (x_1, x_2, x_3,…, x_n) and *m* output variables ($f_1(x)$, $f_2(x)$,…, $f_m(x)$) or ($f_1(x)$, $f_2(x)$,…, $f_m(x)$) (see Figure 1.10.). Simulation optimization entails finding optimal settings of the input variables, i.e. values of x_1, x_2, x_3,…, x_n which optimize the output variable(s). Such problems arise frequently in engineering, for instance, in process design, in industrial experimentation, in design optimization, and in reliability optimization.

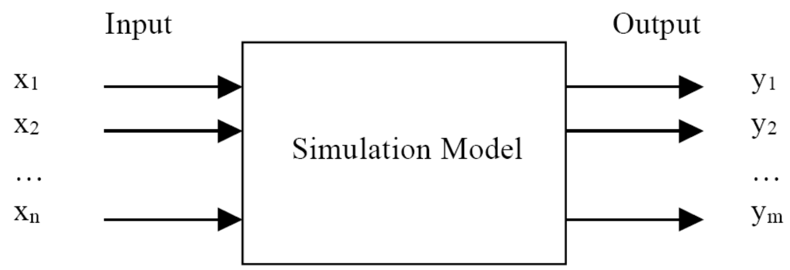


FIGURE 1.10. Graphical illustration of a simulation model

A general simulation optimization model is schematically portrayed in FIGURE 1.11. The output of a simulation model is used by an optimization strategy to provide feedback on progress of the search for the optimal solution. This in turn guides further input to the simulation model.

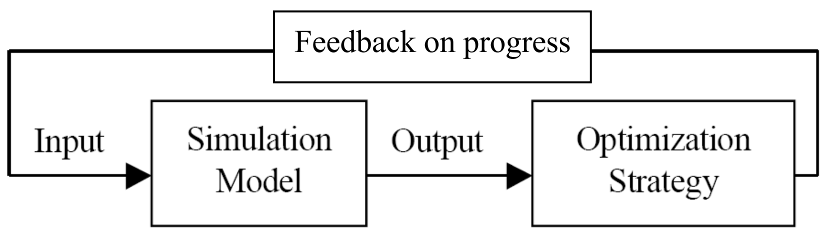


FIGURE 1.11. Graphical illustration of a simulation optimization model

Simulation optimization is an area that has attracted the attention of many researchers and has been widely investigated in simulation literature. The following section provides a brief overview of optimization methods used in simulation modelling.

1.7.2. SIMULATION OPTIMIZATION METHODS

There might be outlined several classes of approaches to simulation task optimization. Thus, according to Carson and Maria (1997), there can be distinguished the following classes of optimization methods: gradient-based search methods, stochastic optimization, response surface methodology, heuristic methods, A-teams methods, and statistical methods. These and respective subgroups are presented in FIGURE 1.12. below.

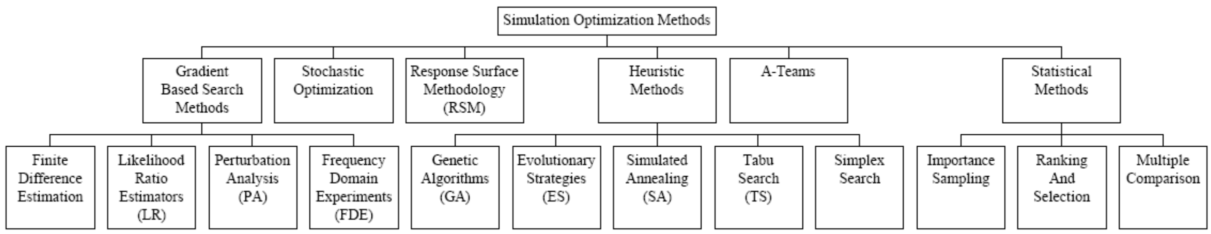


FIGURE 1.12. Classification of simulation optimization methods as per Carson and Maria (1997).

The methods presented above are described in more detail in the sections that follow.

1.7.2.1. Gradient-based search methods

Methods in this category estimate the response function gradient ∇f to assess the shape of the objective function and employ deterministic mathematical programming techniques. Frequently used gradient estimation methods are described below.

- *Likelihood Ratios (LR).* In the likelihood ratio method, also called the score function, the gradient of the expected value of an output variable with respect to an input variable is expressed as the expected value of a function of a) input parameters, and b) simulation parameters e.g. simulation run length, output variable value etc. The construction of a likelihood ratio that has desirable computational and variability characteristics is an important issue in the development of LR gradient estimators (Glynn, 1989b). LR methods are discussed in Glynn (1989a), and Reiman and Weiss (1986).

- *Perturbation Analysis (PA).* In infinitesimal perturbation analysis (IPA) all partial gradients of an objective function are estimated from a single simulation run. The idea is that in a system, if an input variable is perturbed by an infinitesimal amount, the sensitivity of the output variable to the parameter can be estimated by tracing its pattern of propagation. This will be a function of the fraction of propagations that die before having a significant effect on the response of interest. IPA assumes that an infinitesimal perturbation in an input variable does not affect the sequence of events but only makes their occurrence times slide smoothly. The fact that all derivatives can be derived from a single simulation run, represents a significant advantage in terms of computational efficiency. On the other hand, the estimators derived using IPA are often biased and inconsistent. For a comparative study of finite differences, LR and IPA, see L'Ecuyer (1991).

- *Frequency Domain Method (FDM).* A frequency domain experiment is one in which selected input parameters are oscillated sinusoidally at different frequencies during one long simulation run. The output variable values are subjected to spectral (Fourier) analysis, i.e. regressed against sinusoids at the input driving frequencies (Morrice and Schruben, 1989). If the output variable is sensitive to an input parameter, the sinusoidal oscillation of that parameter should induce corresponding (amplified) oscillations in the response.

1.7.2.2. Stochastic Optimization

Stochastic optimization is the problem of finding a local optimum for an objective function whose values are not known analytically but can be estimated or measured. Classical stochastic optimization algorithms are iterative schemes based on gradient estimation. Proposed in the early 1950s, Robbins-Monro and Kiefer-Wolfowitz are the two most commonly used algorithms for unconstrained stochastic optimization. These algorithms converge extremely slowly when the objective function is flat and often diverge when the objective function is steep. Additional difficulties include absence of good stopping rules and handling constraints. More recently, Andradottir (1990) proposed a stochastic optimization algorithm that converges under more general assumptions than these classical algorithms. Leung and Suri (1990) reported better results with the Robbins-Monro algorithm when applied in a finite-time single-run optimization algorithm than when applied in a conventional way. In the stochastic counterpart method (also known as sample path optimization) a relatively large sample is generated and the expected value function is approximated by the corresponding average function (Shapiro (1996), Gurkan et al. (1994)). The average function is then optimized by using a deterministic non-linear programming method. This allows statistical inference to be incorporated into the optimization algorithm which addresses most of the difficulties in stochastic optimization and increases the efficiency of the method.

1.7.2.3. Response Surface Methodology (RSM)

Response surface methodology is a procedure for fitting a series of regression models to the output variable of a simulation model (by evaluating it at several input variable values) and optimizing the resulting regression function. The process starts with a first order regression function and the steepest ascent/descent search method. After reaching the vicinity of the optimum, higher degree regression functions are employed. Applications of RSM in simulation optimization are described in Biles (1974) and Daugherty and Turnquist (1980). Using a criterion which considers the bias as well as the variance of the simulation response variable, Donohue et al. (1990) developed optimal designs in common second-order design classes including central composite, Box-Behnken, and full-factorial. In general, RSM requires a smaller number of simulation experiments relative to many gradient based methods.

1.7.2.4. Heuristic Methods

Heuristic methods discussed below represent the latest developments in the field of direct search methods (requiring only function values) that are frequently used for simulation optimization. Many of these techniques balance exploration with exploitation thereby resulting in efficient global search strategies.

- *Genetic Algorithms (GA).* A genetic algorithm is a search strategy that employs random choice to guide a highly exploitative search, striking a balance between exploration of the feasible domain and exploitation of "good" solutions (Holland, 1992). This strategy is analogous to biological evolution. From a biological perspective, it is conjectured that an organism's structure and its ability to survive in its environment ("fitness"), are determined by its DNA. An offspring, which is a combination of both parents' DNA, inherits traits from both parents and other traits that the parents may not have, due to recombination. These traits may increase an offspring's fitness, yielding a higher probability of surviving more frequently and passing the traits on to the next generation. Over time, the average fitness of the population improves.
- *Evolutionary Strategies (ES).* Similar to GA, evolutionary strategies (ES) are algorithms that imitate the principles of natural evolution as a method to solve parameter optimization problems. Rechenberg is credited for introducing ES during the sixties at the Technical University of Berlin, but Schwefel made the first attempt towards extending this strategy in order to solve discrete parameter optimization problems (Schwefel, 1995).

- *Simulated Annealing (SA).* Simulated annealing is a stochastic search method analogous to the physical annealing process where an alloy is cooled gradually so that a minimal energy state is achieved. SA avoids getting stuck in local optima (hill climbing) and keeps track of the best objective value overall. SA performs well on combinatorial problems. Several versions of this heuristic exist (see Fleischer, (1995) and Alrefaei et al. (1995)).

- *Tabu Search (TS).* Tabu search was developed by Fred Glover (1989, 1990) for optimizing an objective function with a special feature designed to avoid being trapped in local minima. TS is used for solving combinatorial optimization problems ranging from graph theory to pure and mixed integer programming problems. It is an adaptive procedure with the ability to utilize many other methods, such as LP algorithms and specialized heuristics, which it directs to overcome their limitations of getting stuck in local optima. For any TS implementation, the following are needed: a forbidding strategy, a freeing strategy, a short-term strategy, and a stopping criterion (Osman, 1993).

- *Nelder And Mead's Simplex Search.* The search starts with points in a simplex consisting of p+1 vertices (not all in the same plane) in the feasible region. It proceeds by continuously dropping the worst point in the simplex and adding a new point determined by the reflection of the worst point through the centroid of the remaining vertices. Disadvantages of this method include the assumption of convex feasible region and implementation problems involving the handling of feasibility constraints. Box's complex search is an extension of Nelder and Mead's simplex search modified for constrained problems (Reklaitis et al., 1983). See also Azadivar and Lee (1988), Barton and Ivey (1991), and Tomick et al., (1995) for enhancements to the Nelder-Mead method. Hall and Bowden (1997) concluded that Nelder-Mead method performs better than ES or TS with smooth convex response surfaces.

1.7.2.5. A-Teams

An A-team (asynchronous team) is a process that involves combining various problem solving strategies so that they can interact synergistically. De Souza and Talukdar (1991) viewed an A-team as a process that is both fast and robust. They have demonstrated that A-teams consisting of GA and conventional algorithms, such as Newton's Method and Levenberg-Marquardt algorithms, for solving sets of nonlinear algebraic equations, result in considerable savings in the amount of computational effort (number of function evaluations) necessary for finding solutions.

1.7.2.6. Statistical Methods

- *Importance Sampling Methods*. Importance sampling has been used effectively to achieve significant speed ups in simulations involving rare events, such as failure in a reliable computer system or ATM communication network (Shahabuddin, 1995). The basic idea of importance sampling is to simulate the system under a different probability measure (e.g. with different underlying probability distributions) so as to increase the probability of typical sample paths involving the rare event of interest. For each sample path (observation) during the simulation, the measure being estimated is multiplied by a correction factor to obtain an unbiased estimate of the measure in the original system. The main problem in importance sampling is to come up with an appropriate change of measure for the rare event simulation problem at hand.

- *Ranking and Selection*. Ranking and selection methods are frequently employed for practical problems, for instance, finding the best combination of parts manufactured on various machines to maximize productivity, or finding the best location for a new facility to minimize cost. In these optimization problems, some knowledge of the relationship among the alternatives is available. These methods have the ability to treat the optimization problem as a multi-criteria decision problem. When the decision involves selecting the best system design, the technique of indifference zone ranking may be employed. When the decision involves selecting a subset of system designs that contains the best design, the technique of subset selection may be employed. In either case, the decisions are guaranteed to be correct with a pre-specified probability. Many ranking and selection procedures can be found in Gupta and Panchapakesan (1979).

- *Multiple Comparisons With The Best*. If the problem is to select the best of a finite number of system designs, multiple comparisons with the best (MCB) is an alternative to ranking and selection. In MCB procedures inference about the relative performance of all alternatives tested is provided. Such inference is critical if the performance measure of interest is not the sole criterion for decision making, e.g., expected throughput of a manufacturing system may be the performance measure of interest but cost of maintaining the system is also important. According to Hsu and Nelson (1988), MCB combines the two most frequently used ranking and selection techniques, namely, indifference zone and subset selection inference. Goldsman and Nelson (1990) devised an MCB procedure for steady state simulation experiments based on batching. This MCB procedure can be implemented in a single run of each alternative under consideration, which is important if restarting simulation experiments is unwieldy and/or expensive.

A more thorough discussion and choice of methods for the task in focus is presented in CHAPTER 2 of the present paper.

1.8. CONCLUSIONS

The increasing number of publications over the last decade indicates the importance of operations research methods in the field of optimizing logistic operations at a container terminal. Until now the focus is not on optimizing the transport chain as a whole but on optimizing several separate parts of the chain. A tendency from relatively theoretical publications to more practical ones can be seen. Furthermore, operations research methods are applied more and more in real terminals. One of the drivers in this respect is an increased availability of modern information and communication technology that only allows the application of these methods.

It has been illustrated that the container turnover 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 the problem of creating optimization and decision support tools becomes even more acute.

In this introductory chapter there have been presented resources of the logistics chain of marine container terminals. Among the variety of container terminal resources, Baltic Container Terminal pool of resources represents quite a simple chain not utilizing automation such as AGVs where a vast majority of congestions are attributable to human factor. Further in CHAPTERS 3 and 4 it will be illustrated that such a dependence causes a variety of unevenly distributed delays at different stages of logistics chain. This feature is common for a vast majority of container terminals, which makes the approach described in this work applicable for other container terminal systems with minor adjustment.

For increasing simulation modelling efficiency there are applied different methods of optimization which can be grouped as follows: gradient-based search methods, stochastic optimization, response surface methodology, heuristic methods, A-teams, and statistical methods. Specific choice and more detailed description of simulation optimization methods in order to arrive at the aim of the research will be discussed in more detail in CHAPTER 2.

2. SIMULATION MODEL DEVELOPMENT

The present chapter focuses on creation of simulation model in the Rockwell Software Arena simulation environment. The simulation model parameters were estimated basing on the BCT historical data with the help of a two-tier algorithm described in detail in section 3.2. TWO-TIER PARAMETER ADJUSTMENT ALGORITHM of CHAPTER 3.

The essence of simulation modelling is to help the ultimate decision-maker solve a given problem. Therefore, we combine efficient problem-solving techniques with good software engineering practice. Simulation studies normally propose the following steps for creating a model (Akbay, 1996):

1. **Problem Definition:** Clearly defining the goals of the study so that we know why are we studying the problem and what questions do we hope to answer.
2. **System Definition:** Determining the boundaries and restrictions to be used in the system or process and investigating how the system works.
3. **Input Data Preparation:** Identifying and collecting the input data needed by the model.
4. **Conceptual Model Formulation:** Developing a preliminary model either graphically (e.g., block diagrams) or in pseudo-code to define the components, descriptive variables and interactions that constitute the system.
5. **Experimental Design:** Selecting the measures of effectiveness to be used, the factors to be varied and the levels of those factors to be investigated, i.e., what data need to be gathered from the model, in what form and to what extent.
6. **Model Translation:** Formulating the model in an appropriate simulation language.
7. **Verification and Validation:** Confirming that the model operates the way the analyst intended (debugging) and that the output of the model is believable and representative of the output of the real system.
8. **Experimentation:** Executing the simulation to generate the desired data and to perform a sensitivity analysis.
9. **Analysis and Interpretation:** Drawing inferences from the data generated by the simulation.
10. **Implementation and Documentation:** Putting the results to use, recording the findings and documenting the model and its use.

The accumulated experience of modelling marine container terminals and obtained simulation results allow outlining methodology steps taking due regard for subject specificity.

The methodological steps specific to marine terminal simulation are as follows:

- 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. This approach is elaborated below in section 2.3. DEVELOPING LOGICAL STRUCTURE.
- 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, verification, and validation. This important aspect is considered separately in CHAPTER 4.
- Modelling and adjusting inputs of the model, i.e. creating sub-model blocks for scenario modelling (what if vessel and container statistics change?). This stage is considered in CHAPTER 4.
- Application for solving practical problems. CHAPTER 5 of the present paper presents utilization of the model for choosing an appropriate set of resources subject to several constraints.

2.1. GENERAL APPROACH TO SIMULATION MODELLING OF CONTAINER TERMINAL PROCESSES

The existing mathematical models of marine container terminals known to the author lack one important thing: these do not explicitly address to parameters of the terminal resources which results in a missing link between resource unit performance and its marginal influence on the productivity of the terminal. Formally speaking, these models work in a space of abstract parameters (e.g. variable coefficients in regression models) which is not suitable for creating realistic detailed microsimulation models.

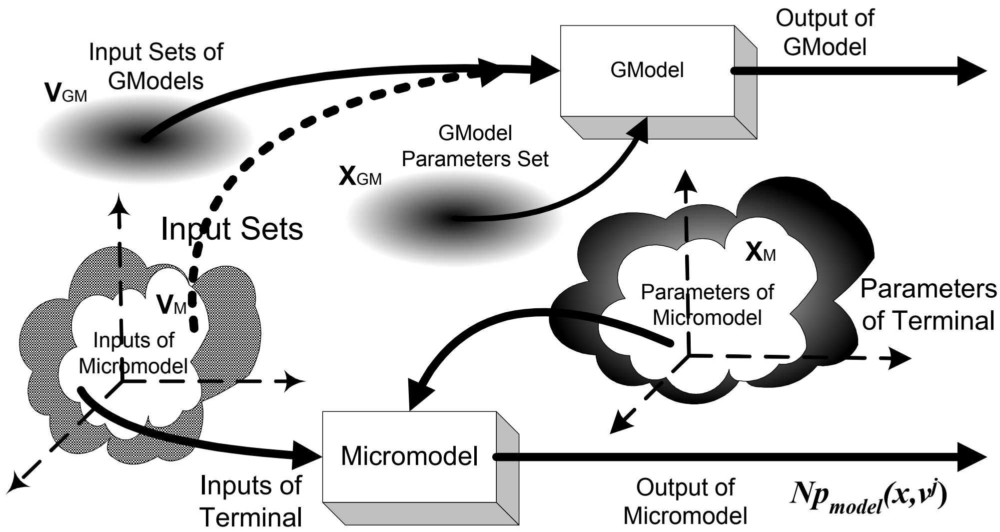


FIGURE 2.1. Illustrated comparison of spaces of parameters and inputs of general regression-based models and spaces used in microsimulation modelling.

At the same time, as mentioned by Gambardella et al. (1996) and Murty et al. (2003), existing non-commercial simulation models of maritime container terminals are quite limited in terms of micro-operation adequacy and detail level which is schematically illustrated in FIGURE 2.1. above.

First of all it is explained by programming complexity of the logical structure of micro-operations and arising thereof inter-relations, especially when programming resource interaction points. As a consequence, the number of parameters of the model drastically decreases the scope of parameter adjustability without calling for the help of sophisticated methods.

The resulting object value for marine container terminal simulation generally is the terminal productivity (referred to as NP for Net Productivity) which is the total number of containers movements (ashore and aboard including hatch cover operations and re-stows) per hour. Generally, for internal purposes the net productivity (taking into consideration only technology-related time costs from the moment of vessel arrival at the berth). Thus, there is only one research target value, representing a criterion of technical productivity with no regard to associated financial costs. Provided no additional information as to parameter feasible boundaries, parameter adjustment becomes quite a complicated task.

Thirdly, virtually every micro-operation parameters are randomly distributed values, whose distribution show no normality, but can be approximated by asymmetric triangular distributions. Thus, the number of parameters is three higher than in a case of a deterministic model. The more parameters of the model, the lower is the marginal impact of each of those on the object value, and consequently, the harder it is to determine the influence of each of the parameters on the productivity NP. At the same time the researchers face the problem of parameter choice that would bring a balance between the degree of detail level and computability.

Fourthly, going to microscopic level is a complicated task which calls for a tremendous amount of effort for primary data collection (micro-operation time measurement) and analysis of secondary statistical data and indirect data collection methods.

Commercial terminal monitoring systems allow real-time database modification and access, which allows an online interaction with the modelling system for immediate adjustments. Such a real time interaction between the two systems allows a more precise prediction (e.g., changing weather conditions, equipment breakdowns, etc.).

These and other factors adversely affect creation of marine container terminal micro-simulation systems. However, a constantly growing number of container freight calls for maximal terminal performance. Thus, there appear a number of questions vital for terminal management:

- *Why cannot the enterprise reach performance that would be close to that of the lowest link of the logistics chain?*
- *How does number of tug-masters affect the efficiency of the technological chain?*
- *Should a re-engineering take place, what new pool of resources would be the optimal?*

As per the knowledge of the author, the existing publicly available models of marine container terminals cannot completely cover these questions.

Thus, there emerges a need for the MCT models that would be able to address to the questions mentioned above as well as addressing to the *'what if'* scenario testing. Playing such scenarios allows identifying the micro-operations whose durations the terminal is most sensitive to. Estimating costs concerned with decreasing such a dispersion and related performance benefits based on simulation modelling results facilitates terminal management with a rational solutions.

Another problem for micro-simulation approach is the model parameter dimension, once solving this issue would make micro-simulation models a truly effective tool for numerous purposes.

2.2. CHOOSING LEVEL OF 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 basic 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 (Merkuryev et al. 2002):

Model 1: a general model of BCT incorporated 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.

The verification of the lowest level model 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 simulation logic was refined and approved by terminal management (Merkuryev et al. 2003).

2.2.1. HIERARCHICALLY INTEGRATED BCT MODELS

In order for a container terminal to rationally employ the available resources, a rational vessel arrival schedule should be adhered to. This, however, lies beyond the scope of this research.

It should be pointed out that *Model 1* (see APPENDIX I) 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-effective way. Therefore, optimal resource allocation is important for the core business of BCT, and will be given substantial attention in this project.

Model 2 (see APPENDIX II) 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 (found in APPENDIX III) 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 (Merkuryev et al. 2002)

These possibilities are provided in *Model 4* considered below which represents the lowest level of detailing of container terminal operations. 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.

2.3. DEVELOPING LOGICAL STRUCTURE

Customization of the BCT simulation system asked for reviewing of logistics processes that was performed in co-operation with terminal personnel, involving both the terminal management and technical specialists responsible for various stages of vessel processing, e.g., planning of discharge and loading processes and their operational management, as well as information technology aspects.

Review of terminal logistics processes discovered some new important aspects of terminal operation that later on were incorporated into the simulation system, e.g.:

- operations with hatch covers
- processing restow containers
- management rules (for instance, to assign technical means for processing a vessel)

The following core features of great importance to terminal operations were identified:

- berth time (total time vessel moored alongside until casting off)
- berth productivity (total moves divided by berth time)
- gross productive time (time operations start until last move done)
- gross productivity (total moves divided by gross productive time)
- net productive time (total gross time less stoppage for meal breaks)
- net productivity (total moves divided by nett productive time)

It was decided that the simulation model has to provide control of individual terminal resources like the possibility of adding and/or taking away yard equipment allocated to ship to shore cranes, which can be subdivided in following categories:

- quay cranes
- yard cranes
- forklifters (RoRoFlt's or reachstackers)
- tugmasters (trucks)

Providing these features will allow the terminal management to monitor and adjust terminal operations in due time, as well as enable the simulation model to be connected to the terminal information system which will be discussed in more details in Chapter 3.

2.4. Resource unit overview

In order to proceed with elementary operations modelling, let us review the stages of the logistics chain of Baltic Container Terminal and the resources involved.

2.4.1. Quay crane

The quay crane performs the following steps in the discharging logistics chain:

- the quay crane performs horizontal movement of the trolley
- the trolley descends the spreader onto specific container location on the vessel
- the spreader twistlocks are locked into container cornercastings and thus lifts the container off the vessel
- horizontally transfers the container to the location of the truck
- placing the container onto the truck
- the spreader is released, and the trolley is heading for another container on the vessel as the truck travels to the storage yard

In order to be able to mathematically formulate and study the task we have to arrive at some reasonable degree of detailing ignoring some minor details, whereas not to lose the essence of the object studied.

Thus, for the modelling there are the following three quay crane operations critical for the total time spent at the quay crane:

- time necessary for container preparation for loading onto truck
- quay crane waiting for the truck to arrive
- time spent for placing container onto truck and releasing the spreader

Regarding the aims of the modelling it is reasonable to introduce an ideal or reference quay crane operational cycle, i.e. assumed no time delays through waiting for another resource. The waiting time will be defined as follows: the quay crane holding the container will be considered waiting or delay by another resource when the truck queue is empty. The modelling ideology in order to put that in practice will be described below.

Besides handling the containers, the quay crane also performs supplementary operations on discharging and loading restow containers (unwanted containers to remain on the vessel which close access to containers to be processed and are removed and replaced upon finish of operations) and removing hatch covers of the container compartments. The quay crane temporarily stores the restow containers and hatch covers at the backreach yard for short-term storage. Modelling of supplementary operations (handling hatch covers and restow containers) is considered separately at the end of the present chapter.

2.4.2. Truck

Once the container is loaded onto the truck, it leaves the crane and following a specific route proceeds to specified container location at the storage yard. The co-ordination is performed through a dispatcher who communicates to the truck driver the ID of the location on the storage yard where the container belongs to. Having spent some time, the tractor arrives at the location of discharge at the yard crane and queues into the yard-crane queue (if the truck is the single resource in the yard crane queue, it is processed immediately). After the container is taken off the truck, the empty truck leaves for the quay crane again which completes the truck operational cycle. Thus, an ideal delay-free operational cycle consists of the following times:

- placing container onto truck by the quay crane
- travel time to the container storage yard
- discharge time by the yard crane
- reverse travel time

2.4.3. Yard crane

Processing 40ft containers in the outbound export operations the yard crane places the containers to be loaded onto vessel on the trucks and when doing import operations it takes the containers off the trucks for placing on the container storage yard.

As the truck approaches the yard crane, the latter places the automatic spreader twistlocks onto cornercastings on top of the container until the twistlocks lock tight**.** However, the grabbing not always succeeds at a single attempt, therefore the average time costs on grabbing and lifting the container are significantly higher than those for placing the container onto storage yard and releasing the grab. This peculiarity had to be taken account for when creating the simulation model. The movement of container to its location on the yard is done with the help of positioning system integrated in the cockpit of the yard crane.

Thus, an ideal cycle delay-free operational cycle of the yard crane is made up from the following components:

- picking container off the truck
- moving container to its storage location on the yard
- yard crane travelling to the locations of the next truck

2.4.4. Forklift

Forklifts are elements of the 20ft container logistics chain performing loading and unloading containers on/off the trucks at the storage yard (analogy of the yard crane in the 40ft chain). Some models of forklifts are capable of processing 40ft containers, although in the scope of this study these will be involved only in 20ft chain.

The truck is usually loaded with two 20ft containers. In modelling forklift-truck and yard crane-truck it has to be accounted for the truck's increased waiting time for the second container.

2.5. SIMULATION MODEL VARIABLES

Let us consider *Model 4* which features the lowest level of BCT operation. FIGURE 2.2. portrays the structural scheme of resource types necessary for vessel loading and discharge processes.

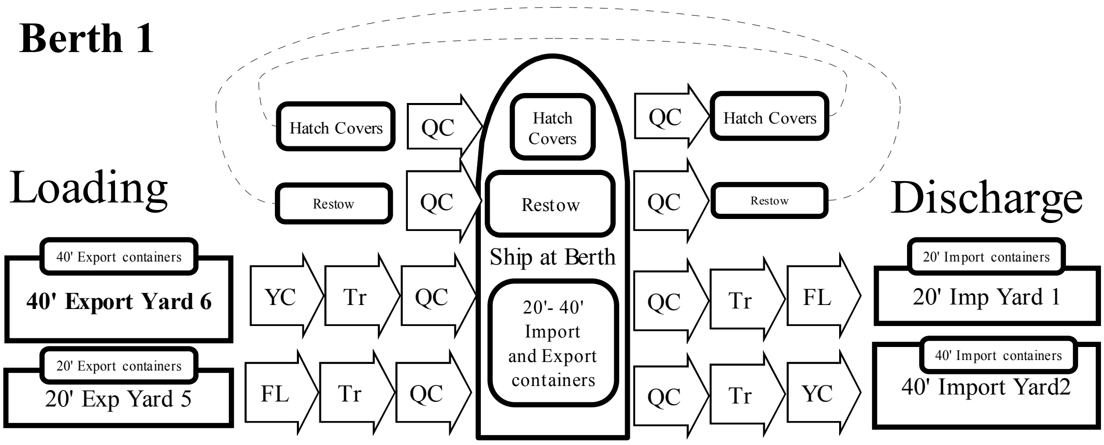


FIGURE 2.2. Resource allocation structure within micro-simulation *Model 4.* Legend: YC -Yard Crane, Tr -Trucks, QC - Quay Crane, FL - ForkLift.

The right-hand side of the scheme labelled *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 *Model 4* is illustrated in FIGURE 2.3.

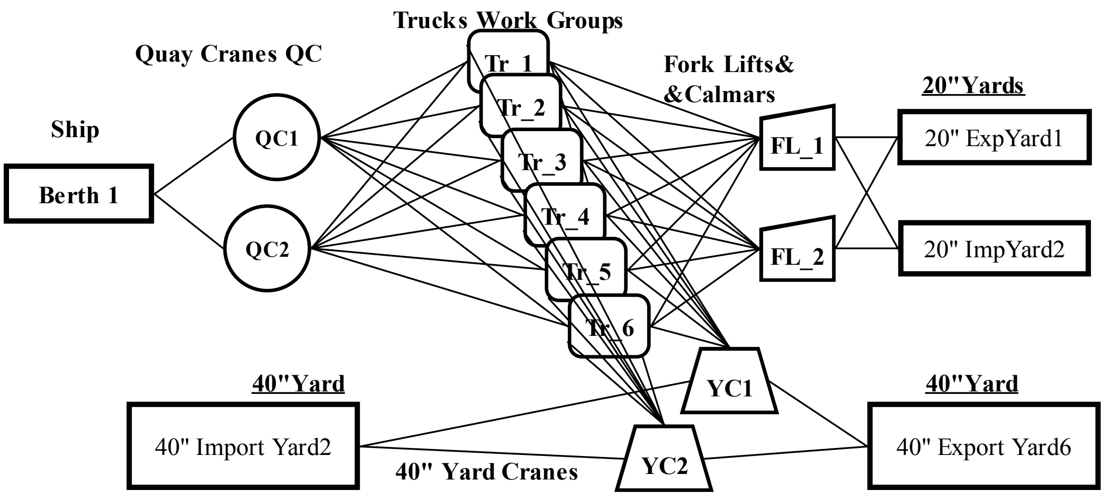


FIGURE 2.3 Logical links between different types of resources in micro-simulation *Model 4*

Thus, *Model 4* presents interaction of one or more quay cranes with any of the six available trucks. Depending on the type of container loaded onto truck (20ft or 40ft), the truck is served by forklift or yard crane respectively.

The following pool of resources is available at a single point of time: *QCranes* =1, 2; *Trucks*=1, 2, 3, 4, 5, 6; *YCranes* =1, 2; *Forklifts*=1, 2. This allows analyzing the efficiency of using of each of the 2x6x2x2=**48** theoretically existing combinations of resources.

2.5.1. Simulation 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.

Up to the present moment, there has been modelled only one separate 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

2.5.2. Input variables

Input variables are initial number of units of predefined types being transferred by the quay crane when loading or discharging a vessel.

- Number of 20' import (to be discharged) containers
- Number of 40' import (to be discharged) containers
- Number of 20' hatch cover operations
- Number of restow containers

- Number of 20' export (to be loaded) containers
- Number of 40' export (to be loaded) containers

In total there are six integer variables whose values lie between 0 and 500.

2.5.3. State variables

State variables, as follows from the name, define the current state of the model when processing input data. These define the pool of resources available to the model, parameters defining their performance (durations of operations and their variance) as well as the algorithm for the use of resources (e.g., operation start/stop times for each resource as well their location at BCT premises).

2.5.3.1. Quay crane variables

- *QCrane* time variable **Tq1i20'** – QC takes import 20' container
- *QCrane* time variable **Tq2i20'** – QC puts import 20' container
- *QCrane* time variable **Tq1i40'** – QC takes import 40' container
- *QCrane* time variable **Tq2i40'** – QC puts import 40' container
- *QCrane* time variable **Tq1h** – QC takes hatch
- *QCrane* time variable **Tq2h** – QC puts hatch
- *QCrane* time variable **Tq1r** – QC takes restow
- *QCrane* time variable **Tq2r** – QC puts restow
- *QCrane* time variable **Tq1e20'** – QC takes export 20' container
- *QCrane* time variable **Tq2e20'** – QC puts export 20' container
- *QCrane* time variable **Tq1e40'** – QC takes export 40' container
- *QCrane* time variable **Tq2e40'** – QC puts export 40'

2.5.3.2. Yard cane variables

In the same manner variables for yard cranes *YCranes* (excluding 20', hatches, restow) are defined:

- *YCrane* time variable **Ty1i40'** – YC takes import 40' container
- *YCrane* time variable **Ty2i40'** – YC puts import 40'
- *YCrane* time variable **Ty1e40'** – YC takes export 40' container
- *YCrane* time variable **Ty2e40'** – YC puts export 40'

2.5.3.3. Forklift variables

For modelling forklift there are only two operations with 20ft containers:

- Forklift time variable **Tf1i20'** – forklift takes import 20' container
- Forklift time variable **Tf2i20'** – forklift puts import 20'
- Forklift time variable **Tf1e20'** – forklift takes export 20' container
- Forklift time variable **Tf2e20'** – forklift puts export 20'

2.5.3.4. Truck variables

To each truck there are assigned 8 random time variables. This set of variables takes positive integer values from 50 to 1000:

- Truck time variable **Tt1i20'** – truck moves import 2x20' containers to the 20' yard
- Truck time variable **Tt2i20'** – empty Truck moves from 20' import yard
- Truck time variable **Tt1e20'** – truck moves export 2x20' containers
- Truck time variable **Tt2e20'** – empty truck moves from 20' import yard
- Truck time variable **Tt1i40'** – truck moves import 40' container to the 40' yard
- Truck time variable **Tt2i40'** – empty truck moves from 40' import yard
- Truck time variable **Tt1e40'** – truck moves export 40' container
- Truck time variables **Tt2e40'** – empty truck moves from 40' import yard

In total there are 12+4+4+8=28 modes and 2x28=56 different values on upper and lower boundaries of respective triangular distribution, i.e. in total there are 84 independent parameters defining 28 triangular distributions of duration of the modelled operations. All the generators are characterized by three parameters: $min \leq mode \leq max$. Random number generators can be easily reprogrammed for other distributions.

2.5.4. Control variables

Control variables directly change the state of the system and/or the algorithm of resource distribution. Thus, control variables define durations of completing current operations. These values assign time lengths for each single container, being generated by the random value generators described above. The variables among others include interruptions in the operations of resources, e.g. lunch breaks, equipment malfunction, etc.

2.5.5. MONITORING VARIABLES

Monitoring variables' function is to trace the changes of the model. These include around 50 variables such as number of loaded and discharged containers and hatch covers, respective times of starting and ending current operations variables defining other model processes.

2.5.6. VISUALIZATION VARIABLES

Visualization variables are a group of special variables, which depending on the state of the respective resources animate corresponding changes on model output screen (container, truck, and other icons).

2.5.7. OUTPUT VARIABLES

Output variables are a part of monitoring variables and calculated indicators of state variables such as **Qcrane** ready for incorporating into database. The same database also includes records on quay performance, e.g. net productivity **NPm** (moves/hour). The following values appear to be originally known:

1) Number of containers or its statistical distribution of vessel arrival (i.e. number of export/import containers, restow containers, and hatch covers)
2) Duration variations in most of the loading and discharge operations (i.e. internal variables values);
3) Limitations on resource use (e.g., the number of quay cranes is limited to two units) both quantity- and time-wise.

The most important and labour-intensive process is adjustment of the main state variables of the model. Adjusting state variables represents a task of stochastic optimization and calls for a special methodology for application on container terminals.

2.6. AGGREGATED PARAMETERS

The calibration of the parameters is performed in accordance with the top to bottom approach illustrated earlier in the work fro creation of hierarchically embedded simulation models (see section 2.2.1. HIERARCHICALLY INTEGRATED BCT MODELS above). It is applied to aggregated parameters describing separately each resource unit. These aggregated cycles are used for model parameter calibration described in CHAPTER 3. MODEL CALIBRATION METHODOLOGY.

FIGURE 2.4. illustrates aggregation of micro-operation completion times into an ideal (delay-free) resource cycle.

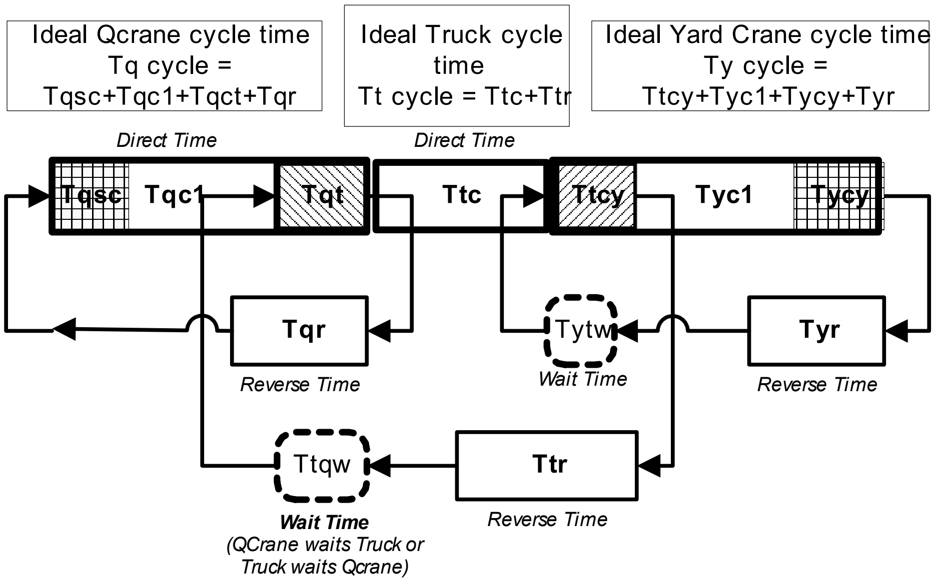


FIGURE 2.4. Aggregation of temporal variables of micro-operations in ideal cycles of respective resources.

The following notations describe respective temporal durations:

- **Tqc**1 – quay crane moving container
- **Ttc** – truck transporting container
- **Tyc1** – yard crane moving container
- **Tqsc** – quay crane grabbing container on the vessel
- **Tqt** – quay crane loading container onto truck
- **Ttcy** – yard crane discharges the truck
- **Tqr, Ttr**, **Tyr** – reverse movement to initial position of respective resource unit (quay crane, truck and yard crane)
- **T*w** – resource idle time spent in waiting for another action, for example:
- **Ttqw** – quay crane waiting for truck
- **Tytw** – yard crane waiting for truck

The respective model blocks obtain micro-operation completion times via model runs which depend on the current value of the resource cycle being adjusted. This calibration is performed via coefficients **K** which are obtained from real-life observed underlying micro-operation durations. Obviously, the coefficients should be altered if the model underperforms with initially chosen coefficients.

Technically, these coefficients remain frozen as model aggregated parameters are being calibrated. The structure of defining such coefficients is portrayed in FIGURE 2.5.

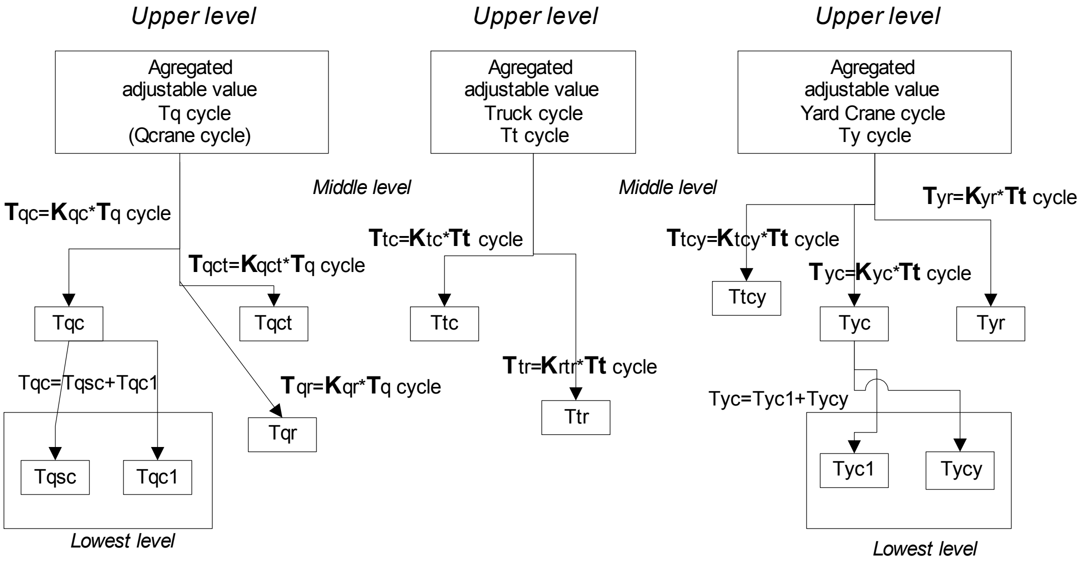


FIGURE 2.5. Structure of aggregation of micro-operation completion times using freezing of coefficients.

Parameter calibration starts with adjustment of resource cycles in the following sequence: quay crane cycle $\mathbf{Tq}_{\mathbf{cycle}}$, truck cycle $\mathbf{Tt}_{\mathbf{cycle}}$, and yard crane cycle $\mathbf{Ty}_{\mathbf{cycle}}$. In such an order top to down the number of parameters of each cycle to be adjusted decreases by one since the sum of coefficients of micro-operations equals one. Therefore any of the sub-parameter coefficients included in the cycle in its turn depends on the others, for instance:

$$\mathbf{Tq}_{\mathbf{cycle}} = \mathbf{Tqc}+\mathbf{Tqct}+\mathbf{Tqr} = \mathbf{Kqc}*\mathbf{Tq}_{\mathbf{cycle}} +\mathbf{Kqct}*\mathbf{Tq}_{\mathbf{cycle}} +\mathbf{Kqr}*\mathbf{Tq}_{\mathbf{cycle}} = (\mathbf{Kqc}+\mathbf{Kqct}+\mathbf{Kqr})*\mathbf{Tq}_{\mathbf{cycle}}$$

and hence $\mathbf{Kqc} + \mathbf{Kqct} + \mathbf{Kqr} = 1.$

Following the calibration sequence outlined above the total number of consequently adjusted parameters is decreased by the number of cycles. However, much more important is the hierarchy of parameters comprising the resource cycle. For instance, it would be reasonable to relate the duration of loading container onto truck **Tqct** to quay crane cycle $\mathbf{Tq}_{\mathbf{cycle}}$ and not to truck cycle $\mathbf{Tt}_{\mathbf{cycle}}$.

In order to illustrate that, let us consider of the crane trolley spreader. If the trolley and/or spreader is modified or replaced with a faster one, this will affect the quay crane cycle alone, since the truck will keep coming for container pick-up at the previous speed. On the other hand, replacing truck with a faster one will not cause any changes to quay crane cycle.

Similar considerations were implemented in structuring aggregation of parameters thus making it an efficient tool for model parameter calibration.

As per FIGURE 2.6. below, first according to the least squared deviation between the observed terminal productivity data $\mathbf{Npj}_{\mathbf{terminal}}$ and net productivity obtained from $\mathbf{Npj}_{\mathbf{model}}$, first resource cycle parameters $\mathbf{Tq}_{\mathbf{cycle}}$, $\mathbf{Tt}_{\mathbf{cycle}}$, and $\mathbf{Ty}_{\mathbf{cycle}}$ are calibrated. Next, in the space of parameters [**Tqr**, **Tqc**, **Tqct**] of the respective submodel **Qcrane** the probability distribution generators of reverse quay crane movement **Tqr**, quay crane processing container **Tqc**, and placing container onto truck **Tqct** are adjusted.

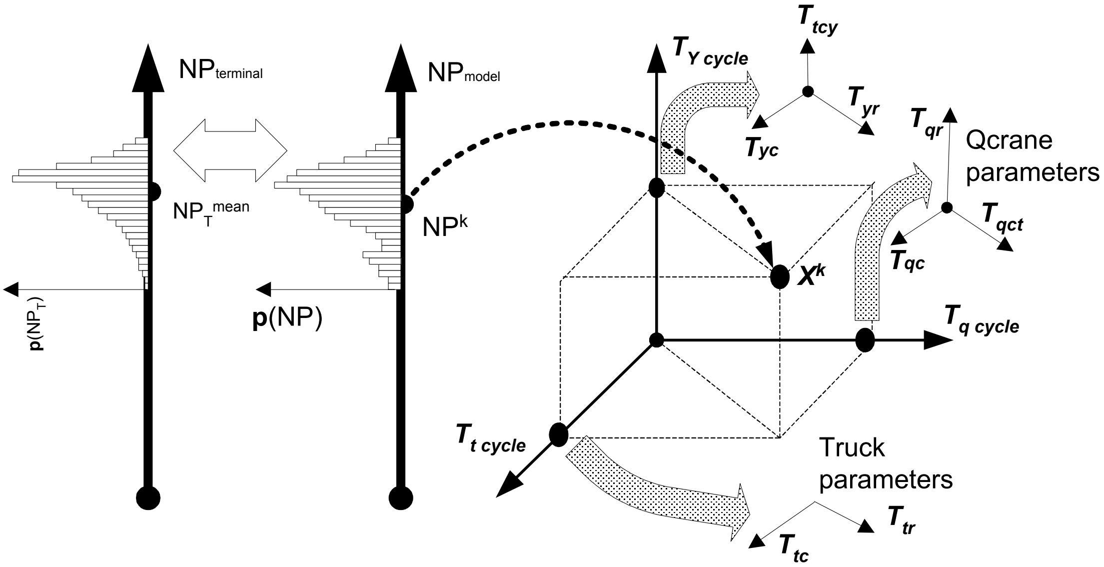


FIGURE 2.6. Illustration of hierarchical top to bottom parameter adjustment.

In the space of parameters [**Ttк**, **Ttc**] of truck sub-model basing on the co-ordinates of $\mathbf{Tt}_{\mathbf{cycle}}$ (from the initial space of aggregated parameters $\mathbf{Tq}_{\mathbf{cycle}}$, $\mathbf{Ty}_{\mathbf{cycle}}$, and $\mathbf{Tt}_{\mathbf{cycle}}$) we adjust the probability distribution generators of empty truck **Ttr** and loaded truck **Ttc** travel times. A similar approach is used for yard crane parameter calibration.

Thus, the sub-models of the lowest levels of detailing are adjusted so that these match known objectives of the higher level of detailing of separate resources and resource workgroups.

2.7. RESOURCE UNIT SIMULATION MODELS

In a general case, the resource unit is represented by either Quay Crane (QC), Truck (TR), ForkLift (FL), and Yard Crane (YC). The former two resource units are universally-fitted to work with 20ft and 40ft containers, whereas forklift is suited for 20ft and yard crane for 40ft container processing. Since the resource units have to be controllable rather then preprogrammed for specific operation cycles, with given intervals they are made available for control.

The resource unit control structure is represented in FIGURE 2.7. below.

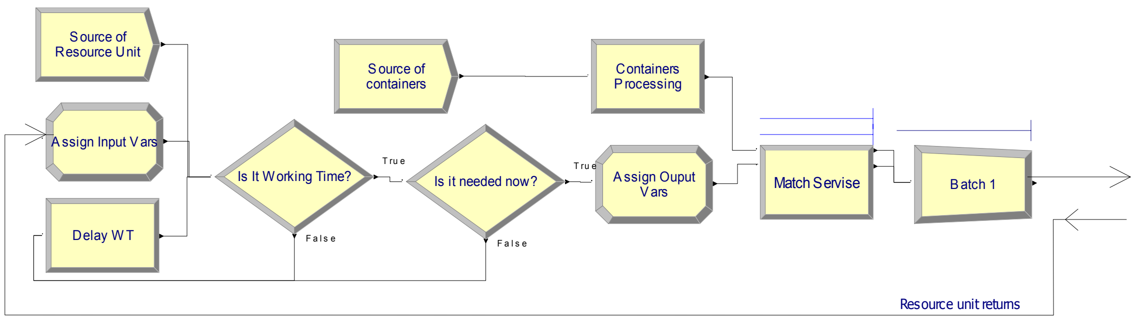


FIGURE 2.7. Logical structure of resource unit

Once a resource unit is created upon the simulation program start the current time is set equal to the *WorkingTime* variable of the resource unit. If the resource is idle at that point of time, the request is repeated after some time until the resource working time starts. Obviously, there exists a management algorithm assigning working time to each resource unit. Once the resource finds itself in working mode the job locations are requested where this resource is needed assigned by the resource control algorithm. In case there are no current resource jobs, the resource is been put on *Delay* function for a while, after which the request is repeated. This brings to decreased resource queuing at locations where they are unnecessary at the given moment. Besides that, during the delay time there might arise a job for the resource unit and the next request might send the resource to a new location instead of wasting time in queue at the existing location.

Such a flexibility of the resource unit model corresponds well to the real-life working algorithms at the Baltic Container Terminal where each resource unit might be sent to any work location at any point of time by the job dispatcher. In the location of resource job the duration of the job is modelled by a respective *Process* block. Random duration deviation from the average value are modelled by a triangular probability distribution which is defined by a set of three parameters. These parameters are not fixed but are defined as variable values; by changing these during model runs one can affect fatigability or productivity drops at night shift times. Besides that, it is able to increase the modelled productivity reflecting personnel proficiency. The cost of additional modelling flexibility is the simulation modelling slowdown due to frequent resource condition requests. However, it is possible to arrive at a reasonable resource condition request frequency that would balance off model error and the increased computational times.

2.7.1. QUAY CRANE SIMULATION MODEL

Let us consider the specific adjustment to be made in the basic resource unit model logics described in the paragraph above in order to be able to properly simulate quay crane container processing. The quay crane prepares for lifting the container off the vessel by aiming the spreader several centimetres above the cornercastings on top of the container. Once a grabbing attempt is successful the grabber is fixed on the container and the quay crane lifts and moves the container to the location of container loading onto truck.

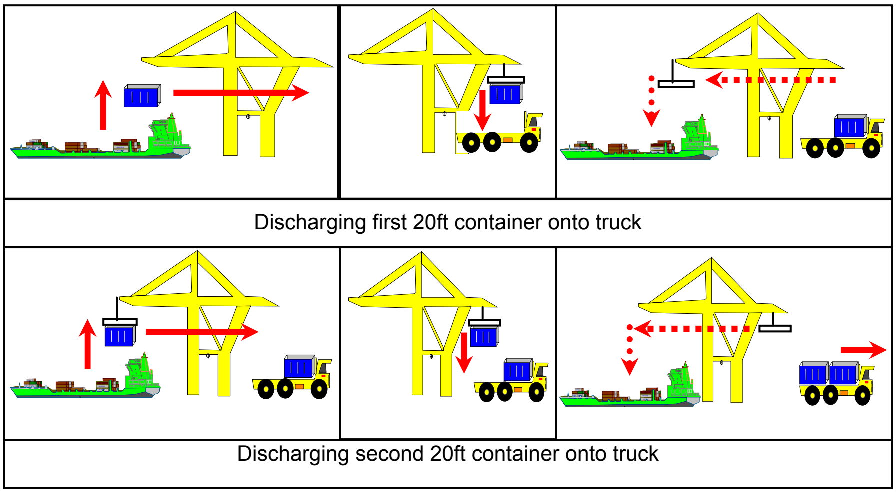


FIGURE 2.8. Illustration of quay crane loading and discharge logics

It was decided to outline three quay crane states: 1) idle, 2) quay crane busy moving container, and 3) quay crane busy loading container onto truck (FIGURE 2.8.).

The durations of the outlined groups of technological operations are randomly distributed subject to some distribution laws, which in turn have to be separately modelled.

In order for the quay crane change the status from idle to container processing, it is necessary to do the following checks: check the input container availability (since there might be more than a single quay crane working on the vessel) and check whether it is a break time or end of the working day. These checking procedures are implemented into three conditional *IF* blocks. In order to visualize the quay crane operations simultaneous to respective operation completion there are *Separate* logical blocks included in the model which basically duplicate the operations in parallel chains of *Separate* blocks as per FIGURE 2.9.

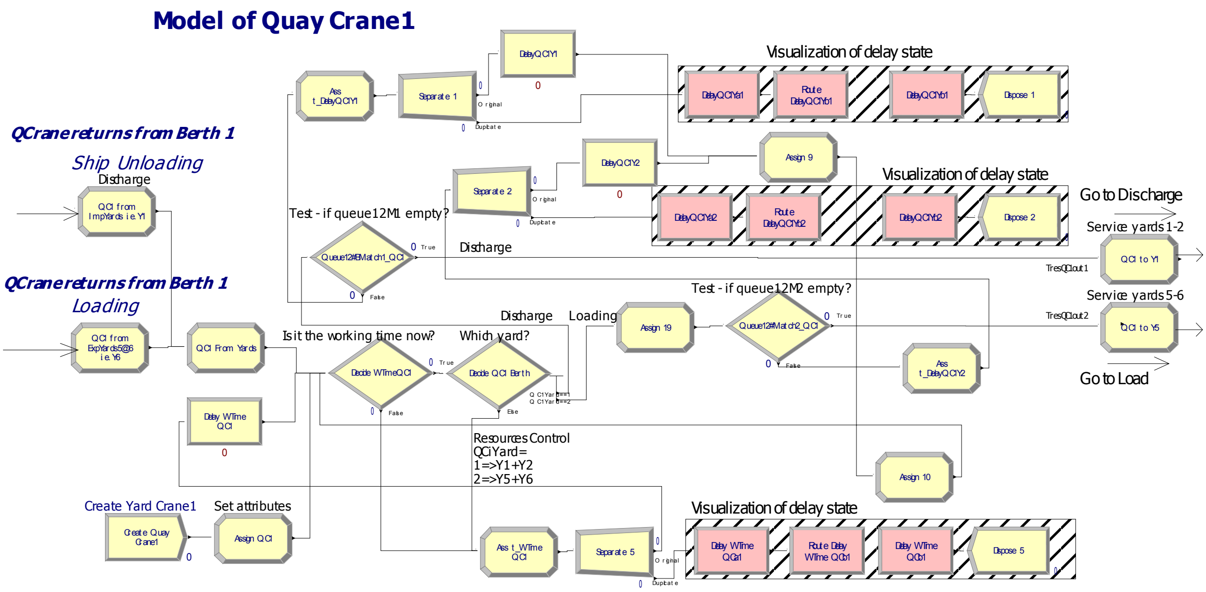


FIGURE 2.9. Quay crane logical model implemented in Arena package

2.7.2. TRUCK SIMULATION MODEL

Contrary to the quay crane mode, in the vessel loading process the empty truck first arrives at the quay crane and only then transfers the container to the storage yard. Thus, both the direction of movement and the location of the yard are not constant. In loading logistic chain the free truck is sent back to the export yard waiting its turn for taking another export container by the yard crane. The figure below represents the logics of the truck simulation model.

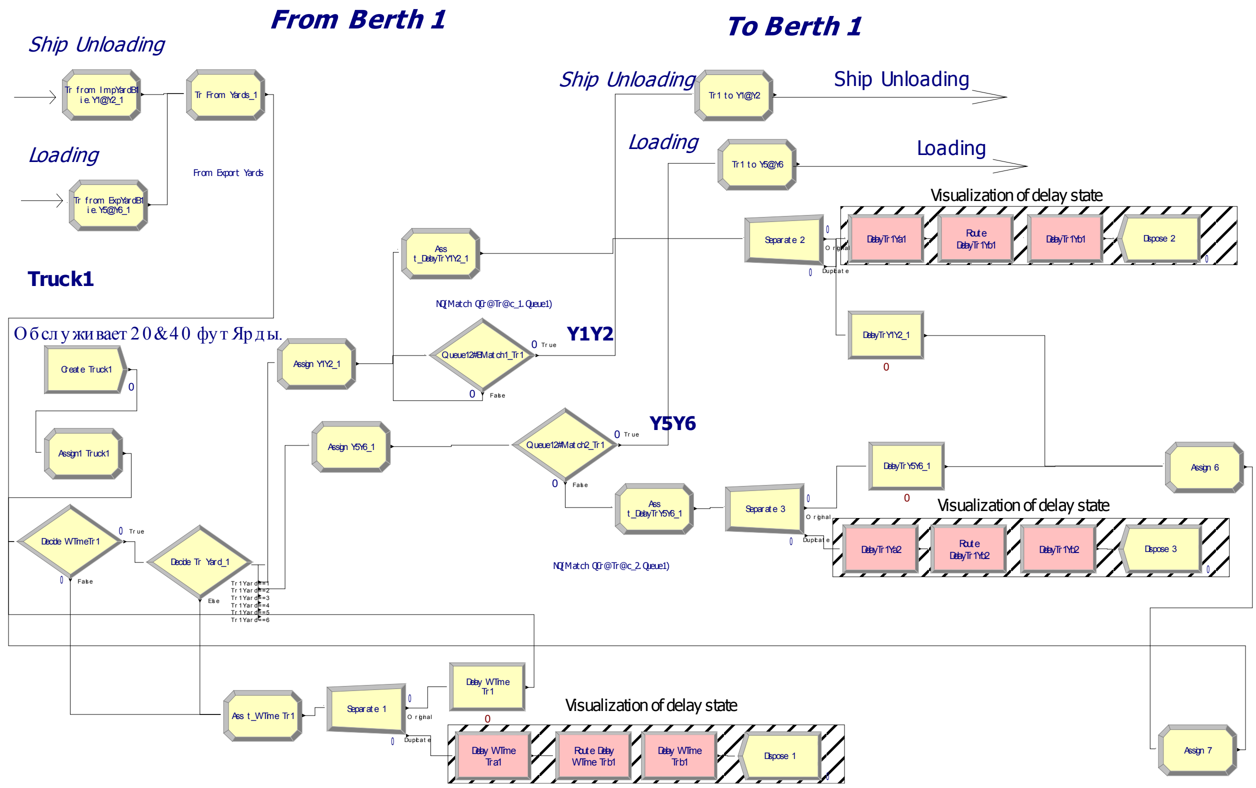


FIGURE 2.10. Truck logical model implemented in Arena package

2.7.3. YARD CRANE SIMULATION MODEL

The yard crane model is represented in FIGURE 2.11. below. Technically, the logics of the yard crane follows the logics of the quay crane described above with minor modifications through conditional *IF* blocks.

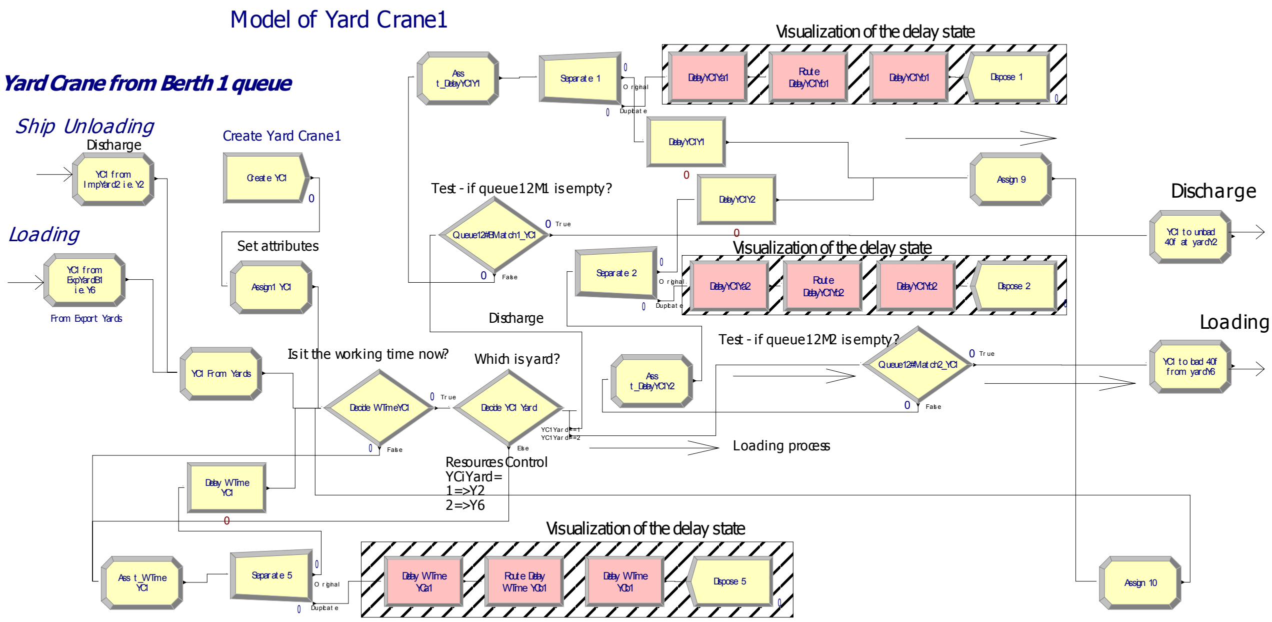


FIGURE 2.11. Yard crane logical model implemented in Arena package

2.7.4. FORKLIFT SIMULATION MODEL

Contrary to yard and quay crane, forklifts are mobile resource units easily switchable between yards, workgroups, and berths. In the simulation model the forklifts are employed only in 20ft logistics chain. The implementation of forklift model is illustrated in FIGURE 2.11.

2.8. MODELLING RESOURCE OPERATIONAL CYCLES

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.

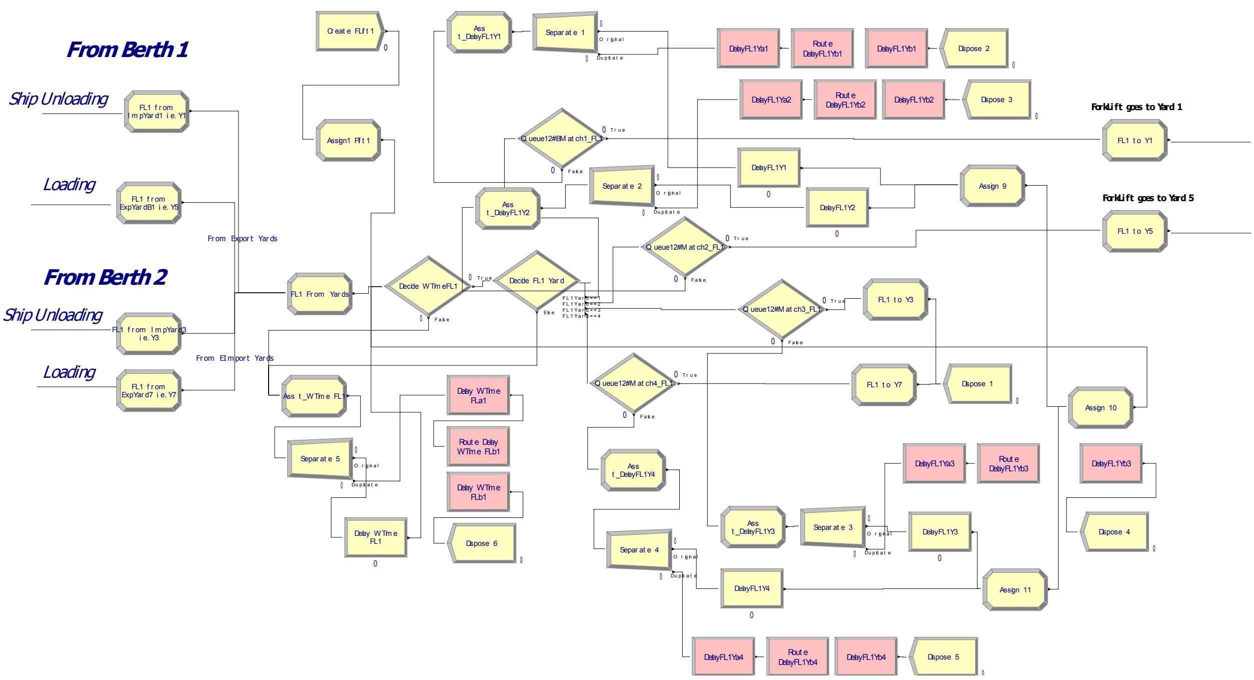


FIGURE 2.12. Forklift logical model implemented in Arena package

In order to facilitate model comprehensibility as well as calibration, there were introduced resource operational cycles, i.e. aggregated resource elementary operations in cyclical repetition. The paragraphs that follow introduce to the three resource cycles featured in the model: quay crane cycle, yard crane cycle, and truck cycle.

2.8.1. Quay 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 2.13. below. Let us denote $\mathbf{Tq_{cycle}}$ the fastest no-delay work cycle.

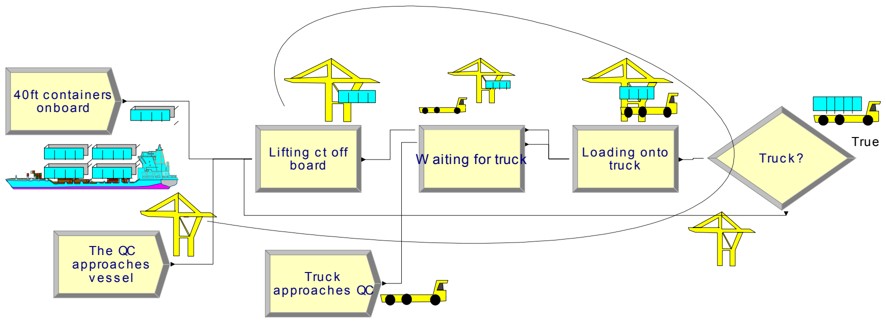


FIGURE 2.13. Quay crane operational cycle

2.8.2. Yard crane operational cycle

The principle of modelling is very much the same as for the quay crane described in the previous paragraph. The major difference is the object to be served: the yard crane performs loading container on the truck and not discharging.

The yard crane modelled operational cycle is displayed in FIGURE 2.14. Fur further reference, $\mathbf{Tq_{cycle}}$ stands for the fastest no-delay work cycle.

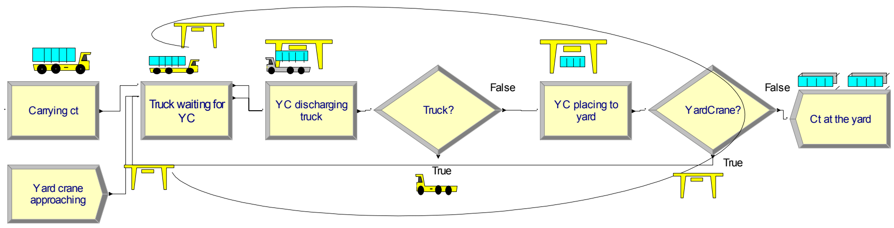


FIGURE 2.14. Yard crane operational cycle

2.8.3. TRUCK OPERATIONAL CYCLE

Modelling logics of truck operational cycle is more complicated than that of the crane operational cycles (see FIGURE 2.15.). 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 $\mathbf{Tt_{cycle}}$.

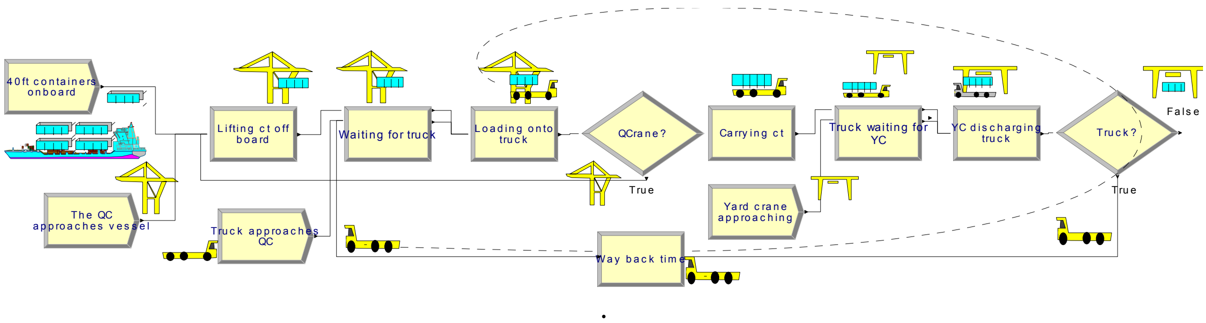


FIGURE 2.15. Truck operational cycle

2.9. MODELLING 40FT CONTAINER CHAIN

The 40ft container logistic sequence is divided into two chains: discharge and load processes described in the section to follow.

2.9.1. DISCHARGE (EXPORT) CHAIN

The total time of processing a single container **Unload 40' total time** can be expressed by times of completing elementary processes, namely:

Unload 40' total time = U40tt =

= Tc&q + Tcq + Tcq&t + Tcqt + Tct + Tct&y + Tcty + Tcy,

where:

Tc&q – the quay crane waiting for container's being ready to be discharged

Tcq – quay crane picking the container from the board of the ship till the point of being ready to be loaded on truck

Tcq&t – crane holding container waiting for the truck. It should be pointed out that either quay crane with a container is awaiting truck, or a truck holding a container to be loaded on the vessel is waiting for the quay crane (simultaneous waiting delay cannot occur, except for the case when the container's loading on the truck is delayed due to whatever reason).

Tcqt – time elapsed for loading container on the truck with container, quay crane and the truck simultaneously employed.

Tct – time necessary for the truck to carry the container to the yard where it is supposed to be stored

Tct&y – the waiting time of the yard crane for the truck carrying the container

Tcty – discharging container from the truck by the yard crane

Tcy – further container processing (placing on the storage spot) by the yard crane

Thus, the total elapsed time for the truck would equal

Tttot = Tct&q + Tcqt + Tct + Tct&y + Tcty + Treturn

where:

Tct&q – truck waiting for the quay crane to pick the container off the truck

Tcqt – container loading time

Treturn – empty truck returning to pick another container

It should be pointed out that the period of the truck waiting for the quay crane to load the container onboard **Tct&q** is a non-stationary value, as it is highly dependent on the number of the trucks waiting in the line for the quay crane.

Let us consider matching of the elements of the servicing chain starting with the discharge process.

The working time of the quay crane when discharging **Tuq** is comprised of the following time components:

$$\mathbf{Tuq = Tcq + Tcqt + Tcq + Tcq\&t + Tcqt + ...}$$

It follows that the quay crane starts waiting for the truck if

$$\mathbf{Tcq + Tcqt + Tcq < Tct + (Tcty\ OR\ Tctf) + Treturn}$$

The term **(Tcty OR Tctf)** implies that it is either the **Tcty** time taken if the truck is carrying a 40ft container or the **Tcty** time if the truck carries a 20ft container. Generally speaking, the truck return time **Treturn** does not equal the duration of its travelling carrying the container. This is determined both by different way lengths to the yards and the different average travelling speed of a truck carrying a container compared to when it is empty. Therefore, in the model there exists a separate block for adjustment of the returning time **Treturn**, as well as its possible distribution. For example, depending on the daytime, the light exposure is different, which affects the speed of work (although electric lights decrease this dependence, there is still a performance gap).

In a general case, there would occur a delay of the quay crane if

$$\mathbf{Tcq + Tcqt + Tcq < Tct + (Tct\&y + Tcty)\ OR\ (Tc`t\&f + 2Tc`tf) + Treturn}$$

The component **(Tct&y + Tcty) OR (Tc`t&f + 2Tc`tf)** depicts the influence of the preceding conditions of truck discharging (the ineffective time during truck discharging). If the sign of the inequality above changes to opposite, this means that the truck is waiting for the crane. The duration of quay crane working on a single 40ft container would equal

$$\mathbf{TQ = Tc\&q + Tcqt + Tcq}$$

The truck work cycle time and returning to the quay crane for the next container is determined by the sum

$$\mathbf{TT = Tcqt + Tct + Tct\&f + Tctf + Treturn}$$

In reality this period of time is several times higher than the quay crane working cycle time, therefore more trucks are necessary in order to discharge the vessel more effectively. Let the number of simultaneously working trucks be increased up to **Nt**. Then for **Nt** load/discharge processes the quay crane will be secured against delays due to truck unavailability. In case the discharging of the trucks is not accompanied by delays, the full cycle time of single truck would be

Ttcycle = (Tcqt + Tct + Tcty + Treturn)/Nt

whereby the number of trucks **Nt** should be such, so that

TT =< TQ

That is, it is possible to decrease ineffective time while the quay crane is idle and waiting for the truck down to zero, whereby increasing the throughput potential of this node of the technological chain.

The logical structure of the technological chain of 40ft container processing during load and discharge operations is depicted in FIGURE 2.16.

2.9.2. LOADING (IMPORT) CHAIN

The logics of the loading operation is analogous to that of the discharge operations outlined above. The order of discharge operations represents a swapped order of loading: the loading chain for 40ft containers starting at the yard crane and ending at the quay crane. Besides processing 40ft containers, the quay crane's operations include loading and discharging 20ft containers, restow containers, and hatch covers. Trucks also shift from single 40'ers to double 20'ers, which is randomly ordered.

FIGURE 2.16. portrays simplified structure of 40ft loading and discharge logistics chain. The next section discusses discharging of 20ft containers.

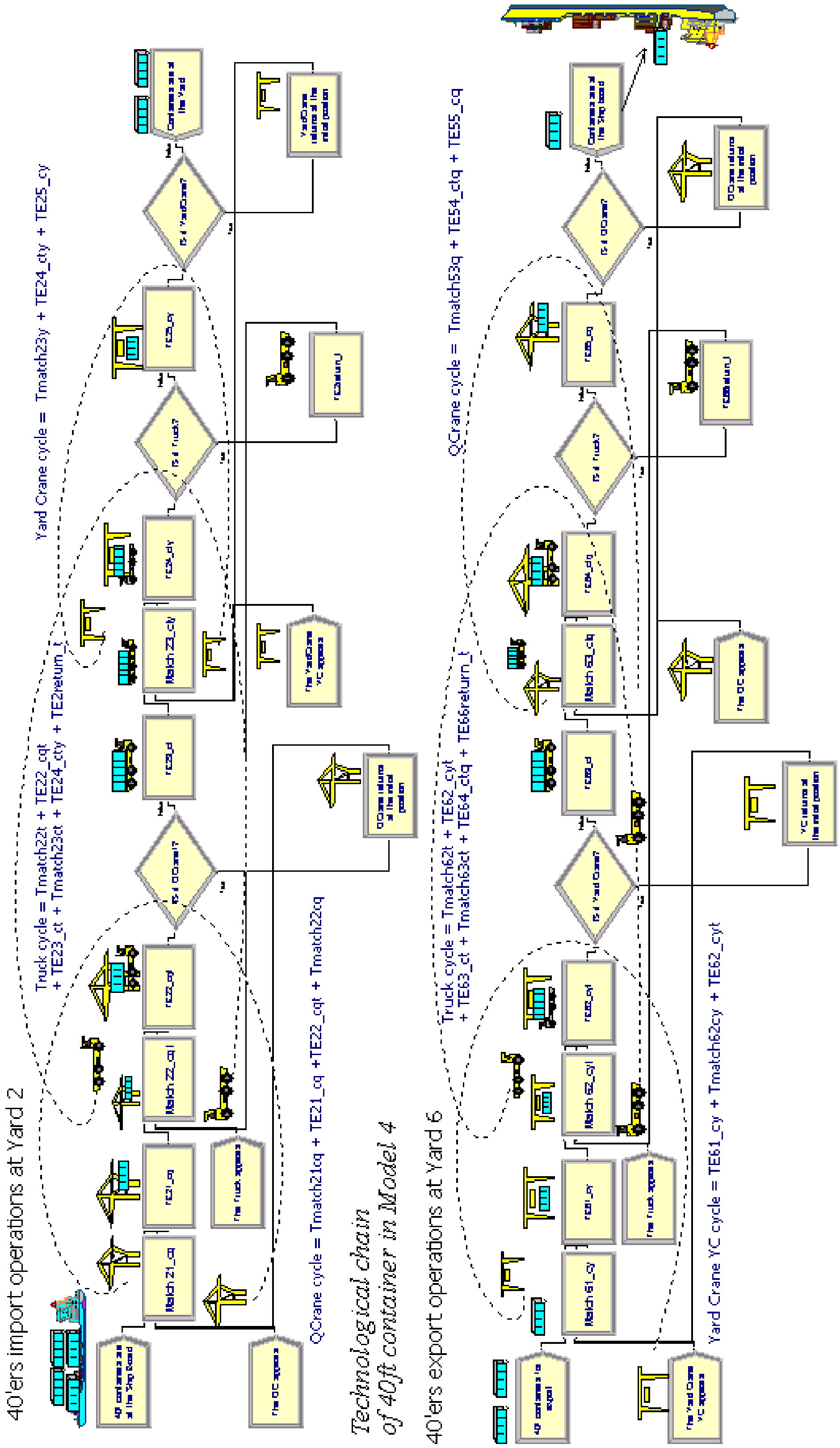


FIGURE 2.16. Logistics chain of 40ft container processing BCT simulation model.

2.10. MODELLING 20FT CONTAINER CHAIN

Similarly to the 40ft container sequence, the technological chain of 20ft containers is considered as discharge and load processes.

2.10.1. DISCHARGE (EXPORT) OPERATIONS

Similarly to the discharge process of 40ft containers, the total time spent on moving one single container from the board of the vessel to its position on the yard equals. These three first operations are analogous to 40ft container operation described above.

These are operations causing additional delay of the truck being loaded. Loading of another container on truck would cause a mere doubling of operation completion time. So, the truck is busy being loaded for two time units of operations of each of the 2 containers plus additional time of crane moving to the vessel for picking up container and moving it to the truck.

Unload 20" total time = U20tt = Tc\`&q + Tc\`q + Tc\`q&t +Tc\`qt + Tc\`&q + Tc\`q + Tc\`qt + Tc\`&q + Tc\`q +Tc\`qt + Tc\`&q + Tc\`q + Tc\`qt + Tc\`t + Tc\`t&f + Tc\`tf + Tc\`f + Tc\`tf + Tc\`f = 2Tc\`&q + 2Tc\`q + Tc\`q&t +2Tc\`qt + Tc\`t + Tc\`t&f + 2Tc\`tf + 2Tc\`

where (besides the notation in the 40ft chain):

- **Tc\`t&f** – truck carrying a container waiting for the forklift
- **Tc\`tf** – discharging of the truck by the forklift
- **Tc\`f** – forklift processing the container to its place on the yard

Compared to the total time estimation in the 40ft container chain, it might be seen that the model of processing 20ft containers is analogous to that of 40'ers. The major difference lies in different duration of completing the same technological operations. Thus, the technological chain of processing 20'ers represents processing 2x20'ers blocks (a virtual 40' chain), whereby the difference is that the truck is discharged by a forklift and not a yard crane. The structure of the technological chain of 20'ers is represented in FIGURE 2.17. below.
The complete time cycle for a truck carrying 20'ers would equal

T'ttot = Tc\`t&q + 2Tc\`qt + Tc\`t + Tc\`t&f + 2Tc\`tf + T'return

Again, a matching of technological chain unit cycles is necessary. Let us start with discharging, then the quay crane working time **T’Uq** is comprised of the following intervals

T’Uq = Tc`q + Tc`qt + Tc`q + Tc`q&t +Tc`qt + ...

It follows that the crane is awaiting the truck under the following condition

Tc`q + Tc`qt + Tc`q < Tc`t + (Tc`tf OR Tc`ty) + T’return

It should be kept in mind that the term **(Tc`tf OR Tc`ty)** means that the time **Tc`ty** should be taken if the truck is carrying a 40ft container or **Tc`tf** if the truck carries 20’ers. It should be also noted, that the truck return time **T’return** with a 40’er does not necessarily equal the time when carrying 20’ers. In general, there would be a delay for the quay crane if

2Tc`q + 2Tc`qt + Tc`q < Tc`t + (Tct&y + Tcty) OR (Tc`t&f + 2Tc`tf) + Treturn

If the sign of the inequality changes to opposite, it means that the truck is idly waiting for the crane. Basing on the expression obtained, one would expect a rather soon formation of truck queue in front of the crane, once it shifts from discharging 40’ers to 20’ containers.
The duration of processing one single 20’ container by the quay crane would then equal

T’Q = 2Tc`&q + 2Tc`qt + 2Tc`q

The truck complete cycle (to the point of returning to the quay crane) is determined by the sum:

T’T = 2Tc`qt + Tc`t + Tc`t&f + 2Tc`tf + (T’return OR Treturn)

Similarly to 40ft container logistics chain, this period of time is several times higher than the quay crane cycle period, therefore the number of trucks should be increased so that the performance on this node is increased too. Let the number of simultaneously working trucks be increased up to **Nt**. Then for **Nt** load/discharge processes the quay crane will be secured against delays due to truck unavailability. In case the discharging of the trucks is not accompanied by delays, the full cycle time of single truck would be

T’tcycle = (2Tc`qt + Tc`t + 2Tc`tf + T’return)/Nt

Similarly to 40'er chain, the number of trucks **Nt** can be found such that **T'T =< T'Q.** That is, by changing **Nt** it is possible to increase the throughput of this node of the 20'er chain.

FIGURE 2.17. on the next page depicts structural design of the 20ft import and export logistics chains.

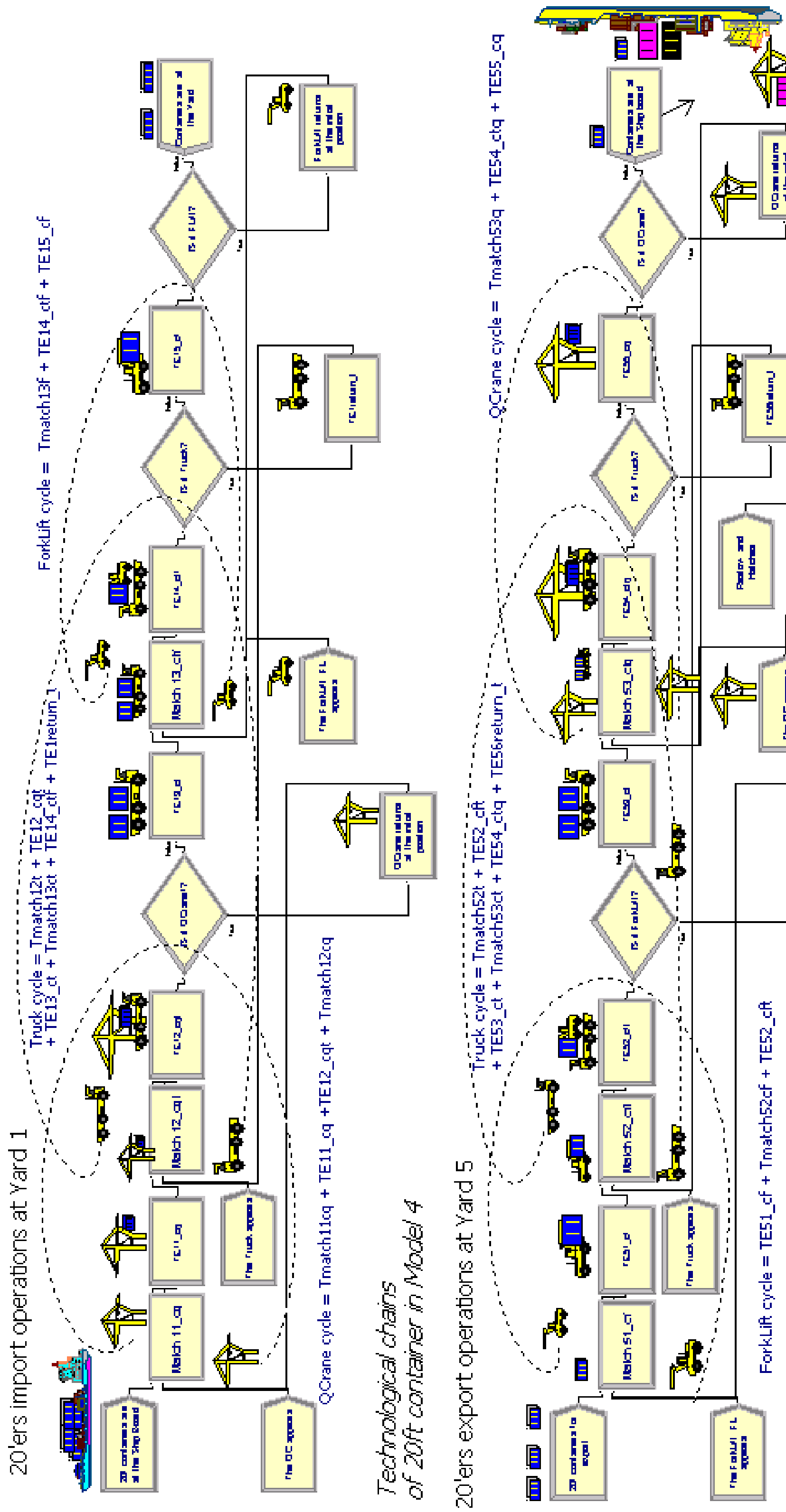


FIGURE 2.17. Logistics chain of 20ft container processing BCT simulation model.

2.10.2. LOADING (IMPORT) OPERATIONS

Similarly to the section above, the loading operations run in reverse order, chain end resources being swapped. Thus, the starting point of the load chain could be a forklift processing 20ft containers, the end point of the chain being also the quay crane.

2.11. MODELLING SUPPLEMENTARY BERTH OPERATIONS

Besides the import and export container move operations, the net productivity is highly affected by the supplementary operations of the quay crane such as hatch cover and restow container removal and replacement. Handling hatch covers has a tremendous effect on the productivity of the quay crane and consequently of the whole logistics chain. Thus, removing and later replacing a hatch cover takes up five to ten times longer than handling a single container, whereas restow container handling is up to five times slower than processing an average container. Taking into consideration the impact, the model had to account for the productivity effect caused by supplementary operations. An example of schematic structural model is represented in FIGURE 2.18.

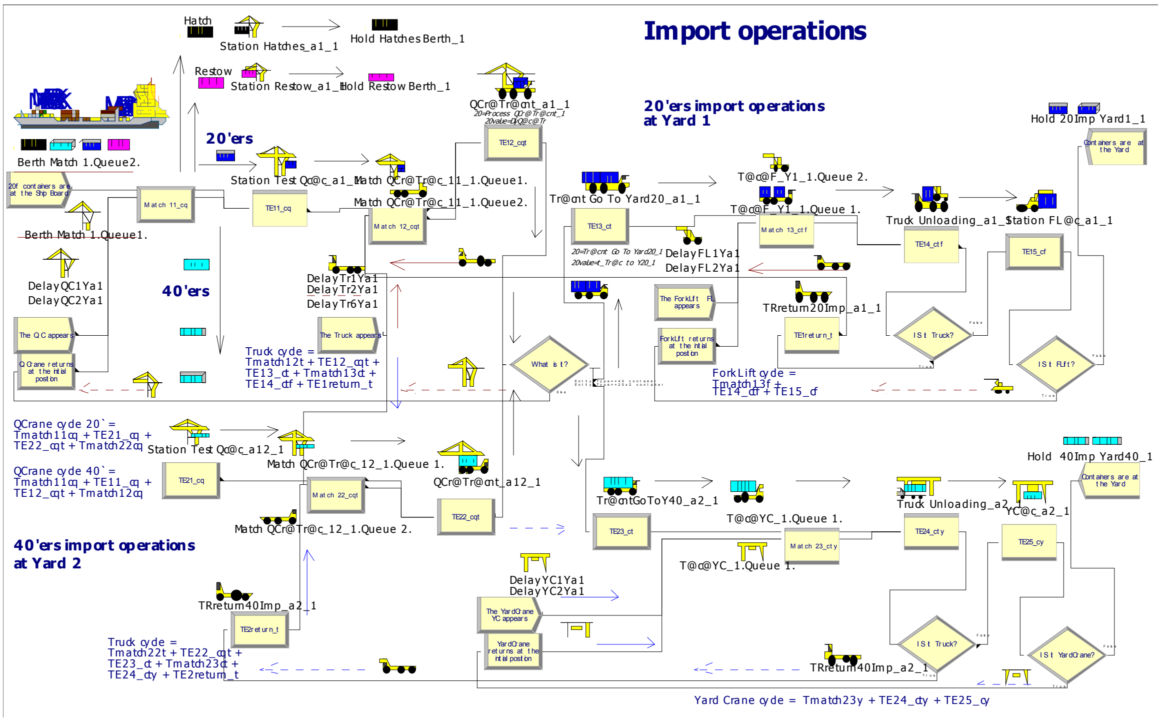


FIGURE 2.18. Overview of structural model of import operations.

Obviously, the operational model is much more complicated than portrayed on the graphs above, containing more than 100 logical blocks and over 700 internal variables.

2.12. GRAPHICAL USER INTERFACE

The paragraphs that follow present an overview of graphical user interface elements developed for model visualization, monitoring, and variable input.

2.12.1. INPUT INTERFACE

This section represents the graphical user interface for inputting and altering the micro-simulation model variables. User interface examples are illustrated in FIGURES 2.19. and 2.20.

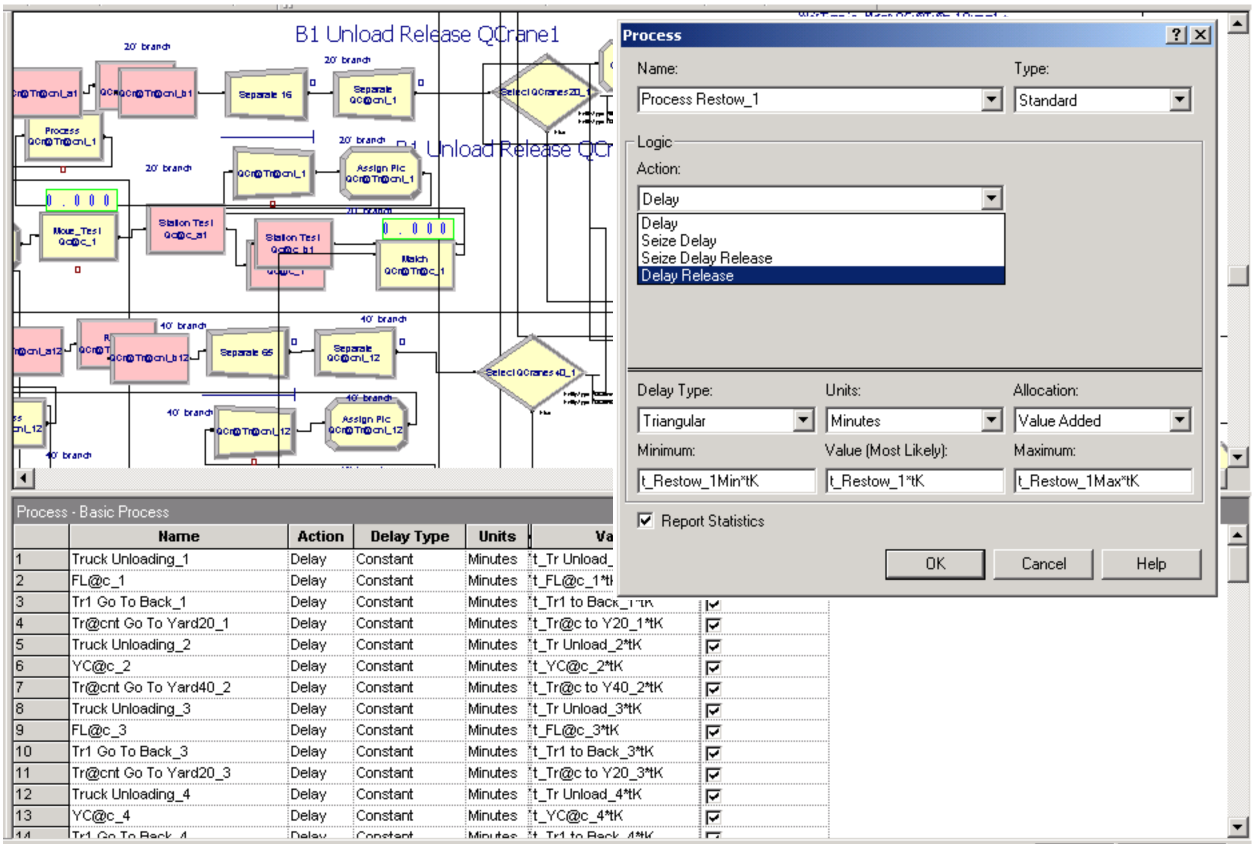


FIGURE 2.19. User interface for input of line- and vessel-specific variables in BCT micro-simulation model

The user interface is flexible enough to provide a high degree of customization, and depending on the user requirements, the interface might feature combination of any of the model variables.

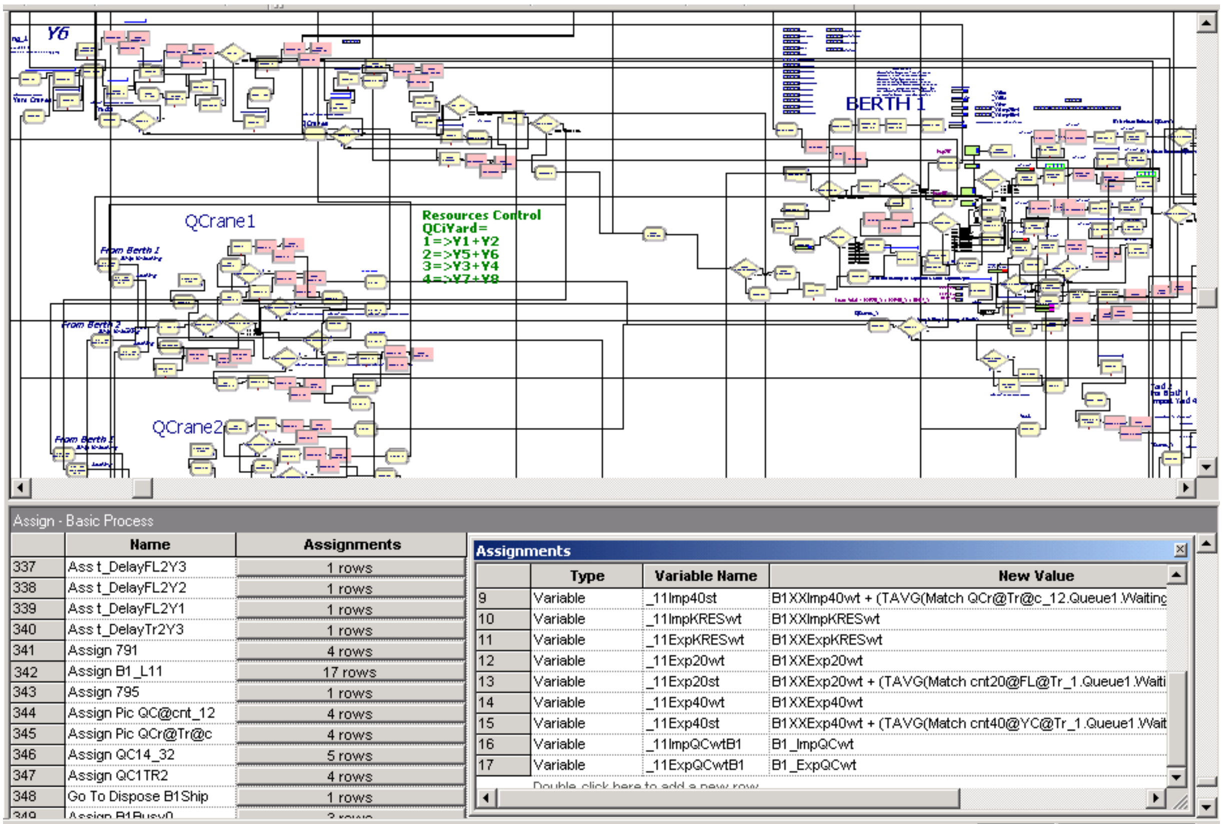


FIGURE 2.20 User interface for process and internal variable adjustment in BCT micro-simulation model

2.12.2. USING THE BUILT-IN SUMMARY REPORTS

The summary report of *Arena 5.0* software contains variables, functions, and indicators whose value and change dynamics must be monitored throughout the model run cycle. The examples among others include:

- statistics on number and type of moves performed on each vessel (20ft, 40ft containers, restow moves, and hatch covers),
- statistics on vessel arrival time,
- statistics on duration of each container processing operation.

2.12.3. MODEL OUTPUT

The user output interface is flexible and adjustable for the needs of the end-user. It is supposed that main output will concentrate mainly on resource busy/idle time graphs to be able to estimate work efficiency and model respective scenarios.

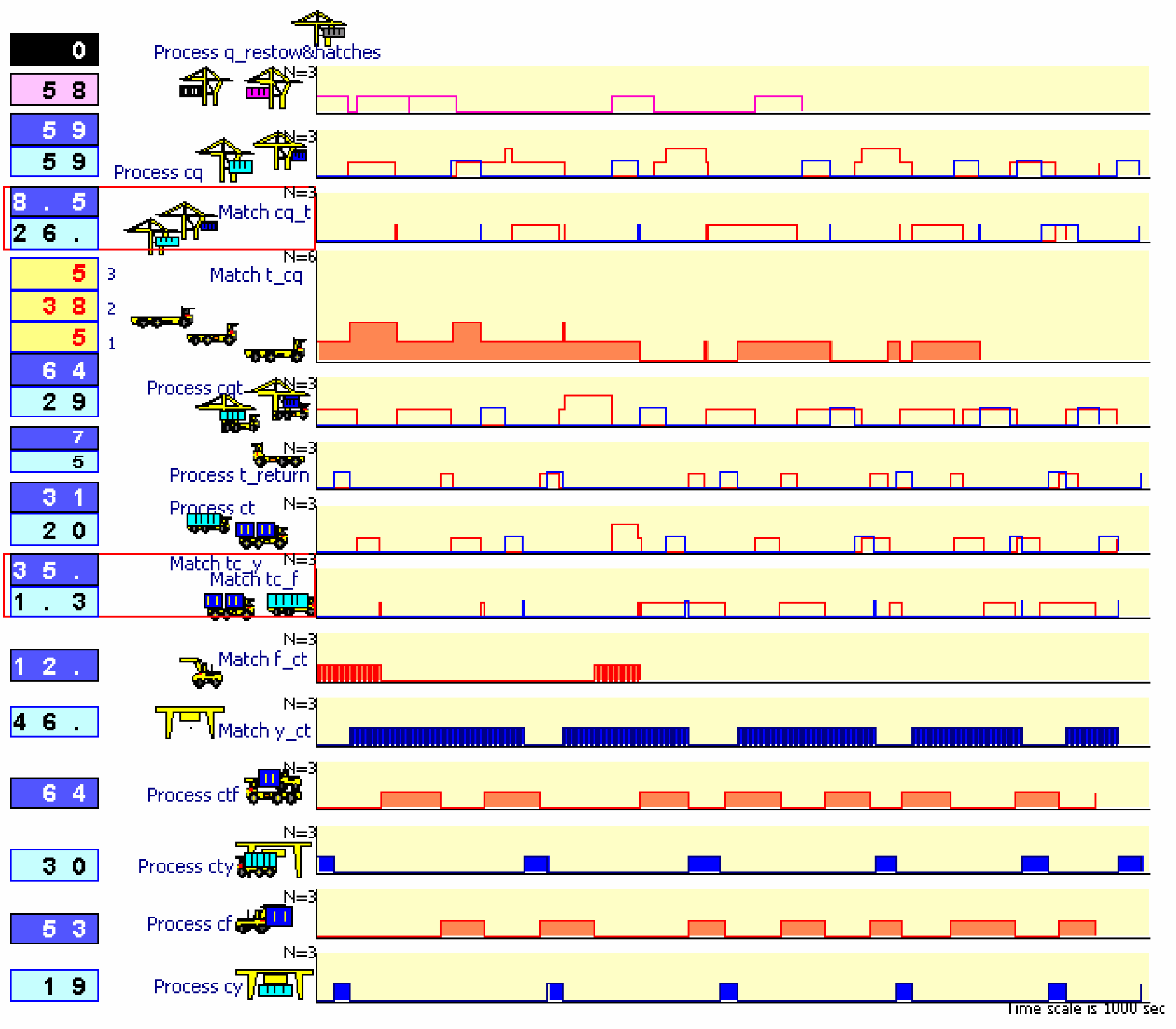


FIGURE 2.21. Micro-simulation output interface: tracing resource dynamics

An example of output window is shown in FIGURE 2.21. above.

2.12.4. VISUALIZATION AND 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 of the model visualization screen featuring real-time monitoring of several variables and processes is presented in FIGURE 2.22.

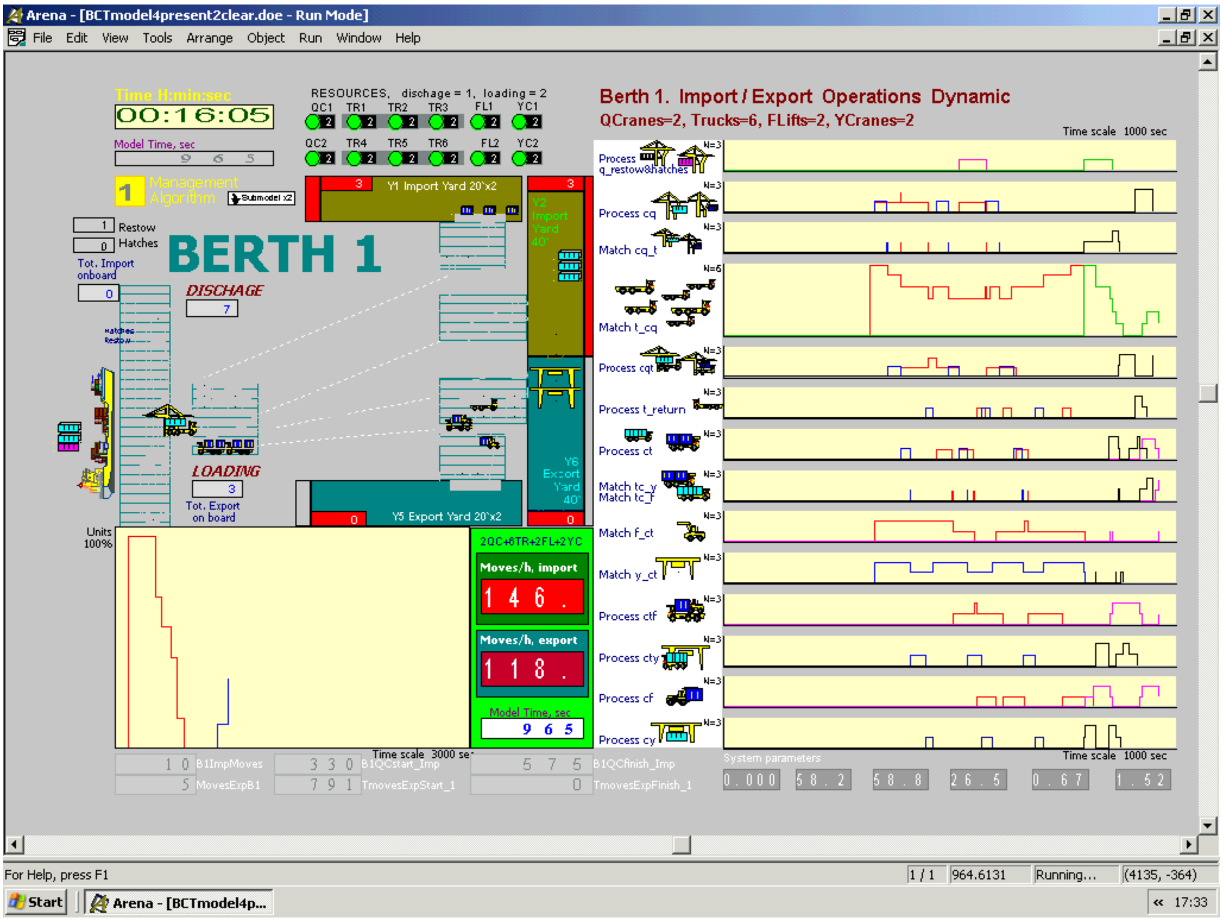


FIGURE 2.22. Micro-simulation visualization and monitoring

2.13. CONCLUSIONS

In this chapter there has been illustrated and explained the structure of the BCT micro-simulation model. Thus, there have been explained modelling logics and techniques of separate resource units (quay crane, yard crane, forklift, and truck), operational resource cycles, supplementary berth operations, and resource interaction logics. The simulation model was implemented in the *Rockwell Software Arena 5.0* simulation package and some approaches were adjusted for the logics of this software; the arising programming issues were left out of the scope of this paper. The simulation model allows flexible and customizable visualization and monitoring parameters and variables with up to per-second data availability. The simulation model can be used in batch mode for creating a statistical base for the parameter calibration methodology based on Kolmogorov-Smirnov test described in CHAPTER 3. MODEL CALIBRATION METHODOLOGY.

Since the number of trucks lies in the range of 3 to 6 machines depending on the management decision, there is inevitable equipment working time wastes as a result of productivity fluctuation. Creating and applying a commonly used analytical approach to estimation of the effect of random fluctuations to resource cycle on the total productivity of the logistics chain represents quite a complicated task, however, for a specific set of parameters simulation modelling could provide a quantitative statistical estimation.

However, in spite of modelling and monitoring complexity, the expected benefits from optimized sets of resources and working operations compensate for the associated modelling costs incurred due to the huge costs of resources – taken the cost of a single quay crane lies around ten million Euro. Illustration of modelling benefits is described in CHAPTER 5. PRACTICAL APPLICATIONS OF SIMULATION MODEL of the thesis which presents application of the model for choice of equipment at Baltic Container Terminal.

3. MODEL CALIBRATION METHODOLOGY

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

$$\boldsymbol{v^j = (v^j_{20Import}, v^j_{40Import}, v^j_{hatches}, v^j_{restow}, v^j_{20Export}, v^j_{40Export})}, \tag{3.1.}$$

where

- $\boldsymbol{v^j_{20Import}, v^j_{40Import}}$ - number of import (inbound) 20ft and 40ft containers,
- $\boldsymbol{v^j_{hatches}}$ – number of hatch covers to be processed for freeing up necessary containers,
- $\boldsymbol{v^j_{restow}}$ - number of re-stow containers (containers to be temporarily moved ashore to free up access to other containers),
- $\boldsymbol{v^j_{20Export}, v^j_{40Export}}$ - number of export (outbound) 20ft and 40ft containers,
- $\boldsymbol{j=1,2,\ldots, N_v}$, where $\boldsymbol{N_v}$ – set of feasible combinations (3.1.) for the vessels to be processed by the terminal.

Any vessel belongs to a definite set of vessels which cannot be large, 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 $\boldsymbol{x} \in \boldsymbol{X^{\sim}}$ represents durations of resource micro-operations in technological chains of moving containers and hatch covers. Probability distributions of vector co-ordinates $\boldsymbol{x_i}$ is approximated by asymmetric triangular distributions, each defined by three parameters, namely the lower boundary $\boldsymbol{xmin_i}$, mode $\boldsymbol{xmod_i}$, and upper boundary $\boldsymbol{xmax_i}$. The feasible scope of $\boldsymbol{x_i}$ vector values is subject to technological constraints which define the set $\boldsymbol{X^{\sim}}$.

$$\boldsymbol{a_i \le xmin_i,\ xmaxi \le b_i,\quad xmin_i < x_i < xmaxi,\ i = 1,2,\ldots, N_x} \tag{3.2.}$$

where - $\boldsymbol{a_i}$, $\boldsymbol{b_i}$ lower and upper restraining boundaries for parameter $\boldsymbol{x_i}$,

$\boldsymbol{N_x}$ - dimension of model parameter space.

Let us denote

$$\{\boldsymbol{Np^j}_{terminal}\ , \boldsymbol{v^j}\}$$

$$\text{where } \boldsymbol{Np^j}_{terminal} \in \boldsymbol{R}^+, \boldsymbol{v^j} \in \boldsymbol{V}^{\sim} \tag{3.3.}$$

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

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

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

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

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

$$\boldsymbol{f}[\boldsymbol{Np^j}_{terminal}\ , \boldsymbol{v^j}, \boldsymbol{Np_{model}(x,v^j)}] \leq \boldsymbol{CR(N_t)} = \varepsilon_{\mathbf{f}} \tag{3.4.}$$

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

$$\boldsymbol{Np_{model}(x,v^j)},\ \boldsymbol{Np_{model}} \in \boldsymbol{R}^+,\ \boldsymbol{x} \in \boldsymbol{X}^{\sim},\ \boldsymbol{v^j} \in \boldsymbol{V}^{\sim} \tag{3.5.}$$

that would depict input vectors $\boldsymbol{v_j}$ of a feasible set of inputs $\boldsymbol{v^j} \in \boldsymbol{V}^{\sim}$ into a scalar function $\boldsymbol{Np}_{model} \in \boldsymbol{R}^+$ defined on the set of parameters $\boldsymbol{x} \in \boldsymbol{X}^{\sim}$ as long as condition (3.4) holds (see FIGURE 3.1. below).

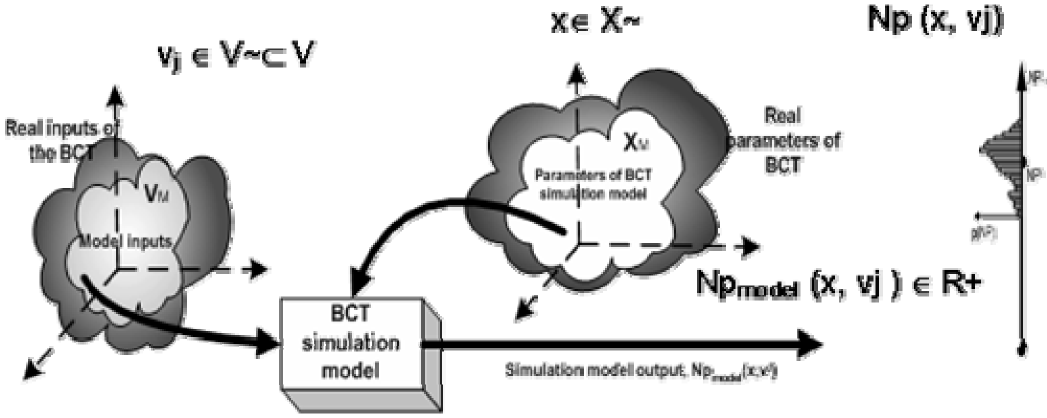


FIGURE 3.1. Illustration of parameter calibration methodology.

The logical structure of such a model must correspond to the structure of logistics 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 proceed to calculations and model verification for adequacy using real-life numerical data, it is first required to determine the feasible set of parameters $X^{\sim}$, i.e. to find more precise boundaries for vectors $\boldsymbol{a}$ and $\boldsymbol{b}$ as per (3.2.). The next step would be estimating parameters of triangular distributions $(xmin_i,\ xmod_i\ xmax_i)$, $i = 1, 2, \ldots, N_x$, where $xmin_i$ is the lower boundary $\boldsymbol{xmin_i}$, $\boldsymbol{xmodi}$ – the mode, and $\boldsymbol{xmaxi}$ standing for the upper boundary. The primary estimations is 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 $\boldsymbol{NP_{model}}$ represents a random function, depending on a number of variables $\boldsymbol{x}_i$, 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 $\boldsymbol{NP_{terminal}}$ of the terminal as value inverse to the average time of container move from vessel to the truck. Since $\boldsymbol{NP_{terminal}}$ data in the terminal database are stored as average values relying on the number of loaded, discharged, and re-stow 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)

$$\|\boldsymbol{NP_{model}} - \boldsymbol{NP_{terminal}}\| = \boldsymbol{f(x)} \rightarrow \min \qquad (3.6.)$$

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

However, in our case both the function $\boldsymbol{f(x)}$ and the parameters $\boldsymbol{x}$ 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 (3.5):

$$\boldsymbol{f}[\boldsymbol{Np^j}_{terminal}\, ,\, \boldsymbol{Np^j}_{\boldsymbol{model}}] - \boldsymbol{CR(N_t)} \leq \varepsilon_f \qquad (3.7.)$$

Let us next concentrate on selecting an optimization method appropriate for the task in focus.

3.1.1. CHOICE OF ALGORITHM: OVERVIEW OF DIRECT SEARCH METHODS

CHAPTER 1 has presented a brief overview to the variety of optimization methods (see page 37). The specificity of the task in focus where the object function is implicit and non-differentiable leads us to application of the so-called *direct search methods* of non-linear programming (Kleijnen, 1997).

The general concept lies in constructing a sequence of vectors $x[0]$, $x[1]$, …, $x[n]$, such that $f(x[0]) > f(x[1]) > f(x[n])$. As a starting point $x[0]$ can be chosen any feasible point, but it is worthwhile to use all of the available information as to function $f(x)$ behavior so that the point is as close as possible to the minimum point. The iteration from point $x[k]$ to point $x[k+1]$, k = 0, 1, 2, ..., breaks down to two stages:

1. Choosing the direction of step from point $x[k]$
2. Calculating the step length along this direction

Methods of constructing such sequences are often referred to as *gradient methods* as we progress from larger function values to the lesser ones. Mathematically these methods can be described as:

$$\boldsymbol{x[k+1] = x[k] + a_k p[k],\ k = 0, 1, 2, ...,}$$

where $\boldsymbol{p}[k]$ – is the vector, determining gradient direction; $\boldsymbol{a}_k$ – the length of the step.
Formalized in coordinate form (Kleijnen, 1997):

$$\left|\begin{array}{l} x_1[k+1] = x_1[k] + a_k p_1[k] \\ x_2[k+1] = x_2[k] + a_k p_2[k] \\ \dots\dots\dots\dots\dots\dots\dots\dots \\ x_n[k+1] = x_n[k] + a_k p_n[k] \end{array}\right|$$

Different gradient methods vary in ways of choosing the two parameters: the gradient step duration and step length respectively.

Paragraphs below present the most commonly used direct methods in optimization: direct search method, Nelder and Mead simplex method, and Response Surface Methodology.

3.1.2. DIRECT DESCENT METHOD

The ideology behind the direct search methods lies in the following: there is given an initial point of search $x[0]$. By changing the components of vector $x[0]$ one explores the proximity of the point, in the result finding the direction of incremental drop in the object function to be minimized *f(x).* In this direction the search is continued while the value of the object functions at respective points continues to decline. Once a step does not bring to location of a lesser value of the object function, one applies a smaller size step. If systematic decreasing the step length does not bring to smaller function values, the current search direction is abandoned and a new area of research is chosen (Tseng, 1998).

The algorithm of the direct search method is as follows:

1. Co-ordinate values are given $x_i[0]$ *,* $i = 1, ..., n$ with a starting point $x[0]$
2. $x[0]$ is assumed to be the basis point x^b and the value of $f(x^b)$ is calculated.
3. The co-ordinate x^b_i, $i = 1, ..., n$ of the basis point x^b is cyclically altered by value of Δx_i, i = 1, ..., n , i.e. $x_i[k] = x^b + \Delta\ x$; $x_i[k] = x^b_i - \Delta x_i$. There are also calculated value of $f(x[k])$ and compared to $f(x^b)$. If $f(x[k]) < f(x^b)$ then the corresponding co-ordinate x_i, i = 1, ..., n takes the new value calculated as per expression above. Alternatively, this co-ordinate remains unchanged. Should after alteration of the last nth coordinate $f(x[k]) < f(x^b)$ then the procedure continues at step 4; alternatively – at step 7.
4. $x[k]$ is assumed to be the new basis point x^b and the value of $f(x^b)$ is calculated.
5. The next step is downward stepping from point $x[k] > x_i[k+1] = 2x_i[k] - x^b$, i = 1, ..., n where x^b is the co-ordinate of the former basis point. The value of $f(x[k+1])$ is calculated.
6. Similarly to step 3 above the co-ordinates of point $x[k+1]$ is cyclically altered comparing the respective f(x) values with those of $f\,(x[k+1])$ obtained in step 5 above. After altering the final co-ordinate the value of $f(x[k])$ is compared to value $f(x^b)$ as per step 4 above, otherwise the procedure continues at step 3. The basis point in this case would be the last one of the basis points obtained.

7. The values of Δx and ε_x are compared If $\Delta x < \varepsilon_x$, the calculations stop. In alternative case, the value of Δx is decreased and step 3 is performed again.

The clear advantage of direct search method is the simplicity of application. It does not require knowing the object functions explicitly whereas easily considers constraints on separate variables and even complex constraints on the area of search. It is possible to use the modifications of *co-ordinate descent method*, e.g. by parabolic approximation basing on three points for making the following step (Kleijnen, 1997).

However, the disadvantage of the direct search method is that in case of concave, convex, interrupted or sharp-angled object functions it might not be able provide advancing to the function local minimum point. As it follows from FIGURE 3.2. below, whatever the size of the step in direction x_1 or x_2, from point x` we cannot obtain smaller values of object function.

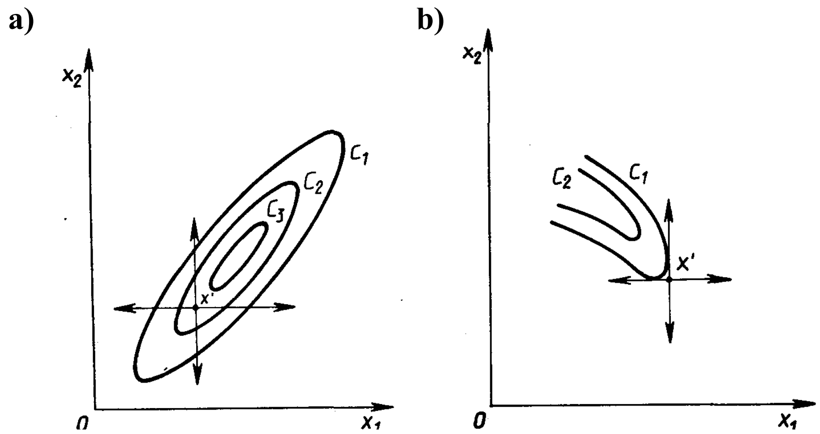


FIGURE 3.2. Unablility to advance to minimum point usign direct search method: a) – C1 > C2 > C3; b) - C1 > C2.

Despite the direct search method attractiveness in terms of simplicity of application, it has been widely criticized for dubious reliability, mostly for the reason mentioned above (Wright, 1996).

Below we consider several other direct methods to be used for Baltic Container Terminal simulation model parameter calibration: Nelder and Mead Simplex Method and Response Surface Methodology.

3.1.3. THE NELDER AND MEAD SIMPLEX METHOD VS RSM

The aim of this section is to compare two classes of algorithms claimed to be the most efficient for optimization of stochastic simulation models: Nelder and Mead Simplex Method and algorithms based on Response Surface Methodology in order to use BCT simulation model parameter adjustment procedure.

Among optimization methods that only use observations of the stochastic response function are the *Nelder and Mead Simplex Method*, *Stochastic Approximation*, *Response Surface Methodology*, and *Simultaneous Perturbation Stochastic Approximation* (Neddermeijer et al., 1999).

Both the Nelder and Mead Simplex Method and Response Surface Methodology are frequently used for the optimization of simulation models. Barton and Ivey (1991) investigated the performance of the Nelder and Mead Simplex Method in simulation optimization, and studied various modifications of the method that might improve its performance, major findings are summarized in section 3.1.6. CONCLUSION: CHOICE OF METHOD.

The particular interest in these algorithms stems from the need for efficient minimization algorithms that can be used in adjusting parameters of the simulation of the Baltic Container Terminal. Such a fitting procedure involves optimization of an objective function that can only be observed indirectly from the microsimulation model, which gives a stochastic response function that cannot be given explicitly as a function of the parameters.

Consequently, microsimulation models are often considered as stochastic black-box models (Pflug, 1996), where the optimization routine acts as a shell around the existing microsimulation program and only uses observations of the stochastic response function. We consider microsimulation models for which all parameters included in the optimization are real-value numbers.

An optimization algorithm for microsimulation models should be efficient in terms of the number of evaluations needed for finding an optimum, since function evaluations (i.e. runs of the microsimulation model) are computationally expensive. The algorithm should be reliable, in the sense that repeated optimizations should give comparable results. Furthermore, the algorithm should be accurate, in the sense that an observed optimum should be close to the real optimum. Accuracy is required in statistical comparison of different parameterizations of a model where one should be confident that indeed the best fitting models are compared (Neddermeijer et al., 1999).

3.1.4. The Nelder and Mead Simplex method

We consider the minimization of an objective function $f(\boldsymbol{x}) = E(F(\boldsymbol{x}))$,
$\boldsymbol{x} \in D \subset \Re^n$, $n \geq 1$, where $F(\boldsymbol{x})$ denotes the stochastic response function of the simulation model and $E(F(\boldsymbol{x}))$ denotes its expected value. The arguments *(x ,...,x)* 1 *n* $\boldsymbol{x}$ = represent the parameters of the microsimulation model.

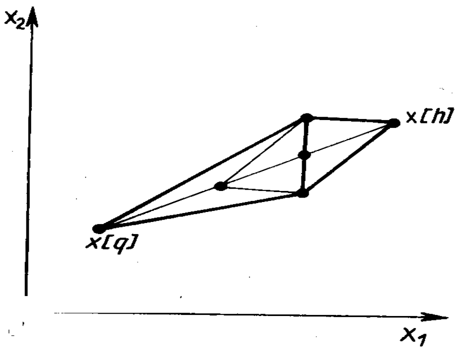


Figure 3.3. Graphical representation of Nelder and Mead Simplex

The Nelder and Mead Simplex Method (further in the text referred to as the NMSM) is a direct-search method that has shown a good performance on both deterministic objective functions (Nelson, 1985) and stochastic functions (Dennis and Woods, 1987). A detailed description of the algorithm can be found in (Barton and Ivey, 1991).

For the minimization of a function of n variables, NMSM defines a *simplex* with (n+1) vertices. During an iteration, the objective function is evaluated at each vertex of the simplex, and the vertex with the lowest value ($\boldsymbol{x}_{low}$), the vertex with the highest value ($\boldsymbol{x}_{hi}$) and the vertex with the next-to-highest value ($\boldsymbol{x}_{nexthi}$) are determined. Vertex $\boldsymbol{x}_{hi}$ is reflected through the centroid $\boldsymbol{x}_0$ of the remaining vertices to find a new vertex ($\boldsymbol{x}_{refl}$):
$\boldsymbol{x}_{refl} = (1+\alpha)\, \boldsymbol{x}_0 - \alpha\, \boldsymbol{x}_{hi}$, $\alpha > 0$, and the objective function is evaluated in vertex $\boldsymbol{x}_{refl}$. Next, a new simplex is constructed as follows (Nelson, 1985):

- If $F(\boldsymbol{x}_{refl}) \geq F(\boldsymbol{x}_{hi})$ then the objective function is evaluated in a contracted vertex between $\boldsymbol{x}_{hi}$ and $\boldsymbol{x}_0$, defined by $\boldsymbol{x}_{contr1} = \beta\, \boldsymbol{x}_{hi} + (1\text{-}\beta)\, \boldsymbol{x}_0$, $0 < \beta < 1$.
- If $F(\boldsymbol{x}_{contr1}) < F(\boldsymbol{x}_{hi})$, then the new simplex is found by replacing vertex $\boldsymbol{x}_{hi}$ by vertex $\boldsymbol{x}_{contr1}$, otherwise the new simplex is found by shrinking the current simplex around vertex $\boldsymbol{x}_{low}$, by replacing vertex $\boldsymbol{x}_i$ by $\delta \boldsymbol{x}_i + (1\text{-}\delta)\, \boldsymbol{x}_{low}$, $\boldsymbol{x}_i \neq \boldsymbol{x}_{low}$, $0 < \delta < 1$.
- If $F(\boldsymbol{x}_{nexthi}) < F(\boldsymbol{x}_{refl}) < F(\boldsymbol{x}_{hi})$ then the objective function is evaluated in a contracted vertex between $\boldsymbol{x}_{refl}$ and $\boldsymbol{x}_0$, defined by $\boldsymbol{x}_{contr2} = \beta\, \boldsymbol{x}_{hi} + (1\text{-}\beta)\, \boldsymbol{x}_0$, $0<\beta<1$.
- If $F(\boldsymbol{x}_{contr2}) < F(\boldsymbol{x}_{refl})$, then the new simplex is found by replacing vertex $\boldsymbol{x}_{hi}$ by vertex $\boldsymbol{x}_{contr2}$, otherwise the new simplex is found by shrinking the current simplex around vertex $\boldsymbol{x}_{low}$, by replacing vertex $\boldsymbol{x}_i$ by $\delta \boldsymbol{x}_i + (1\text{-}\delta)\boldsymbol{x}_{low}$, $\boldsymbol{x}_i \neq \boldsymbol{x}_{low}$, $0 < \delta < 1$.
- If $F(\boldsymbol{x}_{low}) \leq F(\boldsymbol{x}_{refl}) \leq F(\boldsymbol{x}_{nexthi})$ then the new simplex is found by replacing vertex $\boldsymbol{x}_{hi}$ by vertex $\boldsymbol{x}_{refl}$.
- If $F(\boldsymbol{x}_{refl}) < F(\boldsymbol{x}_{low})$ then the objective function is evaluated in an expanded vertex between $\boldsymbol{x}_{refl}$ and $\boldsymbol{x}_0$, defined by $\boldsymbol{x}_{exp} = \gamma\, \boldsymbol{x}_{refl} + (1\text{-} \gamma)\, \boldsymbol{x}_0$, $\gamma > 1$.
- If $F(\boldsymbol{x}_{exp}) < F(\boldsymbol{x}_{low})$, then the new simplex is found by replacing vertex $\boldsymbol{x}_{hi}$ by vertex $\boldsymbol{x}_{exp}$, otherwise the new simplex is found by replacing vertex $\boldsymbol{x}_{hi}$ by vertex $\boldsymbol{x}_{refl}$.

The next iteration begins with the new simplex. If during an iteration a vertex is defined outside the feasible region D, then this vertex is projected onto the boundary of this region. The initial simplex is given by $\left\{\left(x_1^0,...,x_n^0\right),\left(x_1^0+c_1...,x_n^0\right),...,\left(x_1^0+...,x_n^0+c_n\right)\right\}$

where $x^0 = \left(x_1^0,...,x_n^0\right)$ is called the starting point and the size of this simplex is determined by the stepsizes $\left\{c_1,...,c_n\right\}$. The parameters ($\alpha$, β, δ ,γ) are commonly set to (1, 0.5 , 0.5 , 2) (Barton and Ivey, 1991).

3.1.5. RESPONSE SURFACE METHODOLOGY

Myers and Montgomery (1995) consider RSM as a collection of statistical and mathematical techniques useful for optimizing stochastic functions. The methodology is based on approximation of the objective function by a low order polynomial on a small subregion of the feasible region ***D***. The coefficients of the polynomial are determined by regression analysis applied to a number of observations of the objective function. To this end, the objective function is evaluated in an arrangement of points referred to as an experimental design. Based on the fitted polynomial, local best values of the parameters x_1 ,..., x_n are derived, which represent the center point of the new subregion (Neddermeijer et al., 1999).

The RSM algorithm comprises two phases: a first-order phase in which first-order polynomials are fitted iteratively until a plateau is reached, or until too much curvature is found, and a second-order phase in which the objective function is approximated iteratively by second-order polynomials (Cochran and Cox, 1962).

The algorithm starts with constructing the first subregion $[x_1^0 - c_1, x_1^0 + c_1] \times \ldots \times [x_n^0 - c_n, x_n^0 + c_n]$ using the starting values of the parameters $x^0 = (x_1^0, \ldots, x_n^0)$ and the initial step sizes $\{c_1, \ldots, c_n\}$. The parameters are scaled between –1 and +1 such that the subregion corresponds to [-1,1]×... × [-1,1] to avoid numerical problems that may occur when parameters vary in orders of magnitude (Free et al., 1987). In the subregion we fit a first-order polynomial represented by

$$\hat{y} = b_0 + \sum_{i=1,\ldots,n} b_i \xi_i$$

where $\xi = (\xi_1, \ldots, \xi_n)$ are the scaled parameters. To this end the objective function is evaluated in the 2^n points of a 2-level factorial design, given by the factorial points $(x_1^0 \pm c_1, x_2^0 \pm c_2, \ldots, x_n^0 \pm c_n)$ (Myers and Montgomery, 1995). If the design is not within the feasible region D, then it is moved into this region (Smith, 1979). Since we will investigate the objective function for presence of curvature, the objective function is evaluated four times in the center point $(x_1^0, \ldots, x_n^0)$ for testing for lack of fit (Myers and Montgomery, 1995). If there is no systematic curvature present at a 5% significance level, then we test for the presence of a plateau, i.e. we test the hypothesis $H_0 : b_1 = \ldots = b_n = 0$ against the alternative hypothesis $H_1 : \exists i : b_i \neq 0$:. If the null hypothesis is rejected at a 5% significance level then we accept the first-order polynomial and we conclude that a steepest descent direction exists. In this case, a line search is performed in the steepest descent direction given by ($-b_1, \dots, -b_n$) (Myers and Montgomery, 1995). A number of equidistant points in the steepest descent direction will be evaluated, starting at scaled distance 1 from the center point. As soon as a boundary of the feasible region *D* is crossed, the line search is continued along the projection of the search direction on this boundary (Smith, 1979). The line search is ended when an observed value of the simulation response function is higher than the preceding observation. The last point for which the simulation response function was decreasing will be the center point of the next subregion, where again a first-order polynomial is fitted. If the first-order polynomial is not accepted, then a second-order polynomial is fitted in the current subregion. Central Composite Design (CCD) is used for determining the coefficients of the second-order polynomial (Kleijnen, 1975), consisting of the center point $\left(x_1^0, \dots, x_n^0\right)$ which is evaluated four times, 2^n scaled factorial points $\left(x_1^0 \pm c_1, x_2^0 \pm c_2, \dots, x_n^0 \pm c_n\right)$ and $2n$ scaled axial points $\left(x_1^0 \pm \alpha c_1, 0\dots,0\right), \dots, \left(0,\dots,0, x_n^0 \pm \alpha c_n\right)$ where $\alpha = 2^{n/4}$. A CCD is widely used for fitting second-order polynomials (Myers and Montgomery, 1995). The fitted polynomial is represented by

$$\hat{y} = b_0 + \sum_{i=1,\dots,n} b_i \xi_i + \sum_{i=1,\dots,n} b_{ij} \xi_i \xi_j = b_0 + \boldsymbol{?'b} + \boldsymbol{?'B?}$$

where **?** = $\left(\xi_1, \dots, \xi_n\right)$ are the scaled parameters not tested for lack of fit.

The stationary point of the quadratic surface is determined by

$$s = -\frac{1}{2} B^{-1} b$$

Let ***E*** be the $n \times n$ matrix of normalized eigenvectors of ***B*** and let $v_1, \dots, v_n$ be the eigenvalues of ***B***. If all eigenvalues are positive, then the quadratic surface has a minimum at the stationary point. If this point lies within the current subregion, then it is taken as the centre point of the new subregion, whereas the stepsizes $\left\{c_1, \dots, c_n\right\}$ that are used for construction of the subregion are decreased by 50%. In the new subregion again a second-order polynomial will be fitted. If all eigenvalues are positive but if the stationary point lies outside the current subregion, the stationary point is not regarded as the centre of the next subregion. The same applies when the eigenvalues are mixed in sign, i.e. the stationary point is a saddle point or when all eigenvalues are negative, i.e. the stationary point is a maximum.

In this case, *ridge analysis* is performed, which means that we search for a stationary point $\boldsymbol{?_R}$ on a given radius R such that the quadratic surface has a minimum at this stationary point (Myers and Montgomery, 1995). Using Lagrange analysis with multiplier μ, this stationary point is given by

$$\boldsymbol{(B- \mu I)\ ?_R = -b/2}$$

and it should hold that $\mu < \min_i v_i$ and $\sqrt{\boldsymbol{?'_R\, ?_R}} = R$. We can write

$$R^2 = \boldsymbol{?'_R\, ?_R} = \sum_{i=1}^{n} \left(\frac{e_i' b}{2(v_i - \mu)} \right)^2 = 2$$

where $\boldsymbol{e_i}$ is the eigenvector corresponding to the i^{th} eigenvalue v_i . We consider the radius of the circumscribed sphere of the subregion, i.e. $R = \sqrt{2}$, which means that we have to find $\mu < \min_i v_i$ such that

$$\sum_{i=1}^{n} \left(\frac{e_i' b}{2(v_i - \mu)} \right)^2 = 2$$

Standard numerical methods for finding the root of an equation are used to determine μ . The stationary point that results from the ridge analysis will be used as the center point of the next subregion, in which again a second-order polynomial will be fitted.

3.1.6. CONCLUSION: CHOICE OF METHOD

The growing demand for complex microsimulation models requires continuous efforts to devise and test robust and efficient optimization methods. Barton and Ivey (1991) investigated NMSM for its use in simulation optimization and reported that the NMSM algorithms often outperformed the RSM algorithms, seeming to be better suited for erratic behaviour of test functions.

Besides that, in accordance with a study by Neddermeijer et al. (1999) on a microsimulation version of a cancer screening microsimulation model and a set of test functions, the RSM algorithms were clearly less efficient than the NMSM algorithms. As per their findings, the slower convergence of the RSM algorithms is first of all caused by the large size of its designs; the authors believe that designs with fewer points could be more efficient. Taking into consideration the above-mentioned arguments and research results, the choice of optimization method falls in favour of Nelder and Mead Simplex Method.

3.2. 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 deviation would be the Kolmogorov-Smirnov test described in section 3.3.2. SECOND OBJECT FUNCTION: KOLMOGOROV-SMIRNOV STATISTIC.

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 lose sensitivity and yield value equal to one (Smirnov, 1970).

So, in the test point which lies far enough from the minimum point the test loses efficiency (see FIGURE 3.4. below). Obviously, it is worthwhile to use the Kolmogorov-Smirnov test in proximity to the point of minimum, whereas far from that point we should use other statistical characteristics of the histogram, e.g. the mean value or the median.

Thus, it was decided to use a two-tier methodology of parameter adjustment. First, as the object function we take the absolute value of mean value difference of the model output and the observed BCT data. Then using an optimization method for searching the function minima such parameters of the model are consequently found that allow stopping the procedure once the significance test yields positive result. For the case in focus the significance level t-criterion is chosen at 5% level.

a)

b)

c)

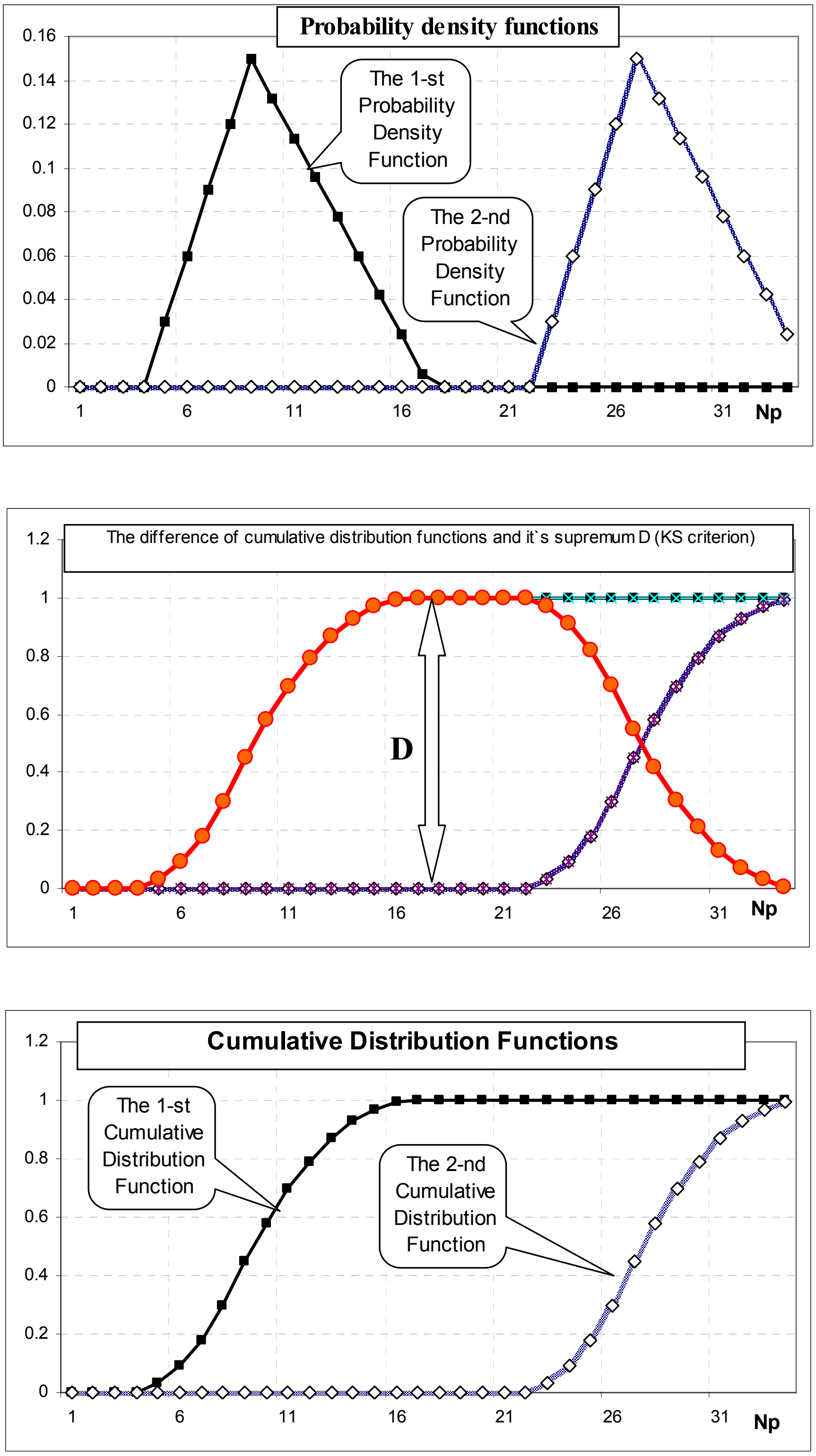


FIGURE 3.4. a) An example of non-overlapping probability density functions, **b)** Respective cumulative probability functions of the two data samples, and **c)** Kolmogorov-Smirnov test becomes unable to determine whether the two samples belong to the same distribution.

Once the t-test mean comparison-based iteration procedure reaches the mentioned threshold value, the object function is replaced with Kolmogorov-Smirnov criterion and the iteration procedure of parameter adjustment starts again. As the threshold value for the new object function is reached, the process of parameter adjustment is complete. 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.

3.2.1. ALGORITHM DESCRIPTION

Let us describe the algorithm of adjustment of aggregated model parameters or resource cycles **Tq, Tt, Ty=Tf**.

In order the Nelder-Mead extreme 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 $\mathbf{X^{(1)}=[T_q^{(1)}, T_t^{(1)}, T_y^{(1)}]}$, $\mathbf{X^{(2)}=[T_q^{(2)}, T_t^{(2)}, T_y^{(2)}]}$, $\mathbf{X^{(3)}=[T_q^{(3)}, T_t^{(3)}, T_y^{(3)}]}$, $\mathbf{X^{(4)}=[T_q^{(4)}, T_t^{(4)}, T_y^{(4)}]}$. The maximum number of iterations $\mathbf{i_{max}}$ 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 **k** values of net productivity $\mathbf{[Np_k^{(1)}]}$, $\mathbf{[Np_k^{(2)}]}$, $\mathbf{[Np_k^{(3)}]}$, $\mathbf{[Np_k^{(4)}]}$, for **k**=142.

STEP 3 The obtained **4*k** values of net productivity $\mathbf{[Np_k^{(1)}]}$, $\mathbf{[Np_k^{(2)}]}$, $\mathbf{[Np_k^{(3)}]}$, $\mathbf{[Np_k^{(4)}]}$, **k**=1,2,…, 142, are input in the database and are used for calculations fo the four values of the object function $\mathbf{f_t^{(i)}} = 11.91638\mathbf{*[mean(Np_{BCT}) – mean(Np^{(i)})]/ s^{(i)}}$, **i=1,2,3,4,** 11.91638 = (142)^(1/2) – standardizing coefficient
$\mathbf{s^{(i)}}$ – square root of sample dispersion of observations $\mathbf{[Np_k^{(i)}]}$, **k**=142.
$\mathbf{f_t^{(i)}}$ – values of the **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.

$$\mathbf{f_t^{(i)} = 11.916*[mean(Np_{BCT}) - mean(Np^{(i)})]/ s^{(i)}}.$$

STEP 5 Testing if inequalty below holds:

$$\mathbf{i > i_{max}} \tag{i}$$

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.

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

$$\mathbf{f_t^{(i)} \geq t^{(*)}}, \tag{ii}$$

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

If the inequailty (ii) is false, we move on to STEP 4.

On the contrary, if the inequailty (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,…,142, are called from the procedure monitiring data base and are used for calculations of four values for the new object function.

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

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

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

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

STEP 8 The following inequality is tested:

$$\mathbf{i > i_{max}} \qquad \text{(i)}$$

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:

$$\mathbf{f_{KS}^{(j)} \geq f_{KS}^{(*)}}, \qquad \text{(ii)}$$

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

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

If the inequailty (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 3.5. below.

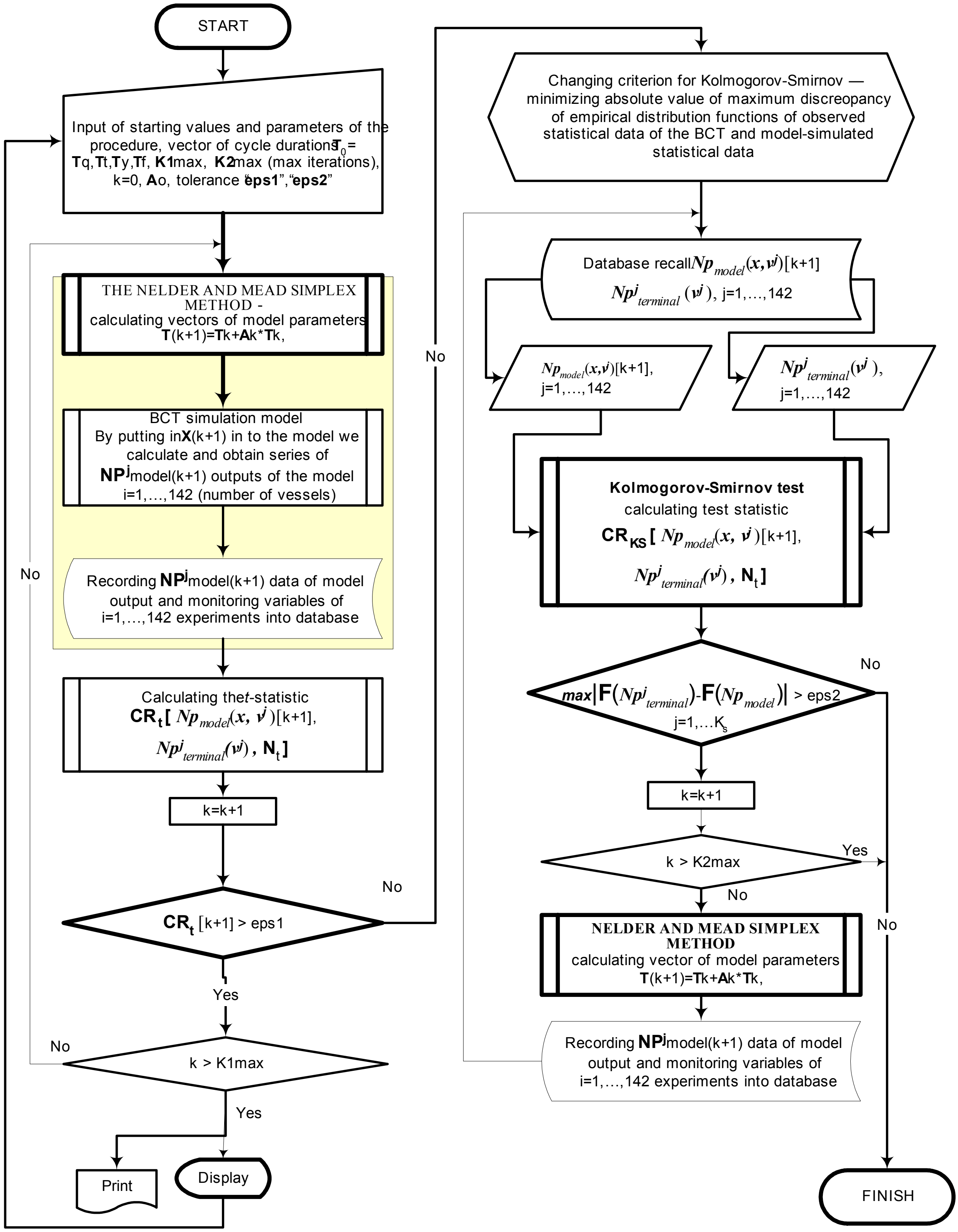


FIGURE 3.5. Graphical representation of parameter adjustment algorithm

3.3. OBJECT FUNCTIONS FOR TWO-TIER ALGORITHM

The section presents the methodology for choice of object function and estimation of its critical values for the Nelder-Mead simplex algorithm described above to stop and swap the criteria of search.

3.3.1. FIRST OBJECT FUNCTION: T-TEST STATISTIC

For the algorithm described above in the previous section it is necessary that the object function is calculated at each step of the algorithm. The first stage it called for minimization of average values of two population samples: that of BCT and the model. Talking in mathematical terms, we should test the hypothesis of equality of two average values μ1 and μ2.

These are called "two-sample" tests. Our goal is usually to estimate μ1 - μ2 and the corresponding confidence intervals and to perform hypothesis tests on:

H0: μ1 - μ2 = 0.

For each sample we compute the relevant statistics (Korolyuk et al., 1978):

Sample 1 -> n1 , $s_1^2 = \sqrt{1/(n_1-1)\sum_1^{n_1}(x_i^2 - \bar{X}_1^2)}$, $\bar{X}_1 = 1/n_1 \sum_1^{n_1} x_{1i}$

Sample 2 -> n2 , $s_1^2 = \sqrt{1/(n_2-1)\sum_1^{n_2}(x_i^2 - \bar{X}_2^2)}$, $\bar{X}_2 = 1/n_2 \sum_1^{n_2} x_{2i}$

The obvious statistic to compare the two sample means $\overline{X}_1 - \overline{X}_2$.
Probability theory tells us that:

1. $\overline{X}_1 - \overline{X}_2$ is the best estimate of μ1 - μ2

2. The standard error is $\sqrt{\sigma_1^2/n_1 + \sigma_2^2/n_2}$

3. $\overline{X}_1 - \overline{X}_2 \sim N\left(\mu_1 - \mu_2, \sigma_1^2/n_1 + \sigma_2^2/n_2\right)$ for large n1 and n2:

Normally, we do not have knowledge of σ1 and σ2 , so we need to estimate them in order to compute hypothesis tests and confidence intervals for μ1 - μ2.

Two different standard estimation procedures are used depending on whether we feel it is reasonable or not to assume whether σ1=σ2

Unequal variance case: σ1 ≠ σ2

Standard error is estimated by $SE(\overline{X}_1 - \overline{X}_2) = \sqrt{s_1^2/n_1 + s_2^2/n_2}$.

The T statistic

$T = (\bar{X}_1 - \bar{X}_2) / SE(\bar{X}_1 - \bar{X}_2)$

has a ***t*** distribution with degrees of freedom that can be estimated by (Smirnov, 1970):

$$\frac{\left(s_1^2/n_1 + s_2^2/n_2\right)^2}{\frac{(s_1^2/n_1)^2}{n_1 - 1} + \frac{(s_2^2/n_2)^2}{n_2 - 1}}$$

If n_1 and $n_2 > 80$, then can use standard Normal distribution in place of ***t***, which removes necessity to estimate degrees of freedom.

Since adjustment of parameters in this case was based on a sample of 142 observations (number of available vessel statistics) the termination criterion for Nelder-Mead method at the first stage was the critical value of normal distribution of ***T*** at given significance level (normally, 5 %).

Denote

$$T = (\overline{Np_{BCT}} - \overline{Np_{\mathrm{model}}}) / SE(\overline{Np_{BCT}} - \overline{Np_{\mathrm{model}}}) \ , \ z = |T| / \sqrt{2} \qquad (3.8.)$$

Normal distribution probability function can be approximated by expression

F(z)=1-(1/2)*exp(-0.0003*z^5 + 0.01107*z^4 - 0.088486*z^3 –

- 0.64335*z^2 - 1.128*z) (3.9.)

If F(z)<0.975 than the procedure is terminated and it is switched to the Kolmogorov-Smirnov goal function. This switching of object function to Kolmogorov-Smirnov test is illustrated in FIGURE 3.6. below.

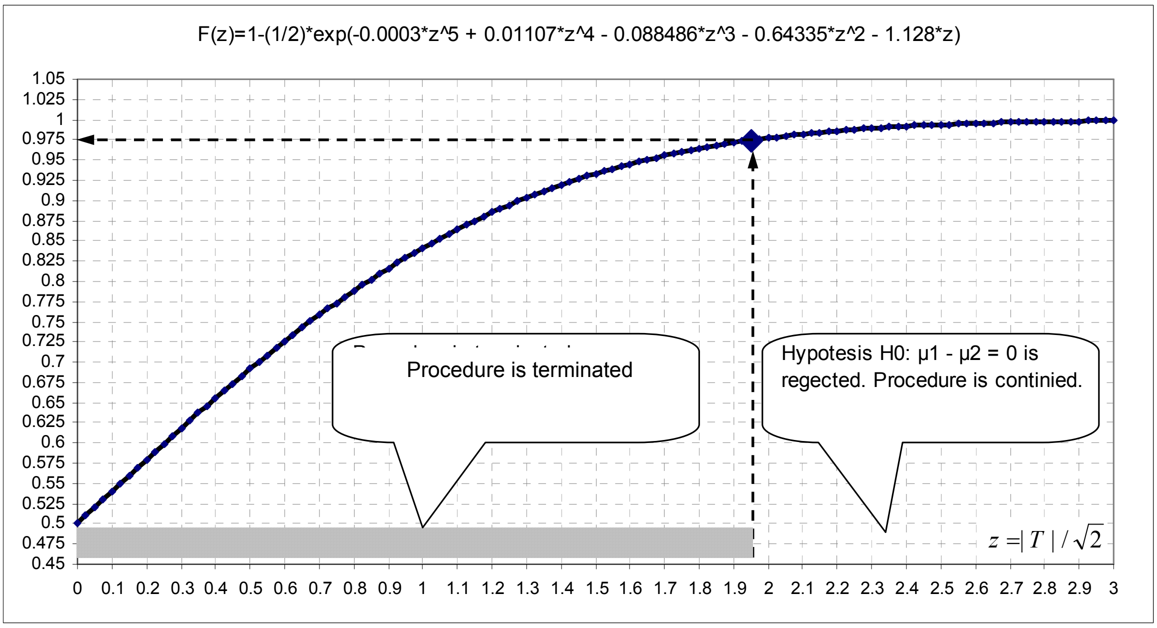


FIGURE 3.6. Hypothesis testing for positive values of z.

The next section presents the second part of the two-tier parameter adjustment algorithm where the object functions is swapped for Kolmogorov-Smirnov test.

3.3.2. SECOND OBJECT FUNCTION: KOLMOGOROV-SMIRNOV STATISTIC

The present section gives a short overview of Kolmogorov-Smirnov based on outlines by Bolshev and Smirnov (1978) test structure and its numerical estimation at different significance levels. The obtained critical values of Kolmogorov-Smirnov criterion are used for signaling Nelder-Mead procedure to terminate.

Let $\xi_1, \xi_2, \ldots, \xi_n$ – mutually independent and evenly distributed random variables and let

$$\eta_1 \le \eta_2 \le \ldots \le \eta_n$$

representing the same ξ_i values but arranged in ascending order. The *empirical* distribution is the distribution of discrete random value ξ^* taking values $\eta_1, \eta_2, \ldots, \eta_n$ with equal probabilities of 1/n:

$$P\{\xi^* = \eta_i | \eta_1, \eta_2, \ldots, \eta_n\} = 1/n ,$$
$$(i = 1, 2, \ldots, n).$$

The *function of empirical distribution* is expressed by the equality:

$$F_n(x| \eta_1, \eta_2, \ldots, \eta_n) = P\{\xi^* < x| \eta_1, \eta_2, \ldots, \eta_n\} =$$

$$= \begin{cases} 0, \text{if } x \le \eta_1 \\ m/n, \text{if } \eta_m < x \le \eta_{m+1}, 1 \le m \le n-1 \\ 1, \text{if } x > \eta_m \end{cases},$$

which is a random value for every x (function of $\eta_1, \eta_2, \ldots, \eta_n$). This function empirical distribution will be referred to as $F_n(x)$.

Since $\mathbf{M}F_n(x) \equiv F_n(x)$, where $\mathbf{M}F_n(x)$ stands for the average value of $F_n(x)$,

$$D\, F_n(x) \equiv \frac{1}{n} F_n(x)[1-F(x)] \rightarrow 0; \; (n \rightarrow \infty),$$

where $F(x)$ is the function distribution of the original values ξ_i (also referred to as the *function of theoretical distribution*), and $F_n(x)$ is an unbiased estimation for F(x).

If the *function of theoretical distribution* is unknown and there is only a hypothesis brought forward assuming this function to be of continuous distribution $F(x)$ not containing any unknown parameters, it might be denoted as follows:

$$H_0 : \mathrm{M}F_n(x) \equiv F_n(x) \quad (|\mathrm{x}| < \infty) \ .$$

At the same time, let us denote alternative hypotheses as:

$$H_1^+ \{\psi[F(x)]\} : \sup_{|x|<\infty} \psi[F(x)](MF_n(x) - F(x)) > 0 ,$$

$$H_1^- \{\psi[F(x)]\} : \inf_{|x|<\infty} \psi[F(x)](MF_n(x) - F(x)) < 0 ,$$

$$H_1 \{\psi[F(x)]\} : \sup_{|x|<\infty} \psi[F(x)]|MF_n(x) - F(x)| > 0 .$$

Where ψ (F) is a given non-negative function (often referred to as the *weight function*)

The Kolmogorov-Smirnov criteria are meant to test the H_0 hypothesis against $H_1\{1\}$ (Kolmogorov criterion) and $H_1^+\{1\}$ or $H_1^-\{1\}$ (Smirnov criterion). The criteria statistics are given by the following expressions

$$D_n = \sup_{|x|<\infty} |(F_n(x) - F(x))| ,$$

$$D_n^+ = \sup_{|x|<\infty} (F_n(x) - F(x)) ,$$

$$D_n^- = -\inf_{|x|<\infty} (F_n(x) - F(x)) .$$

Where the left-hand sides of the equation signs $+$ and $-$ respectively, as well as an absence of a sign indicate the corresponding alternative hypothesis. For purposes of calculation practicability the following alternative expressions can be used:

$$D_n^+ = \max_{1\le m\le n} \left(\frac{m}{n} - F(\eta_m) \right) ,$$

$$D_n^- = \max_{1\le m\le n} \left(F(\eta_m) - \frac{m-1}{n} \right) ,$$

$$D_n = \max(D_n^+, D_n^-)$$

It should be noted that

$$D_n \neq \max_{1\le m\le n} \left| \left(F(\eta_m) - \frac{m}{n} \right) \right|,$$

$$D_n \neq \max_{1\le m\le n} \left| \left(F(\eta_m) - (2m-1)/2n \right) \right|$$

Should H_0 be true, it follows that the distribution patterns of statistics D_n^+ and D_n^- are the same, therefore it is sufficient to use just D_n^+. Thus, it can be inferred that

$$P\left\{D_n^+ \ge x\right\} = \sum_{k=0}^{\mathrm{int}[n(1-x)]} C_n^k \, x(x+k/n)^{k-1}(1-x-k/n)^{n-k} \ , \quad 0<x<1 \ ,$$

where ***int***[y] is the integer part of y.

From asymptotic formulas and theorems outlined in (Smirnov, 1970) it follows that if $n \to \infty$ and $0 < \varepsilon \le x = O\left(n^{\frac{1}{3}} \right)$ then

$$P\left\{ \frac{\left(6nD_n^+ + 1\right)^2}{18n} < x \right\} = \left(1 - e^{-x}\right) + e^{-x}\,\frac{2x^2 - 4x - 1}{18n} + O\left(\frac{1}{n\sqrt{n}} \right),$$

$$P\left\{ \frac{\left(6nD_n + 1\right)^2}{18n} < x \right\} = K\left(\sqrt{\frac{x}{2}} \right) - \frac{1}{18n} \sum_{k=-\infty}^{\infty} \left(-1\right)^k e^{-k^2 x} [P_k(x) + 2k^4 x - k^2] + O\left(\frac{1}{n\sqrt{n}} \right)$$

where $K(y) = \sum_{k=-\infty}^{\infty} \left(-1\right)^k e^{-2k^2 y^2}$.

K(y) is the Kolmogorov distribution function which represents marginal distribution of the random value $\sqrt{n}D_n$ with $n \to \infty$ and

$$P_k(x) = \left[k^2 - \frac{1-(-1)^k}{2} \right]\left(1 - 2k^2 x\right) + 2k^2 x (k^2 x - 3)$$

Put in other words, with n taking greater values, the statistic $\left(6nD_n^+ + 1\right)^2 / (9n)$ is approximately distributed as χ^2 with two degrees of freedom, and the distribution of statistic $\left(6nD_n+1\right)^2/(18n)$ is roughly described by $K\left(\sqrt{x/2}\right)$. Both of these approximations hold with $n \geq 20$. As n takes greater values, the error diminishes in proportion of $1/n$.

Let Q be the necessary significance level denominated as percentage $0 < Q \leq 50\%$ and let $D_n^+(Q)$ and $D_n(Q)$ be the critical values of the statistics D_n^+ and D_n respectively, determined from the following equations:

$$P\left\{D_n^+ \geq D_n^+(Q)\right\} = 0.01Q \qquad \text{and}$$
$$P\left\{D_n \geq D_n(Q)\right\} = 0.01Q$$

If from the experiment it turns out that $D_n \geq D_n(Q)$ then according to the Kolmogorov-Smirnov criterion with the level of significance Q the hypothesis H_0 must be rejected (by analogy, we arrive at the same conclusion if $D_n^+ \geq D_n^+(Q)$).

If $Q \leq 20\%$ then with high degree of precision the following holds:

$$D_n(Q) \approx D_n^+(0.5Q)$$

The statistical error of this rough equality at Q=20 and 10% does not exceed $5 \cdot 10^{-4}$ and $5 \cdot 10^{-5}$ respectively; with decrease in Q, the error drastically decreases.

With $n \geq 10$ in order to calculate $D_n(Q)$ within the $1\% \leq Q \leq 20\%$ interval and $D_n^+(Q)$ with $Q \geq 0.5\%$ we can use the following approximation:

$$\sqrt{\frac{1}{2n}\left(y - \frac{2y^2-4y-1}{18n}\right)} - \frac{1}{6n} \qquad (3.10.)$$

or $\sqrt{\dfrac{y}{2n}} - \dfrac{1}{6n}$, where y= -ln(0.01Q) if $D_n^+(Q)$ is calculated and y= -ln(0.005Q) for calculation of $D_n(Q)$.

For approximate estimation of $D_n(Q)$ for 20%<Q<30% and 10<n<50 it is recommended to find ***y*** value from equation

$$K\left(\sqrt{y/2}\right) = 1 - 0.01Q$$

and apply a more precise formula:

$$D_n(Q) \approx \sqrt{1/(2n)\{y - 1/(18n)[(2y^2 - 4y - 1) - (Q/100)^3(3y^2 - y + 1/2)]\}} - 1/(6n) \qquad (3.11.)$$

With $n \geq 100$ the approximation formulas allow a satisfactory determination of the critical values $D_n(Q)$ and $D_n^+(Q)$ within the interval $0.01\% \leq Q \leq 50\%$. Approximation accuracy in calculation of $D_n^+(Q)$ will be satisfactory for all $Q \geq 0.01\%$.

Let us denote

$$D_n = \sup_{0<Npi} \left|\left(F_n(Np_{BCT}) - F(Np_{Model})\right)\right|, \qquad (3.12.)$$

and use the formula (3.11.) for approximation of dependence of critical value of Kolmogorov-Smirnov function on the level of significance Q

$$Dn(Q) \approx \sqrt{\frac{1}{2n}\left(y - \frac{2y^2 - 4y - 1}{18n}\right)} - \frac{1}{6n} \;, \text{ y= -ln(0.005}Q\text{)} \qquad (3.13.)$$

FIGURE 3.7. illustrates finding of critical value of Kolmogorov-Smirnov function at level of error at 5%.

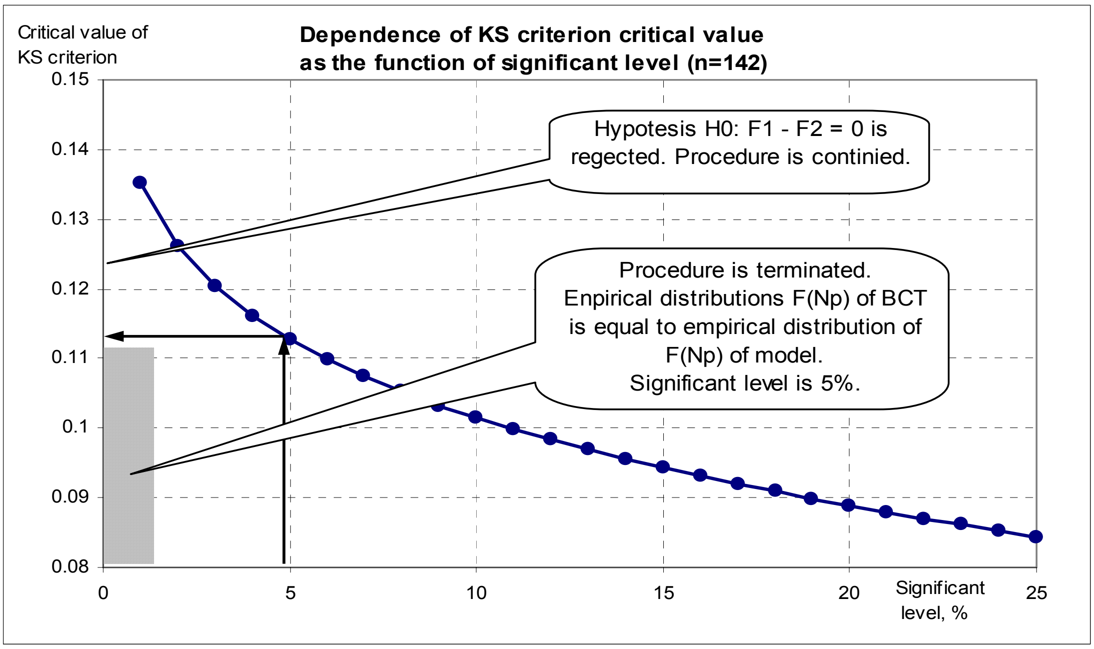


FIGURE 3.7. Kolmogorov-Smirnov critical value (3.10) dependence on magnitude of level of significance.

Thus, for estimation of critical values of object functions we use expressions (3.8) to (3.13). Expressions (3.8), (3.9) are used for switching to Kolmogorov-Smirnov criterion, whereas formulas (3.12) and (3.13) are used for final termination of procedure of parameter adjustment.

3.4. CONCLUSIONS

The parameter adjustment has been presented as the task of optimization 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 algorithm. In order to complete the task, there has been created a two-tier optimization algorithm aimed at minimizing stochastic object function. 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 to find preliminary best fitting rough solutions. The second stage of the algorithm uses the Kolmogorov-Smirnov statistic for 'fine tuning' in order to locate best solutions taking regard of the forms of the statistical distributions of the observed and model data. Such an approach ensures high degree of precision of parameter adjustment with a relatively small number of iterations.

4. MODEL CALIBRATION: APPLICATION OF TWO-TIER ALGORITHM

This section deals with application of the methodological approach described above in CHAPTER 3. MODEL CALIBRATION METHODOLOGY. for modelling probability distributions of generated number of import and export containers, hatch covers, and restow containers basing on the observed data at the Baltic Container Terminal.

According to the objective of the research, BCT micro-simulation model requires input of statistical distributions and their respective calibration with regard to two groups of parameters:

- external parameters (generating container input flow necessary for *'what if...?'* scenario analysis) and
- internal model parameters such as durations of elementary operations, resource cycle statistics etc.

Parameter adjustment for each of the two groups is presented in the following paragraphs. The running parameters of the model are controlled with the help of hierarchically organized monitoring variables of each process modelled, which allows spot measurements. These monitoring variables are recorded in a dynamic database and can be traced for spot analysis of different *'what if...?'* scenarios as illustrated in Chapter 5. PRACTICAL APPLICATIONS OF SIMULATION MODEL.

4.1. ADJUSTING EXTERNAL PARAMETERS

The first group of variables represents input container flow generators which consist of line- (respectively, vessel-) specific parameters and input (number of export/import containers) variables. These parameters are necessary for model flexibility for *'what if...?'* scenario analysis taking into consideration input characteristics differing from the existing BCT operational statistics.

Thus, this group of variables includes the following subgroups:

- **Ckm**: number of units **Ck** on vessel **m** (20' and 40' import containers, restow, hatches, 20' and 40' export containers);
- statistical distribution of every units arrival (number of container variations).

The paragraph that follows presents a brief overview of statistical characteristics of the original input data which served as the calibration basis for creating input generators of the model.

4.1.1. BCT DATA CORRELATION ANALYSIS

In order to construct adequate model of inputs (input generators), let us analyze statistical observed BCT data for correlation of inputs (number of 20ft import and export containers, 40ft import and export container, hatch covers, and restow containers) with net productivity statistics. FIGURE 4.1. illustrates BCT the correlation graphs.

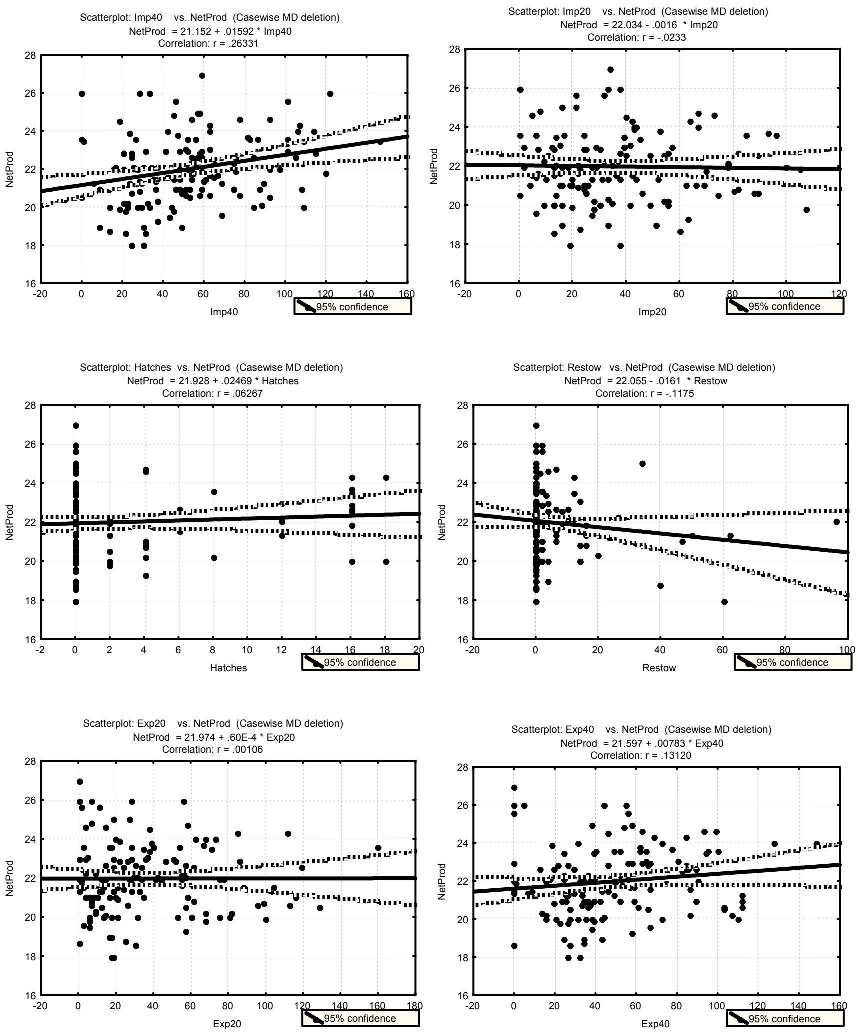


FIGURE 4.1. 95% confidence intervals for observed NP (Y-scale) regressed on other observed real input NP data (X-scale)

The 95% confidence interval analysis of regression lines proves that any of the inputs does not sufficiently influence on NP output data. Consequently, the output values are basically determined by the resources of the terminal discussed in the previous paragraph, whereas adequacy test should be run only for NPm (Net Productivity of the model) histogram. Since absence of significant linear correlation is characterized by a presence of horizontal regression line, thus any horizontal regression line fitting into the 95% confidence intervals portrays absence of significant correlation across the cases observed. Among the regressions presented on FIGURE 4.7 only in one case weak correlation between NP and Import 40' is observed, which does not affect the behaviour of NP. Thus, it might be concluded that within the observed real data, the behaviour of NP is highly dependent on the set of available resources, as well as the magnitude of the productive cycles. Let us concentrate on these factors in the section below.

4.1.2. CREATING INPUT GENERATORS

For statistical analysis of the BCT model there were created generators of input data, whose parameters are adjusted according to histograms of respective real input data. The statistical homogeneity of the two samples is achieved through comparison of Kolmogorov-Smirnov statistics of the output histograms of the generators.

As described in the *Rockwell Software Arena 5.0* package manual, the application of such histograms is as follows:

> *"The generators follow the empirical continuous distribution algorithm:*
> CONTinuous (Prob1,Value1,Prob2,Value2, . . . [,Stream]) ,
> Probi — Cumulative probability,
> Valuei — Value associated with probability Probi,
> Parameter Set — Parameter set ID containing values for Probi and Valuei pairs.
> When evaluating the CONTinuous function, Arena generates a random number between 0 and 1. Arena then searches the probabilities, Probi, until it finds one larger than the random number. Arena linearly interpolates between Valuei -1 and Valuei and returns the interpolated number based on the random sample.
> Example: CONT(0.3,1, 0.8,2, 1.0,3) This function returns a value between 0 and 1 approximately 30 percent of the time, a value between 1 and 2 approximately 50 percent of the time (0.8 - 0.3 = 0.5 or 50 percent), and a value between 2 and 3 approximately 20 percent of the time (1.0 - 0.8 = 0.2 or 20 percent).
>
> The value returned by the empirical continuous distribution is computed using linear interpolation within the range of two successive cumulative probability values that surround the uniform value drawn. The first random variable specified, V1 , is returned if the uniform random number drawn is less than the first

associated cumulative probability, P1.

To draw a random value from the empirical continuous distribution, Arena uses a sequential search through the cumulative probabilities table of the function."

The implementation methodology logics developed to adjust distributions parameters is depicted in FIGURE 4.2. below.

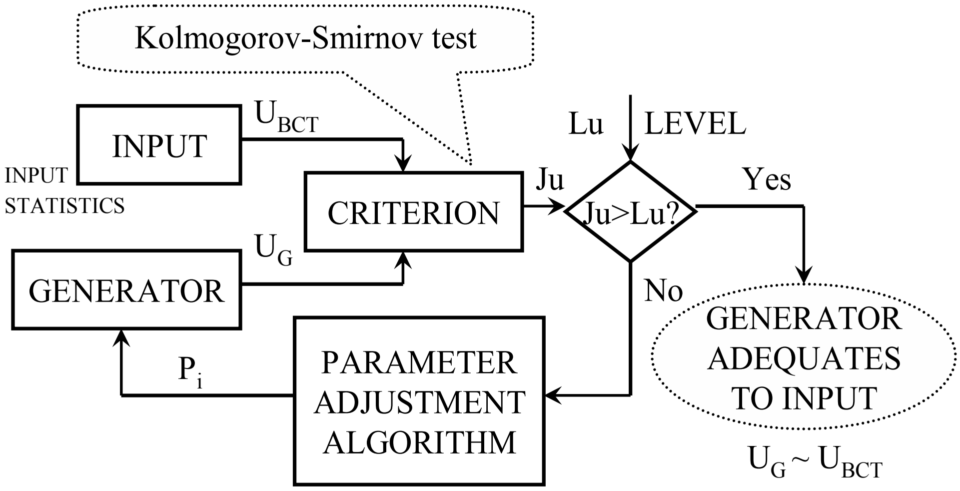


FIGURE 4.2. General methodology for calibration of input generators using Kolmogorov-Smirnov test. Iterational procedure continues until Kolmogorov-Smirnov test identifies statistical identity of the two samples.

Following the logics outlined above, there were created input generators imitating real-life operational statistics. FIGURE 4.3. on the next page portrays comparative results of the modelling: paired case histograms of real data (the panes on the left) and the ones modelled by the generators (panes on the right).

4.2. ADJUSTING INTERNAL PARAMETERS

The second group of variables includes internal parameters of the model describing resource units. This group includes the following subgroups of variables:

- parameters and statistical distributions of each work task duration;
- the number of resources of every type **Nij;**
- working time schedule for every resource unit;
- schedule or algorithm according to which the resource unit is sent to certain locations.

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 shown in FIGURE 4.3.

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

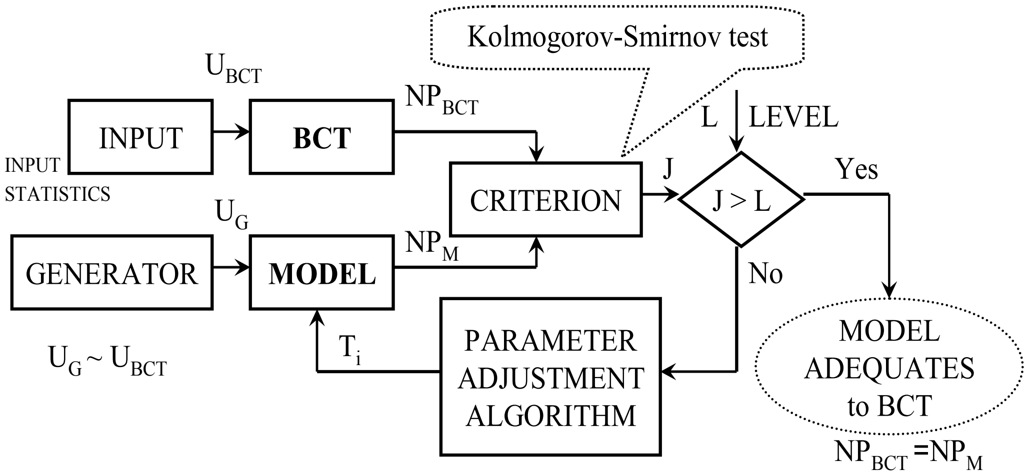


FIGURE 4.3. Logical model of parameter adjustment using Kolmogorov-Smirnov test. Iterational procedure continues until Kolmogorov-Smirnov test identifies statistical identity of the two samples.

Over the course of a separate research there were identified durations of the following basic operation cycles:

- QCrane cycle is Tq = 98 (+/- 10%), sec;
- Truck cycle is Tt = 430 (+/- 10%), sec;
- YCrane cycle is Ty = 110 (+/- 10%), sec;
- Forklift cycle is Tf = 110 (+/- 10%), sec;
- QCrane cycle to move the_restow is= 90 (+/- 10%) *2, sec ;
- QCrane cycle to move the hatch is = 380 (+/- 10%) *2, sec.

The variance of operation durations is determined by a triangular distribution within boundaries +/- 10% of operation cycle values

A comparative model-simulated and observed data output (net productivity) histogram chart is represented in FIGURE 4.4.

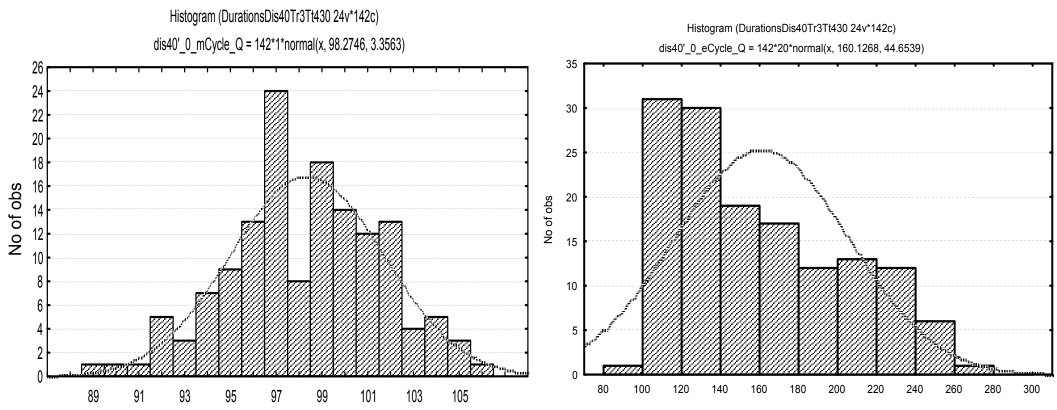


FIGURE 4.4. Quay crane cycle histograms, 40ft import chain. Left-hand side pane illustrates quay crane cycle duration distribution free of delays. The pane on right-hand side shows the histogram of quay crane operational cycle values recorded in simulation modelling. It should be noted that both the form and the boundaries of the distribution are changed.

The comparative analysis of the quay crane and truck histograms shows that the quay crane operational cycle time increases whereas the truck cycles changes insignificantly. This indicates delay-free truck operational regime whereas the quay crane delay time increases dramatically. Consequently, the net productivity might be increased by increasing number of trucks.

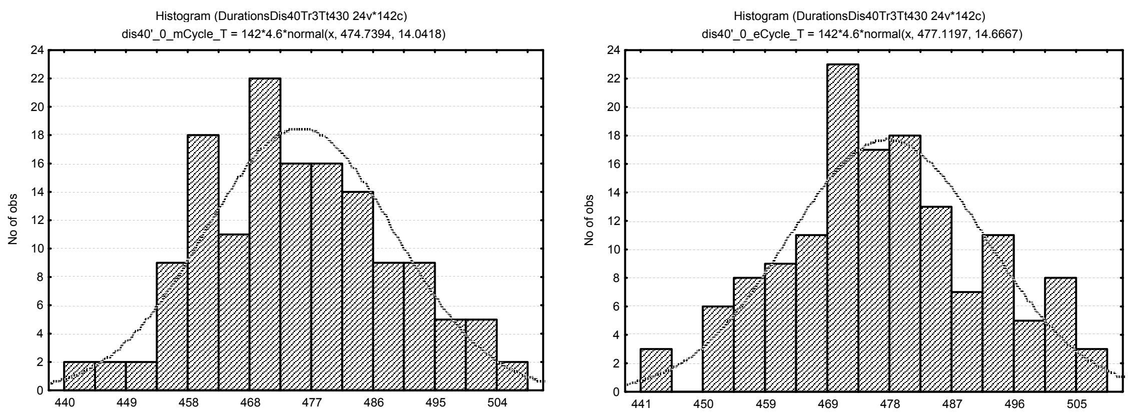


FIGURE 4.5. Truck time cycle, 40ft import chain. Left-hand side pane illustrates truck cycle duration distribution free of delays. The pane on right-hand side shows the histogram of truck operational cycle values recorded in simulation modelling.

The figure above portrays the histogram of operational cycle of the quay crane (left-hand side pane with the mean value of 98.3 +/- 3.4 sec.) and the model monitoring histogram of the same parameter (right-hand side, mean value of 160.1 +/- 44.7 sec.). The reason in discrepancy lies in unproductive idle times of the quay crane waiting for the truck.

When increasing the duration of working, the work cycles of resources become stabilized. The respective statistical characteristics are drastically different from the original histograms of time cycle distributions. Let us consider the effect of dissolution of operation start times as the number of discharged containers is increased, taking as an example discharging of 20ft containers. Reverting to FIGURES 4.4. and 4.5. the left column of histograms illustrates the initial discrepancy of start times of each basic operation. Once the discharge is over, the discrepancy of start times is changed due to idle queuing, which is depicted by the lower diagram.

4.3. MODEL VERIFICATION: OUTPUT ANALYSIS

The Kolmogorov-Smirnov comparison of statistical distributions of observed and model-simulated data proved statistical identity of the two. Please see below comparison of the histograms

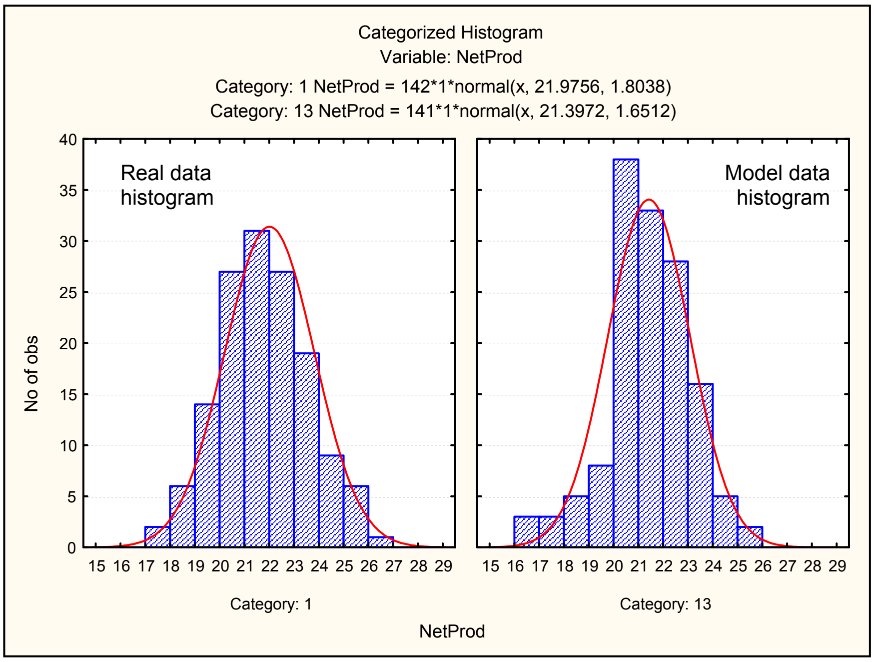


FIGURE 4.6. Comparing modelled and BCT observed output data tested positive by Kolmogorov-Smirnov test

Below one can see the statistic summary table of Kolmogorov-Smirnov test applied to the real and the model data.

TABLE 4.1. Kolmogorov-Smirnov test statistics by inputs. Tests are positive at p>0.10

Variable	Max Neg Differnce	Max Pos Differnce	p-level	Mean Group 1	Mean Group 2	Std.Dev. Group 1	Std.Dev. Group 2
Import 20'	-0.0282	0.0775	p > .10	35.479	33.352	25.651	23.702
Import 40'	-0.0915	0.0141	p > .10	51.732	56.148	29.829	33.006
Hatches	-0.0352	0.0000	p > .10	1.930	2.394	4.578	5.116
Restow	-0.0915	0.0352	p > .10	4.915	5.155	13.162	13.034
Export 20'	-0.1268	0.0141	p > .10	35.542	39.211	31.979	32.292
Export 40'	-0.0915	0.0070	p > .10	48.310	53.380	30.230	29.213
Net Prod	-0.1197	0.0986	p > .10	21.976	21.899	1.804	2.257

As the model output is statistically identical to the observed real data of the BCT terminal, the inputs being also identical, the model can be considered successfully validated representing a statistically reliable simulation (at least, with the given input and respective output values of the BCT terminal).

4.4. CONCLUSIONS

This part of the paper has illustrated application of methodology outlined in CHAPTER 3. MODEL CALIBRATION METHODOLOGY for parameter adjustment and consequent model validation against Baltic Container Terminal observed statistical data.

The chapter has also illustrated application of the same methodology for adjustment of model input generators of container flow against BCT statistical data. Use of validated generated input generating procedure allows application of the model for prediction and ‘what if?’ scenario analysis not limited to container terminal statistics.

Adjustable input generators expand model flexibility and the scope of application. This technology can be applied for analyzing future trends, where statistic data does not reflect current trends. For instance, application of generated input would feature simulation analysis with the current trend of increasing proportion of 40ft containers. Besides that, the approach represented above good potential for visual material well-suited for BCT personnel training.

5. PRACTICAL APPLICATIONS OF SIMULATION MODEL

The chapter below presents an overview of the practical applications of the Baltic Container Terminal simulation model that were performed for the management of BCT. It should be noted that the full scope of application of the model is much broader than presented below due to physical limitations of the given paper, however, these remain for further research.

5.1. PERFORMANCE ANALYSIS: 'WHAT IF?' SCENARIOS

As it was illustrated earlier, due to model statistical reliability, it can be considered as a fair estimate for the operations at BCT. Thus, by using the model with the actual data the management of the terminal can obtain useful information. Put it another way, the '*what if?*' analysis allows training of workgroups, in order to achieve better mutual understanding and co-ordination by playing different scenarios thus increasing overall performance. In analyzing the model the outmost interest for the BCT management is concentrated on two main tasks:

- The first task is to determine the appropriate number of trucks with the given number and location of storage yards. As the costs of using resources are not given, the rational number of trucks should be determined following another logic.
- The second task is obtaining the information from the model for determining the most efficient number of trucks when changing yard locations, which respectively affects the duration of time cycle of each truck.

Let us address to these issues below in some more detail.

5.1.1. NET PRODUCTIVITY AS A FUNCTION OF NUMBER OF TRUCKS

The dependence of net productivity on number of trucks is going to be determined through a set of statistical experiments. The 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**, which earlier was determined as **Tt** = 430sec +/- 10%.

In order to discover the dependence of **NPm(TR)** [where **NPm** denotes **N**et **P**roductivity of the **m**odel, 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. The research results are presented in FIGURE 5.1. below (Merkuryev et al, 2005).

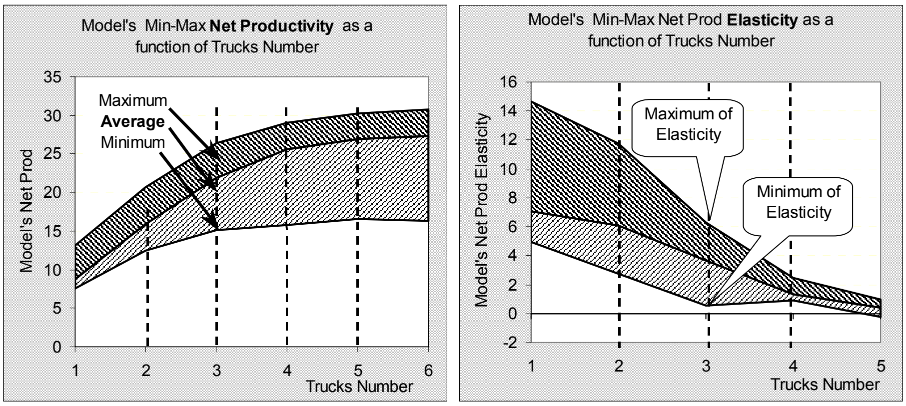


FIGURE 5.1. Dependence of average and upper/lower boundaries of net productivity on the number of trucks (left-hand side pane) and elasticity of net productivity with regard to number of trucks (right-hand side pane)

The first left pane portrays boundary values of **NPm**(TR) and average values of **NPm** for different number of trucks. The first right pane contains elasticity graph **NPm**(TR) which shows that the values of **NPm** are maximal when using 3 trucks. It is possible that the management of BCT followed the same logic when compiling workgroups of 3 trucks.

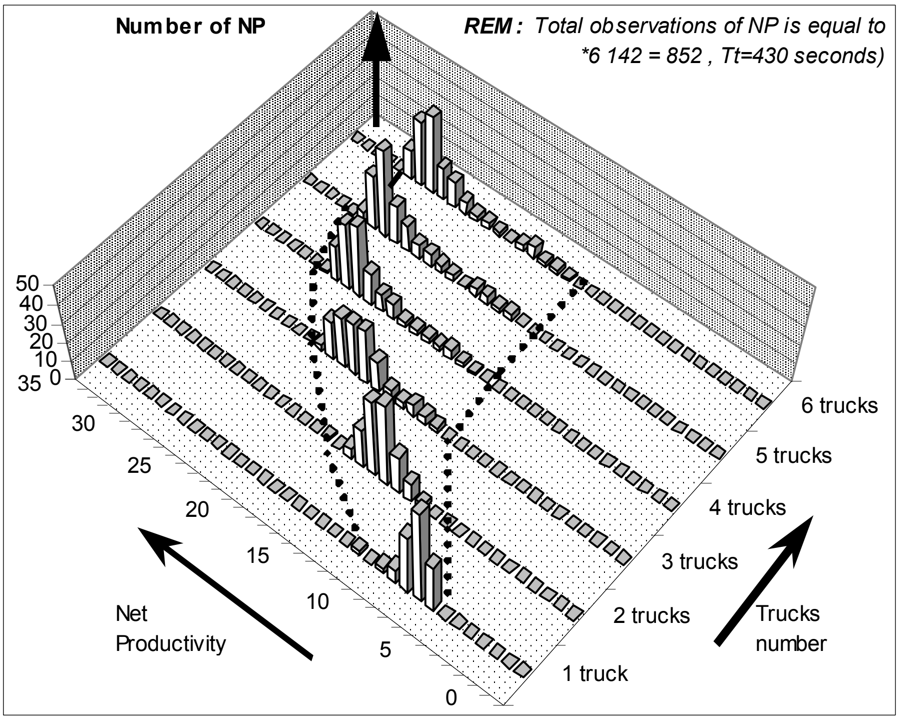


FIGURE 5.2. Histograms of net productivity of the model, obtained with different number of trucks (Z-scale represents number of observations, Y-scale is net productivity (moves/hour), X-scale is the number of trucks)

FIGURE 5.2. portrays histograms of **NPm(TR)** in experimental histograms and gives a rather complete overview of the probabilistic nature of the dependency studied.

5.1.2. NET PRODUCTIVITY AS A FUNCTION OF NUMBER OF TRUCKS AND TRUCK TRAVEL TIME

Obviously, the average truck cycle time implicitly depends on the system of container distribution along the storage yards. Thus, ceteris paribus it is preferable to locate storage yards used more often closer to the berths.

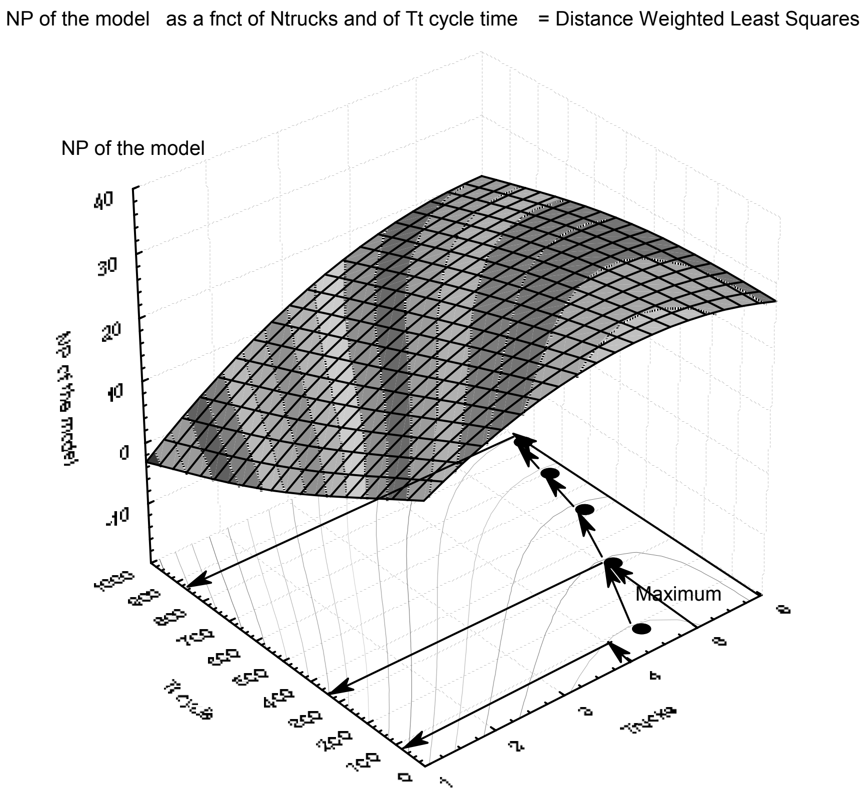


FIGURE 5. 3. Average dependence of average values of net productivity (Z-scale NPm) on the number of trucks **Ntrucks** (X-scale from 1 to 6) and average full truck cycle time **Ttrucks** (Y-scale 0-1000 sec)

Since the yards are normally assigned to shipping lines, their share in import-export structure of the BCT could lead to a change in yard distribution system and their locations. The statistical dependence of the average **NPm** values obtained on the number of trucks **Ntrucks** and average cycle time **Ttrucks** is represented on FIGURE 5.3. as a surface. The figure illustrates dependence of the average value of net productivity on number of trucks and respective work time cycles, whereas the maximum value of **NP** is achieved at **Tt** = 80 seconds, for **Ntrucks** = 5, maximum of **NP** is equal to 330 seconds and for **Ntrucks** = 6, maximum of **NP** is equal to 870 seconds. The **Tt** cycle depicts the duration of delivering cargo by a truck to the yard and its return back (i.e. this duration is proportionate to the distance between the yard and the quay at a constant average speed of the truck).

The state variables allow changing idle time of the quay crane waiting for a truck to arrive, as well as time waiting to be discharged by a forklift or a yard crane, depending on the type of container it carries. FIGURE 5.4. illustrates dependencies of these times on number of trucks and average time of transporting containers during discharge 40ft.

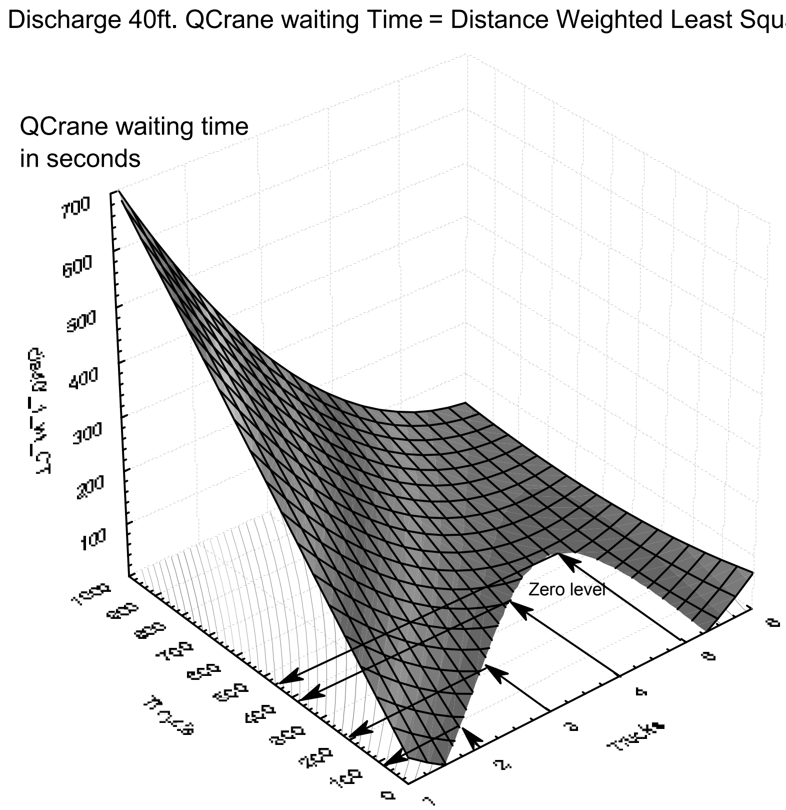


FIGURE 5.4. Dependence of the quay crane average waiting time for the truck when unloading 40ft containers. X- scale is the number of trucks, Y-scale is time cycle of trucks, Z-scale is **Qcrane** waiting time.

From the graph we might see certain optimal number of trucks at predefined travel time (or yard distance) bringing quay crane to zero. This is an important aspect for improving net productivity which to high extent depends on quay crane cycle time. Underlying statistics and initial histograms are available in APPENDIX IV.

5.1.3. DETERMINING OPERATIONAL RESOURCE CYCLES

Another practical challenge brought forward by the management of the BCT for the model was to determine historical quay crane, yard crane, and truck cycle durations **Tq(model)**, **Tt(model)**, **Ty(model)** at some period in the past basing on the respective BCT database data featuring attained net productivity level **NP(n)real** with workgroups of different number of trucks (**Tr**=3, 4, 5).

Technically, the only available information was the net productivity (mean and triangular distribution boundaries for each set of trucks) and number of trucks involved. The originally available information supplied by the BCT management provided the following: **NP(n)real** productivity value for the 40ft container load/discharge chain for the set of 3 trucks available constituted 24 +/-1.5 moves/hour. The productivity of bundle of resources with 4 trucks constituted 30 +/-1.5 moves/hour, and respectively 32 +/-1.5 moves/hour with 5 trucks available. This information is summarized in the table below:

TABLE 5.1. Original input data in order to determine respective resource time cycles **Tq(model)**, **Tt(model)**, and **Ty(model)**

Trucks in brigade	3	4	5
NP	24	30	32
ΔNP	+/-1.5	+/-1.5	+/-1.5

Basing on the information available the At the first stage the identification of the three cycles **Tq(model)**, **Tt(model)**, **Ty(model)** there was applied data of real BCT productivity with the given set of resources (one quay crane, one yard crane, with three, four, and five trucks respectively). Thus, one of the reasonable options of analyzing model adequacy would be minimizing the least squares deviation of the simulation model-yielded from the observed data with different number of trucks available. The logics behind the approach is depicted in FIGURE 5.5. below.

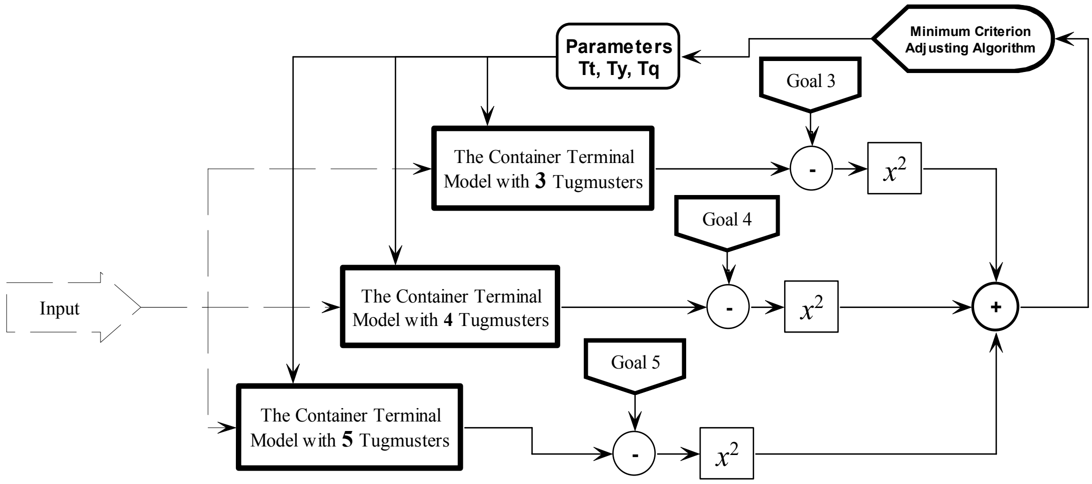


FIGURE 5.5. Graphical representation of logics of resource cycle parameter estimation (Tq, Tt, Ty).

The elapsed truck cycle duration would then equal

Tttot = Tct&q + Tcqt + Tct + Tct&y + Tcty + Treturn (5.1)

where:

Tct&q – truck waiting for the quay crane to pick the container off the truck.
Tcqt – container loading time
Tct – time necessary for the truck to carry the container to the yard where it is supposed to be stored
Tct&y – the waiting time of the yard crane for the truck carrying the container
Tcty – discharging container from the truck by the yard crane
Treturn – empty truck returning to pick another container

It should be pointed out that the period of the truck waiting for the quay crane to load the container onboard **Tct&q** as well as **Tct&y**, the waiting time of the yard crane for the truck carrying the container, are non-stationary values as they are highly dependent on the number of the trucks. These values are not pre-determined, they are obtained during the modelling process since depend on involved resource co-ordination.

With an acceptable degree of precision it is possible to estimate and introduce the following values into the model: **Tcqt**, **Tcty**, **Tct**, and **Treturn**.

With an acceptable degree of precision it is possible to estimate and introduce the following values into the model: **Tcqt**, **Tcty**, **Tct**, and **Treturn**.

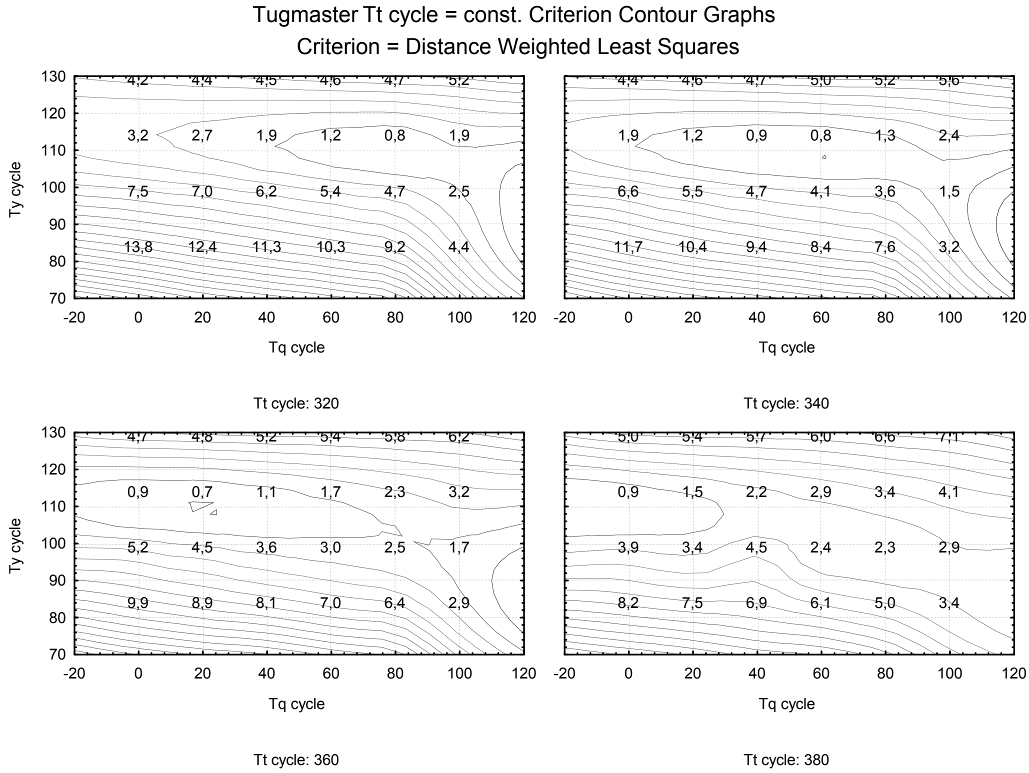


FIGURE 5.6. Adequacy criterion contour graph, where Tt(model) truck cycles are equal to 320, 340, 360, and 380 secs. The criterion is represented as a function of two variables, X-scale: Tq(model), Y-scale Ty(model). As Tt(model) increases, the criterion minimum shifts outwards left from Tq(model)=80 to Tq(model)=20, with Ty(model) held constant at the level of 110 seconds.

Whereas it might be noted that **Treturn** =**Tct** × **K**, where **K**<1. Average values of **Tcqt** and **Tcty** as well as their respective statistical distributions are determined by the technological processes of loading and discharging by the quay crane and the yard crane. Therefore, the actual cycle duration at any point of time cannot be determined precisely, but can be modified manually by adjusting the **Tct** value.

In analogy to the to the truck cycle above, other resource cycles are determined in a similar manner. It should be also noted that the resource cycle durations are correlated not only through the tightly distributed load/discharge micro-operations (e.g., **Tcqt**, **Tcty**) but are also affected by the highly dispersed time losses in queues. Since in practice the durations of elementary operations are not strictly determined, the time of every independent elementary operation was modelled by a separate uniformly distributed random generator whose boundaries are proposed by the BCT personnel.

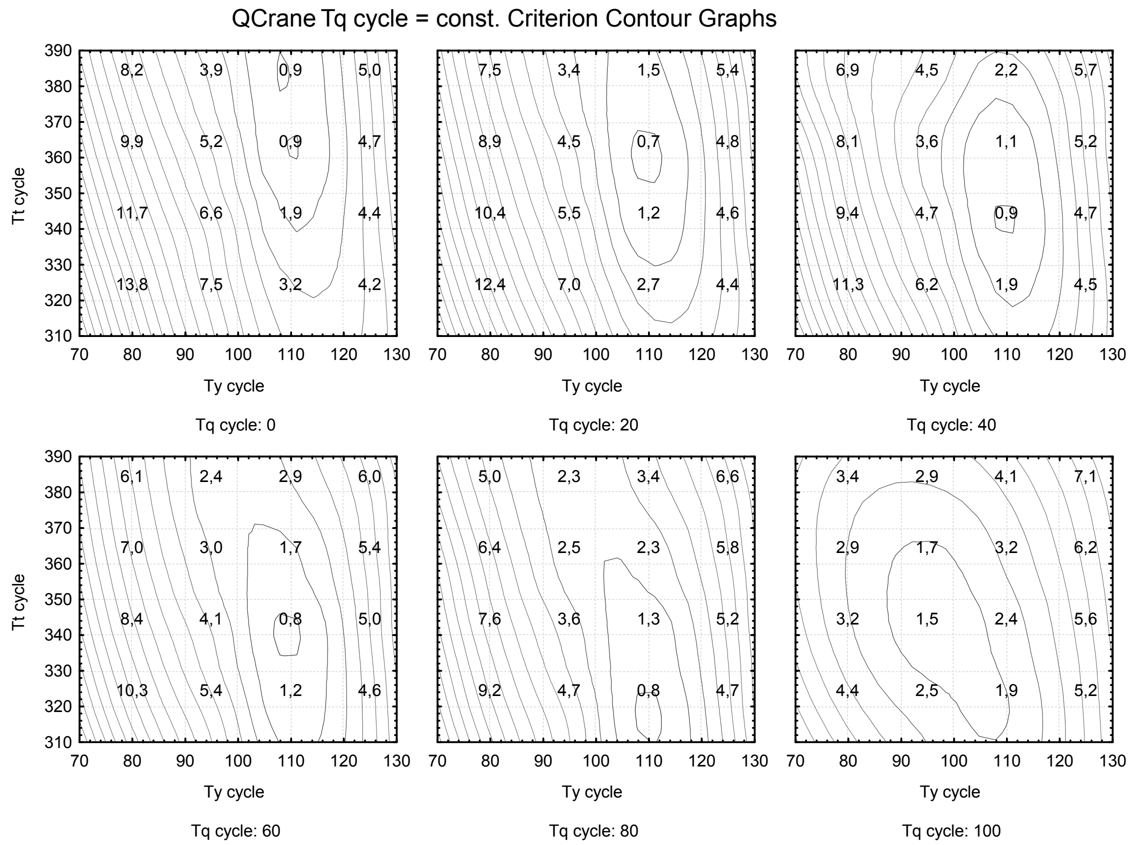


FIGURE 5.7. Contour graph of efficiency criterion, where Tq(model) quay crane's cycles are equal to 0, 20, 40, 60, 80, and 100 seconds. The criterion also represents a function of two variables, Ty(model) plotted on x-scale and Tt(model) on the y-scale. As Tq(model) increases, the criterion minimum shifts downards parralel to y-scale from Tt(model)=380 to Tt(model)=320, with Ty(model) held constant at the level of 110 seconds.

Thus, in order to obtain an average productivity value as a model output, e.g. **NP(3)$_{\text{model}}$**, the model takes in the respective number of trucks (in this case: three) and for each set of resource cycle values **Tq(model)**, **Tt(model)**, **Ty(model)** it simulates discharge of 150 containers at a run (the average number of containers per vessel), basing on which the average productivity value is calculated. In the same manner the average **NP(n)$_{\text{model}}$** productivity value is calculated for all the other input values. So, over the discrete subset of the values of four arguments **n** trucks, **Tq(model)**, **Tt(model)**, **Ty(model)** the value of productivity function **NP(x, y, z, u)** is determined. The task lies in finding the values **y**, **z**, **u** under which the value of the criterion will be minimal.

$$\textbf{Crit(x, y, z, u)} = \text{sqrt}\,[(24 - NP(3, y, z, u))^2 + (30 - NP(4, y, z, u))^2 + (32 - NP(5, y, z, u))^2] \quad (5.2.)$$

where **y** = **Tq**(model), **z = Tt**(model), **u = Ty**(model).

The methodology of the above criterion yielded rather different results, which indicated either existence of local minima or a trough (a continuous set of minima) on the criterion surface, indicating flaws in operation efficiency. A detailed analysis of criterion surface is represented in FIGURE 5.6., 5.7., and 5.8.

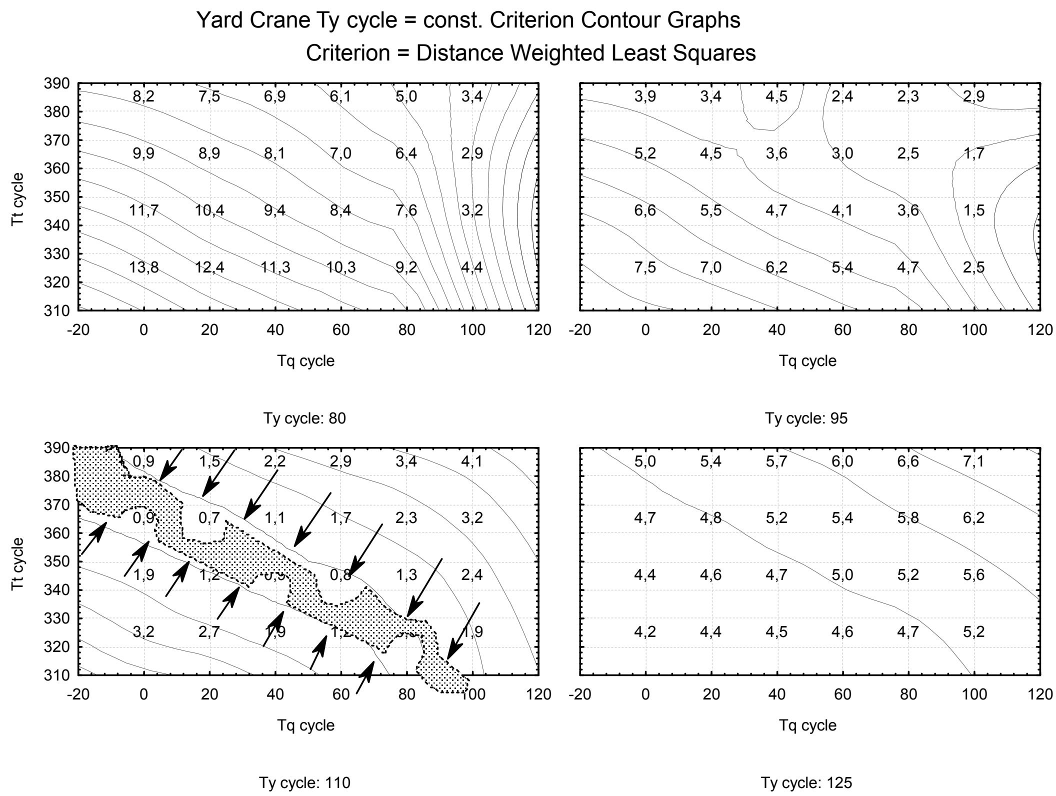


FIGURE 5.8. Criterion contour graph, where Ty(model) yard crane cycles are equal to 80, 95, 110, and 125 seconds. Similarly to previous casees, the criterion is represented as a 2D function of two variables: Tq(model) plotted on x-scale and Tt(model) on y-scale. As Ty(model) increases, the criterion minimum appears at Y = Ty(model) = 110 seconds. The criterion is no local minimum but a trough and is approximated by Tt(model) = 380 – ¾ * Tq(model), Ty(model) = 110 sec.

5.1.3.1. Sensitivity analysis

Now our task lies in analyzing the obtained values of **y**, **z**, and **u** by bringing the criterion to its minimum and testing its sensitivity for variations in input productivity data

NP(3)real = 24 +/-1.5, **NP(4)real** = 30 +/-1.5, **NP(5)real** =32 +/-1.5.

Thus, there should be sought a dependence of the average criterion values on the randomly distributed parameters **y**, **z**, **u**:

$$\mathbf{AverCrit}(\mathbf{x}, \mathbf{y}, \mathbf{z}, \mathbf{u})] = \mathbf{Average}\{\text{sqrt}\,[(24 + \text{delta(i)} - \mathbf{NP(3, y, z, u)})^2 +$$

$$+ (30 + \text{delta(i)} - \mathbf{NP(4, y, z, u)})^2 + (32 + \text{delta(i)} - \mathbf{NP(5, y, z, u)})^2]\} \qquad (5.3.)$$

where **y** = **Tq(model)**, **z = Tt(model)**, **u = Ty(model)**,

delta(1) = random value with uniform random distribution [-1, +1]

delta(2) = random value with uniform random distribution [-2, +2]

delta(3) = random value with uniform random distribution [-3, +3]

As it follows from FIGURE 5.9., the efficiency criterion nature remains unchanged, whereas only the criterion level is being affected. Thus, it might be concluded that the obtained values delivering the criterion minima remain stable to variations in the productivity **NP(i)real**.

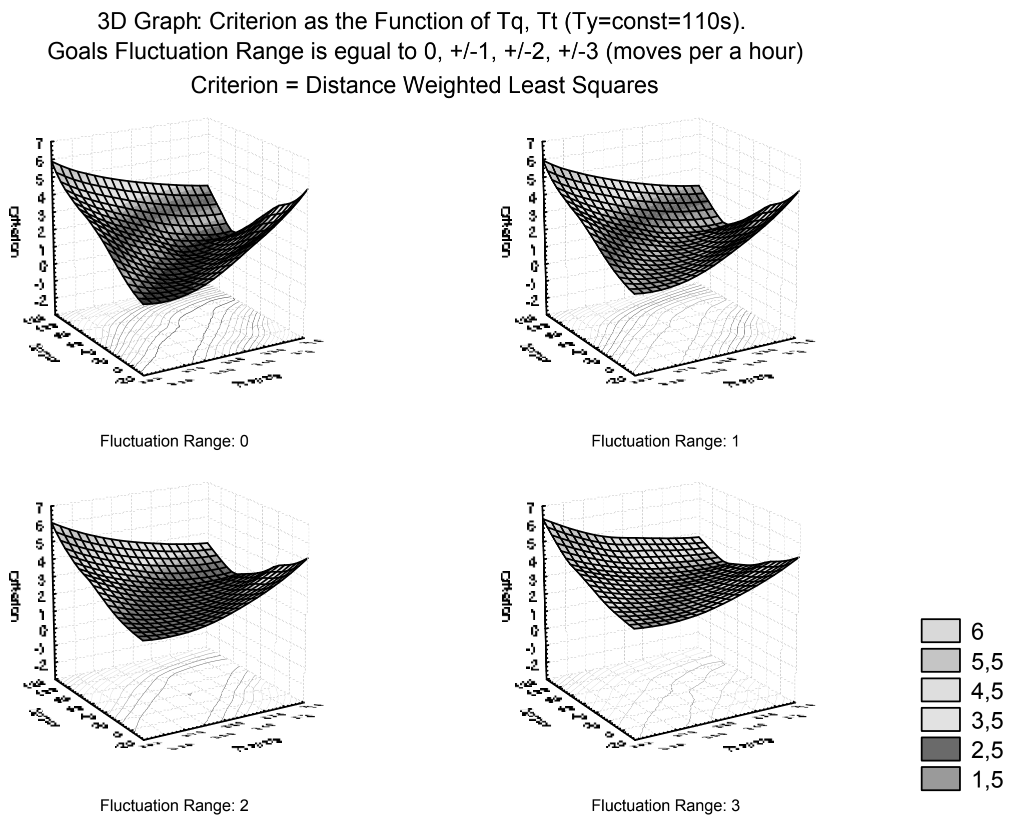


FIGURE 5.9. x-scale: **Tt(model)**, y-scale: **Tq(model)**. The graph illustrates the criterion surface transformation with different values of *delta* [**NP(3)real** = 24 +/- 1, +/- 2, +/- 3, **NP(4)real** = 30 +/- 1, +/- 2, +/- 3, **NP(5)real** =32

5.2. 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 (referred to as **QC1**, **QC2**, and **QC3**), three yard cranes (**Y1**, **Y2**, and **Y3**), and three available truck workgroups of three to six trucks (**Tr_3**, **Tr_4**, **Tr_5**, and **Tr_6**) a logistics 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. The scope of possible combinations of resources is depicted in FIGURE 5.10.

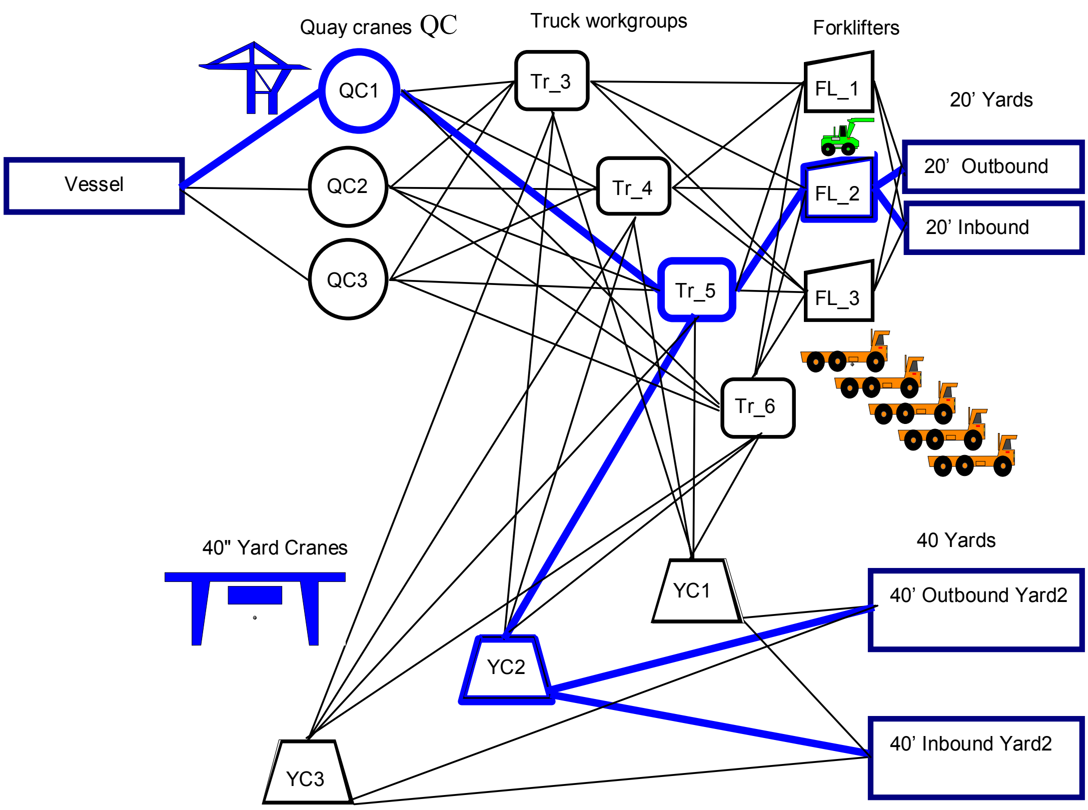


FIGURE 5.10. Scope of possible combinations of resources.

The task would be a simple one if we neglected a set of circumstances. Thus, let us consider a supplier that normally provides the productivity data (or average work cycle duration) for its equipment. This figure would be a good estimate if the equipment is supposed to work isolated; in the case in focus, however, the system factor comes into play. Since any resource unit works in logistics chain with other resources involved, there occur inevitable random delays at different phases of elementary technological operations.

The only obvious piece of information we might have about this chain is that the upper boundary of productivity of the logistics chain cannot exceed that of the chain's slowest resource. However, the only way to find out approximate real productivity is to use an adequate model of the processes under consideration. Using such a model one could simulate the real productivity and its statistical distribution for each combination of resources close to the observed data. Once we succeed in this task, we can use the modelled data as the best closest estimate to the real data for future analysis (Merkuryev et al., 2004).

5.2.1. RESEARCH METHODOLOGY

The economic efficiency of a chosen combination of resources can be calculated as the net difference between the income per hour of operation (net of average fixed costs) at given productivity and costs as per TABLE 5.2. Now in order to obtain numerical results we have to us each combination of resources as input data to the model and make model runs (142 simulated vessels) to gather the necessary statistics.

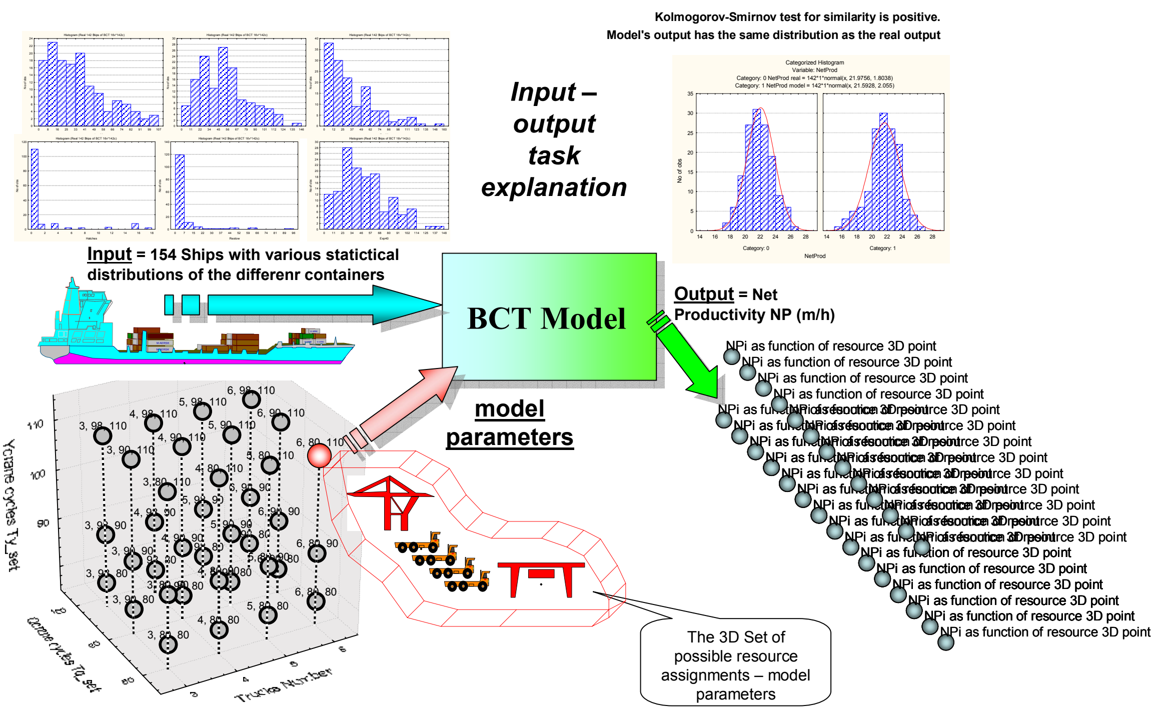


FIGURE 5.11. Illustration of methodology of analysis of resource economic efficiency

The next step is to use the productivity data **NPi** for each set of resources combined with operational costs of respective resources to obtain the financial efficiency results. The total costs of the pool of resources is subtracted from the terminal operational income per hour at given productivity level. The residual sum is our efficiency criterion subject to maximization. By following this procedure for each possible set of resources we will obtain a set of efficiency criteria values out of which we will be able to choose an optimal solution (Merkuryev et al., 2005).

The methodology of obtaining net productivity data through simulation experiments for each combination of resources is explained in FIGURE 5.11. above.

The inputs of the model are observed probability distributions of the containers on incoming vessels. The parameters of the model for each analysis run (one run is based on statistics of 142 vessels) are respective combinations of resources consisting of a quay crane of one of the three available options, truck workgroup of three to six trucks, and one of the three available yard cranes. The output data are productivity data for one of the 142 vessels per analysis run, served by a determined set of resources.

5.2.2. DEFINING MATHEMATICAL PROBLEM

Let us start by considering all the possible combinations of available resources in the *quay crane-truck-yard crane* (for 40ft chain) or *quay crane-truck-forklift* for 20ft container chain. FIGURE 5.10. above represents the variety of possible resource interaction which should be considered in order to achieve the aim of the research. Every path of this map of interactions corresponds to a possible combination of resources and thus defines the set of solutions out of which one would be optimal.

The set of relationships between terminal resources to be considered when addressing the problem studied is illustrated in FIGURE 5.10.

The task in focus considers the following pool of resources:

- Three quay cranes, **QC1**, **QC2**, and **QC3** having different initial cost **Pq1**, **Pq2**, and **Pq3**, and nominal maximal productivity of **Nq1**, **Nq2**, and **Nq3** (which are the average values of the work cycle **Tq1_set**, **Tq2_set**, **Tq3_set**) and complete depreciation duration of **Lq1**, **Lq2**, **Lq3**.
- Four sets of identical tractors **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 **Pt1**, **Pt2**, **Pt3**, **Pt4**,

average full work cycle time **Tt1_set** = **Tt2_set** = **Tt3_set** = **Tt4_set** = 430 seconds +/- 10% and identical service duration **Lt1** = **Lt2** = **Lt3** = **Lt4**.

– Three types of yard cranes **YC1**, **YC2**, and **YC3** having different initial cost **Py1**, **Py2**, and **Py3**, nominal maximal productivity **Ny1**, **Ny2**, and **Ny3** (average cycle duration **Ty1_set**, **Ty2_set**, **Ty3_set**) and expected service durations of **Ly1**, **Ly2**, **Ly3**.

The initial data are wrapped up in a tabular form in TABLE 5.2. below.

TABLE 5.2. Technical characteristics and costs of resources

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

Finally, 36 possible combinations of resource allocation are represented in a 3D graph below, where the X-scale represents the number of trucks in the tug-master workgroup, Y-scale depicts the expected work cycles of the different types of quay cranes, and vertical Z-scale portrays resource operational cycle durations in seconds of different types of yard cranes.

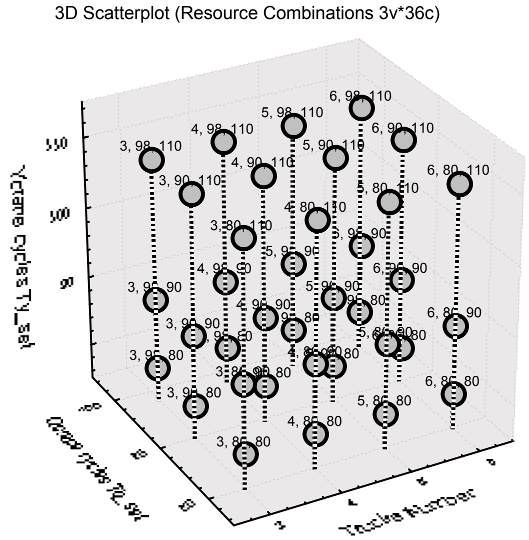


FIGURE. 5.12. 3D interpretation of feasible combinations of resources.

In order to find the efficient solution(s) on the determined set of possible combinations of resources it is necessary to define the function and criteria of efficiency for each model run. In other words, we have to create an algorithm for calculation of efficiency basing on model run results with every set of resources. As per management of the terminal, the main efficiency criterion is the net financial income per working hour for each set of resources.

TABLE 5.3. below contains expenses associated with exploitation of a single resource unit (quay and yard crane, and team of tugmasters) on transportation of a 40ft container along the logistics chain 'vessel – import yard' and the reverse chain 'export yard – vessel'

TABLE 5.3. Example of resource units cost breakdown by resource type.

Net productivity NP, moves/ hour	Depreciation expense, EUR/h	Personnel expense, EUR/h	Fuel and electricity, EUR/h	Repair and maintenance, EUR/h	Total expense, EUR/h
1	20	3.125	0.9	0.2	**23.8**
2	20	3.125	1.8	0.4	**24.9**
...	...	...	...	...	**...**

The next section introduces the mathematical model of the task.

5.2.3. MATHEMATICAL MODEL AND OPTIMIZATION

Let us define the following notations:

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

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

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

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

SENqc – electricity expense of quay crane per operational hour, **QC**, i=1,2,3.

SENyc – electricity expense of yard crane per operational hour **YC**, i=1,2,3.

SENtr – fuel expense of truck workgroup per operational hour **Tr**, 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) **QCi**, 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 expense 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 expense 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 expense 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 **SSS*ijk*(NP)** per operational hour for each type of resource ***i***(i=1,2,3.)***,*** ***j***(j=1,2,3.)***,*** ***k***(i=1,2,3,4.) non-linearly depend on net productivity **NP**(moves per hour) of the whole logistics chain:

SSS*ijk*(NP) = STqc*i* + SSqc*i* + SENqc*i*(NP) + SRMqc*i*(NP) + SRTqc*j*(NP) + STyc*j* + SSyc*j* + SENyc*j*(NP) + SRMyc*j*(NP) + SRTyc*j*(NP) + STtr*k* + SStr*k* + SENtr*k*(NP) + SRMtr*k*(NP) + SRTtr*k*(NP) (5.4.)

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:

$$\mathbf{CRITERION}_{\,ijk}\,\mathbf{(NP) = P(NP) - SSS}\boldsymbol{ijk}\mathbf{(NP) - Sother} \qquad (5.5.)$$

Now the formal task is finding a set of resources which would bring the criterion (5.5.) to a maximum value, namely

$$\underset{i=1,2,3;\ j=1,2,3;\ k=1,2,3,4}{\boldsymbol{Maximum}}\ \mathbf{[\ CRITERION}_{\,ijk}\,\mathbf{(NP)\ ] = Cmax}_{\,u,v,w} \qquad (5.6.)$$

where **u**, **v**, **w** – are specific indices of resources bringing the criterion (5.5.) to a maximum. The task in itself is not the search of the maximum as such, but rather finding the set of resources bringing to it.

5.2.4. VALIDATION OF MODEL-SIMULATED DATA

In accordance with the research methodology outlined above, there were carried out 3×4×3 =36 BCT simulation model experiment runs for different combinations of resources. Each experiment series returned 142 net productivity values **Niw** (**w**=1,2,...,142) through modelling 142 vessels per each model run. The number of different types of containers was modelled by random number generators adjusted in accordance with statistical distributions of real-life observed data.

FIGURE 5.13. below illustrates histograms of real-life observed data (left hand-side pane) and model-simulated output data (right-hand side pane).

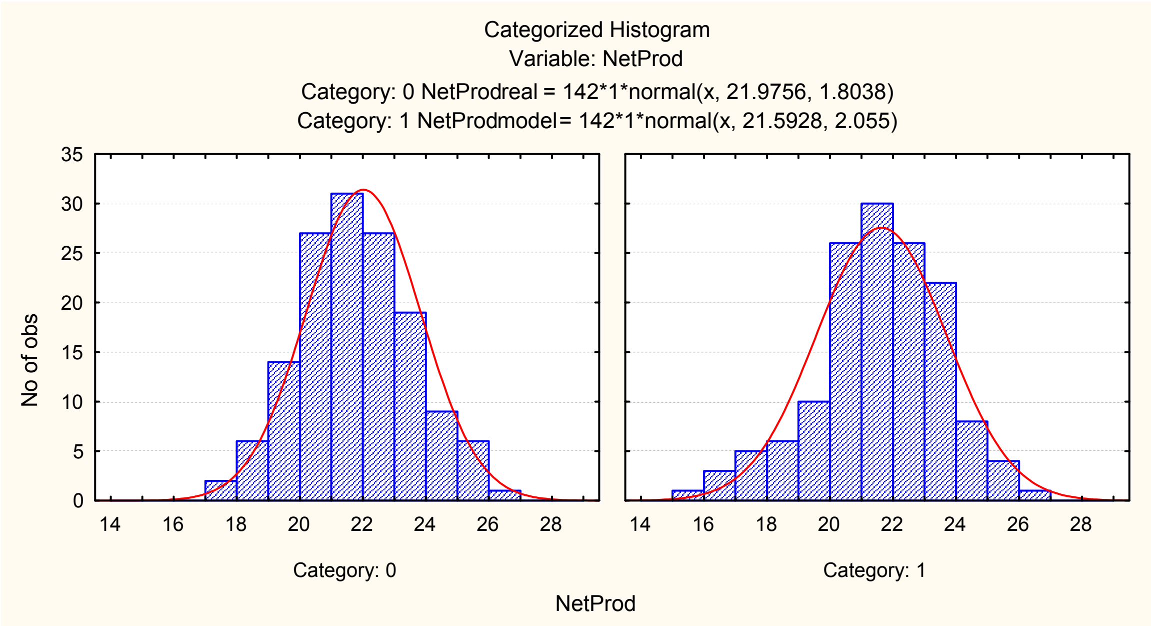
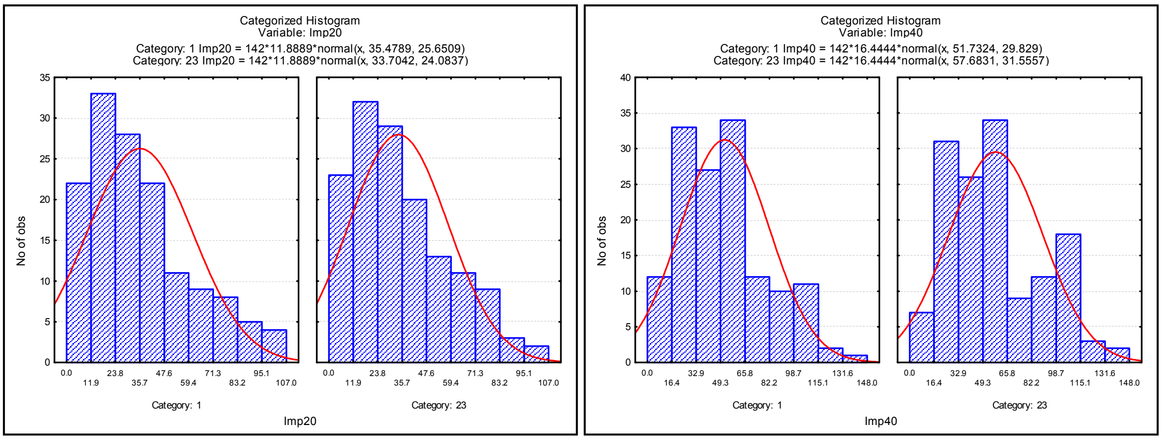


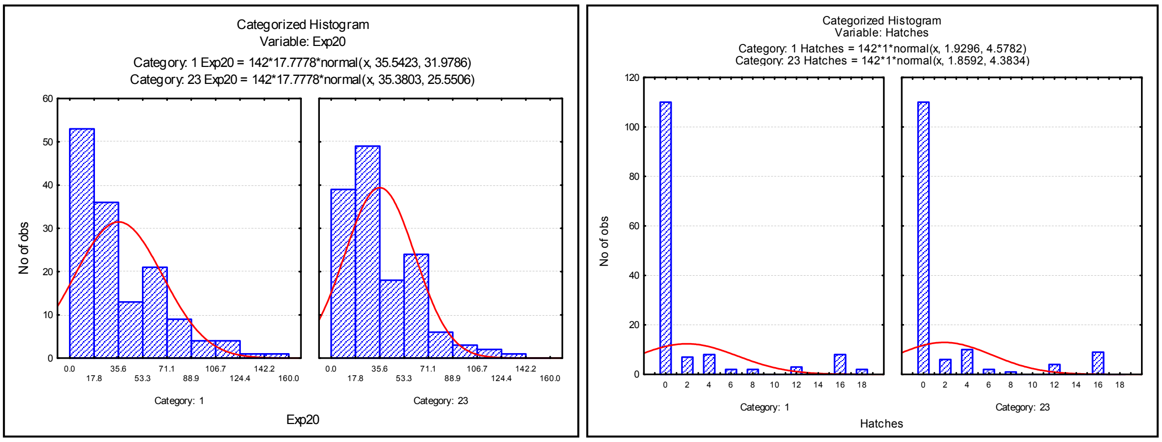
FIGURE 5.13. Distribution histograms of observed productivity data (left pane, sample of 142 observations) and modelled output (right-hand side pane, sample of 142 observations).

The next figure (see FIGURE 5.14.) shows comparison of observed and modelled statistical distribution histograms of net productivity values.

a)



b)



c)

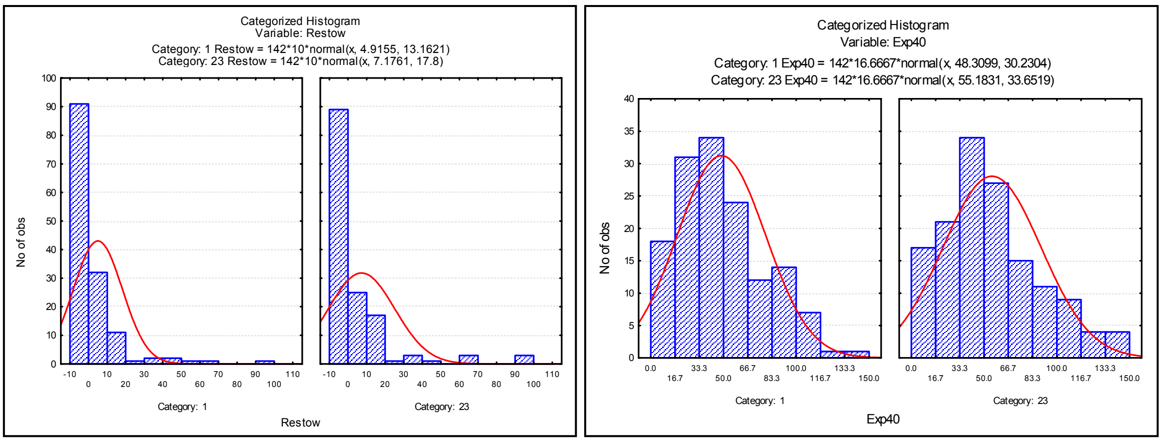


FIGURE 5.14. Paired comparison of distribution histograms of observed and respective model-simulated data a) 20ft import containers (left-hand side pane) and 40ft import (right-hand side pane), b) 20ft export containers (left-hand side pane) and hatch covers (right -hand side pane, and c). 40ft export containers (left-hand side pane) and restow containers (right-hand side pane).

The statistical reliability of the model is confirmed by the Kolmogorov-Smirnov test which identified no significant differences between the observed and modelled productivity data with the same pool of resources.

It is necessary to pay due attention to the following factor. In reality, no resource is employed at a fixed productivity level. For obtaining realistic modelling results the nominal values of resources cycles were varying in a random manner with +/-10% deviation of a preset average value. Thus, the nominal productivity values served as inputs of mathematical distributions of evenly distributed random values of resource cycles. With such an approach the a separate solution sensitivity analysis is no more necessary, since histogram analysis yields information both on solution sensitivity and its sensitivity to variations in parameters of resources.

The resource cycles observed in the model are not evenly distributed random values. Time in queue is a random variable described by a distribution which is neither even nor normal. Besides, the time spent in queuing in our research hardly appears neglectable. The queuing time drastically affects model resource cycles. Leaving a more lengthy discussion aside, let us note that an analytical probability-based research of the whole logistics chain technically represents quite a complicated and challenging task calling for sophisticated analysis.

5.2.5. ANALYZING RESOURCE ECONOMIC EFFICIENCY AND FINDING OPTIMAL SOLUTION

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 5.4.) and the net productivity output data, costs, and the criterion of economic efficiency as per modelled results.

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 3×4×3=36 combinations times 142 vessels (where for each the net productivity was calculated).

Thus, the number of total observations made up 36 (resource combinations) × 142 (vessels modelled=5’112 rows of values and several dozens of parameters (columns).

TABLE 5.4. 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	**29.0**	54.6	90.9	50.2	**94.4**
6	430	90	80	84	85	**36.7**	63.1	162.3	59.6	**81.6**
5	430	110	90	91	109	**28.5**	52.5	112.0	49.6	**70.5**
3	430	90	80	110	91	**25.5**	50.8	63.9	47.3	**93.4**
4	430	80	80	94	80	**28.0**	53.5	88.5	51.1	**86.7**
3	430	80	90	89	79	**22.1**	45.5	56.5	44.6	**74.8**
4	430	110	90	97	114	**27.4**	51.3	87.2	48.5	**87.2**
5	430	110	80	99	106	**27.0**	52.5	108.0	48.0	**62.0**
6	430	110	98	98	111	**26.9**	49.7	128.9	47.8	**42.1**
5	430	90	80	81	89	**34.6**	60.8	129.3	57.3	**98.4**
3	430	90	98	107	90	**23.6**	46.2	59.1	45.2	**85.7**

The examples of dependencies (as per TABLE 5.4.), as well as the criterion (3.2) behaviour at different net productivity (**NP**) levels is represented in FIGURE 5.15.

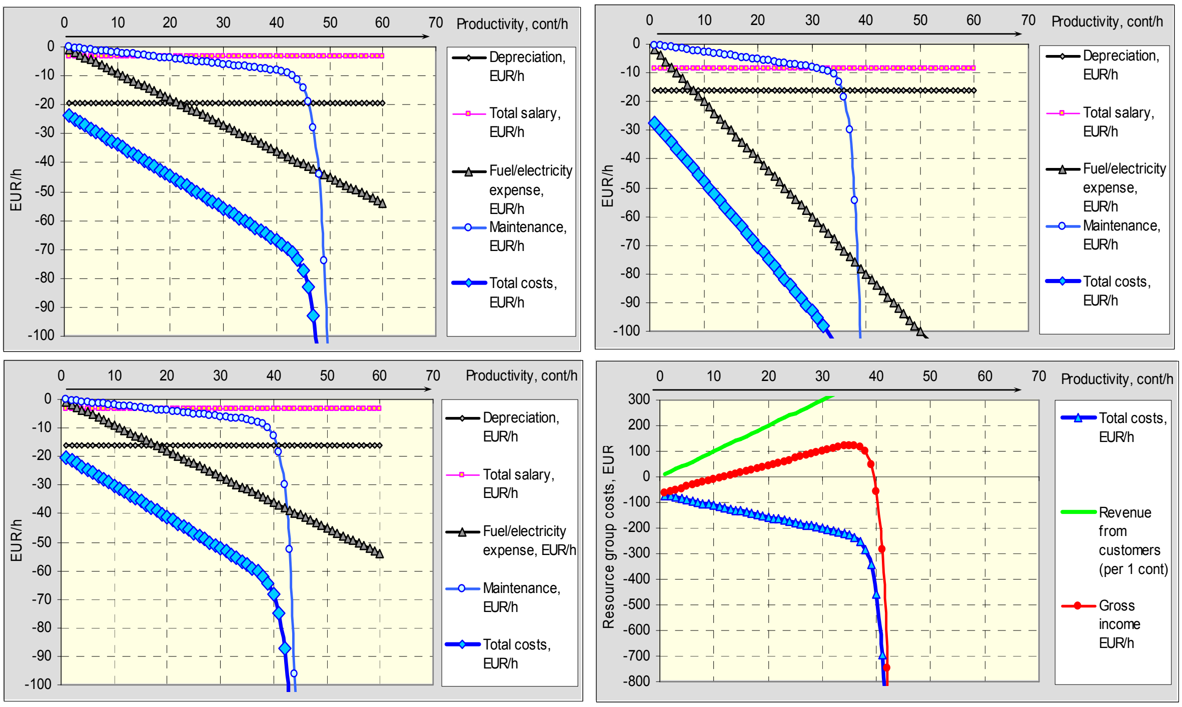


FIGURE 5.15. Example of costs analysis for separate resource units and the set of resources **SSS122** (QC1+4Trucks+YC2). The maximum efficiency is reached at NP=37

The 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. 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 5.15. the sum of these two components illustrate a drop in economic efficiency at overload performance apparently caused by increased wear and tear.

FIGURE 5.16. illustrates the impact of number of trucks involved in the logistic chain on the net productivity NP. From the figure above it follows that at the equal level of productivity the value of the criterion is higher for smaller number of trucks. However, a non-linear dependence of the repair and maintenance costs does not allow extensive exploitation of 3 trucks, and 4 trucks becomes the new optimum. This outcome, however, calls for a more thorough examination.

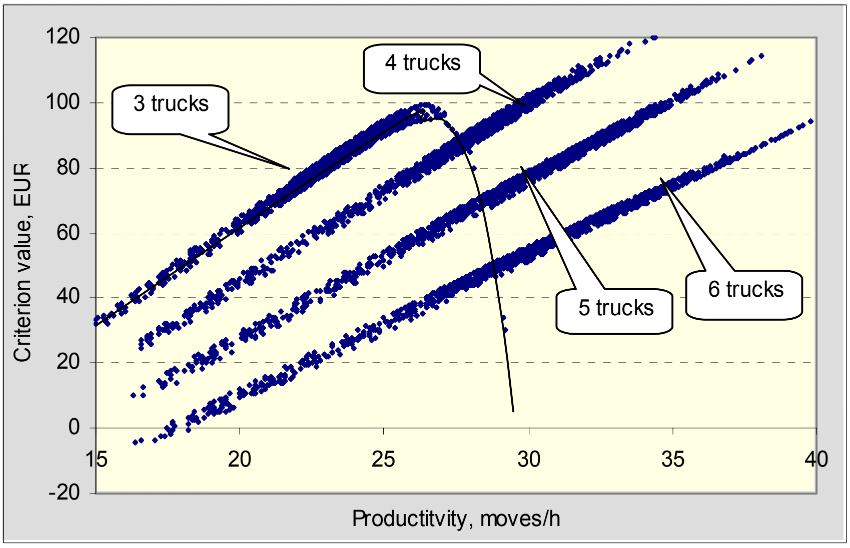


FIGURE. 5.16. Dependence of economic efficiency on the net productivity NP.

The table below presents mathematical expectations of efficiency criterion values for different combinations of resources.

TABLE 5.6. Mathematical expectations of economic efficiency (EUR) found for workgroups of 3, 4, 5, and 6 trucks. Optimal values appear highlighted.

		YC1	YC2	YC3
a) 3 trucks				
	Tq_set \ Ty_set	***80***	***90***	***110***
QC1	***80***	77	78	76
QC2	***90***	78	78	77
QC3	***98***	78	78	**83**
b) 4 trucks				
	Tq_set \ Ty_set	***80***	***90***	***110***
QC1	***80***	**88**	85	77
QC2	***90***	87	86	78
QC3	***98***	85	85	87
c) 5 trucks				
	Tq_set \ Ty_set	***80***	***90***	***110***
QC1	***80***	**82**	78	62
QC2	***90***	80	78	64
QC3	***98***	75	75	64
d) 6 trucks				
	Tq_set \ Ty_set	***80***	***90***	***110***
QC1	***80***	**67**	59	43
QC2	***90***	60	59	44
QC3	***98***	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**.

Taking into consideration the probability-based nature of the simulation, this solution calls for a more thorough analysis.

The expected values for the criteria in tables above have been received from samples of 142 observation in each thus representing random values distributed according to some distribution law. For example, with a brigade of four trucks crane combinations **QC2** + **YC1** and **QC3** + **YC3** result in the same value of criterion equal to EUR 87, which differs from the optimal value of EUR 88 by less than one percent. Thus, at least three combinations of resources might be the optimum solution and to make a final choice we have to take a closer look at the results.

Among the combinations studied the highest impact on economic efficiency of the pool of resources has the number truck vehicles in the load-discharge chain considered in more detail in FIGURE 5.17.

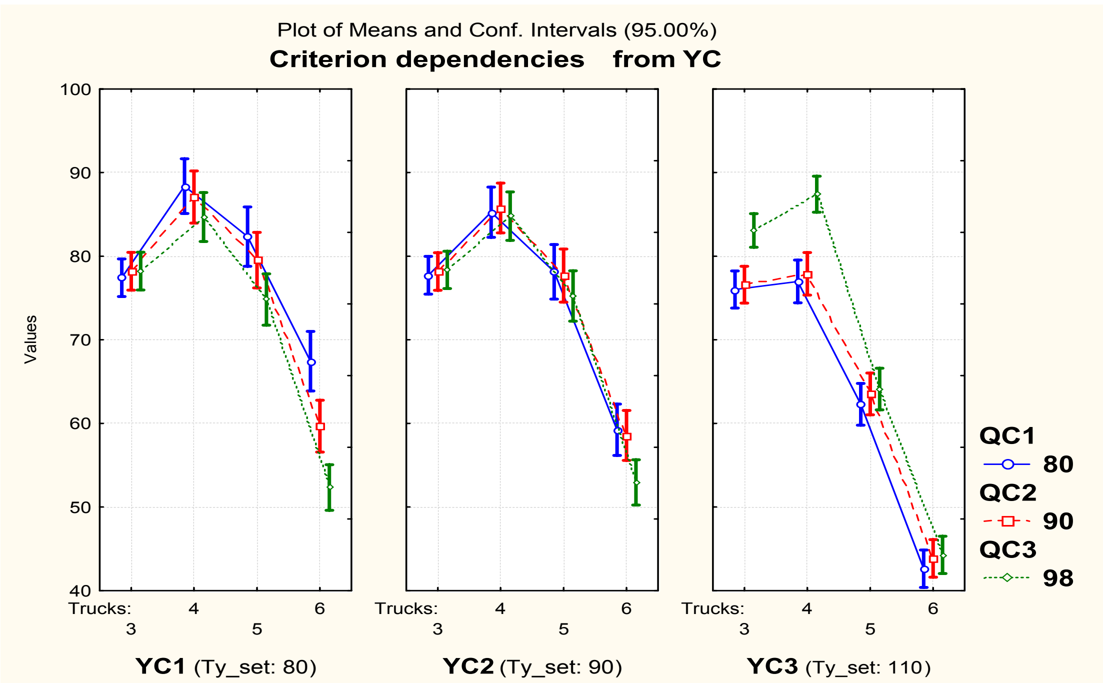


FIGURE 5.17. Analysis data of average values of economic efficiency and respective 95% significance intervals for the considered combinations of resources.

FIGURE 5.17. illustrates the dependencies and respective 95% confidence intervals for different combinations of resources. The x-scale for each pane marks the number of trucks in each brigade, y-scale portrays the level of economic efficiency. The panes (from left to right) correspond to yard cranes **YC1**, **YC2**, and **YC3** and colored line – to levels of economic efficiency reached with **QC1**, **QC2**, and **QC3** respectively. From the graph it might be inferred that the preferable optimum is reached with workgroup of four trucks; however the combinations of quay and yard crane remains to be researched.

As it follows from FIGURE 5.17. above, seven combinations with average value of economic efficiency criterion of above EUR 80 call for a more detailed analysis since their uncertainty intervals overlap, so bringing uncertainty as to combination preference. Let us first consider the possible combinations of resources yielding economic efficiency values close enough to maximum. Let us start by sorting the data of economic efficiency values from the tables above in descending order. FIGURE 5.18. below represents the result of such sorting.

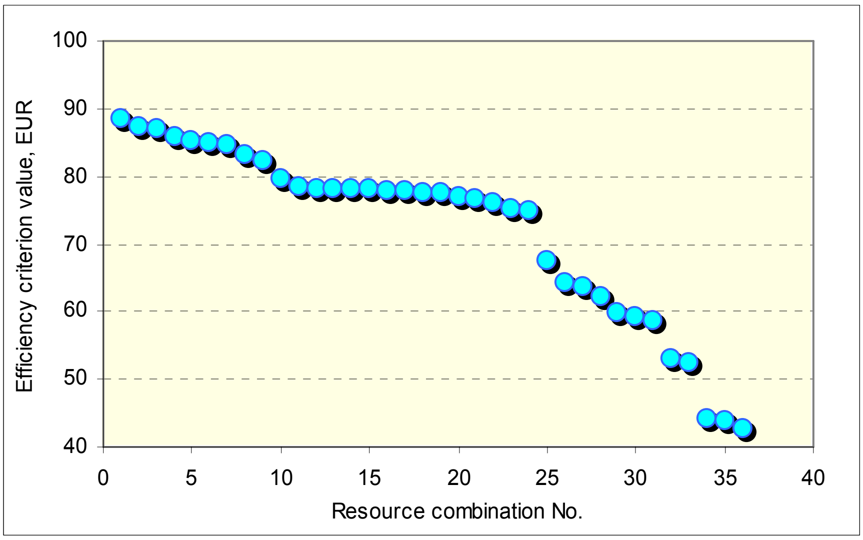


FIGURE 5.18. Plot of average values of economic efficiency arranged in descending order

It follows from the graph that the first nine combinations yield economic efficiency clearly higher than the rest of the data; these outstanding combinations are wrapped up in a tabular form in TABLE 5.7. below.

TABLE 5.7. Nine combinations of resources attaining highest economic efficiency values.

Combination No.	Number of trucks	Tq_set	Ty_set	Resource description	Average efficiency value, EUR
1	4	80	80	Tr=4, QC80, YC80	**88**
2	4	98	110	Tr=4, QC98, YC110	**87**
3	4	90	80	Tr=4, QC90, YC80	**87**
4	4	90	90	Tr=4, QC90, YC90	**86**
5	4	80	90	Tr=4, QC80, YC90	**85**
6	4	98	90	Tr=4, QC98, YC90	**85**
7	4	98	80	Tr=4, QC98, YC80	**85**
8	3	98	110	Tr=3, QC98, YC110	**83**
9	5	80	80	Tr=5, QC80, YC80	**82**

Let us approach these data in a separate case-wise analysis.

5.2.6. ECONOMIC EFFICICENCY HISTOGRAM ANALYSIS

Most efficient resource combinations as per table above arise both from workgroups of three, four, and five trucks. Let us consider the histogram for each of these cases.

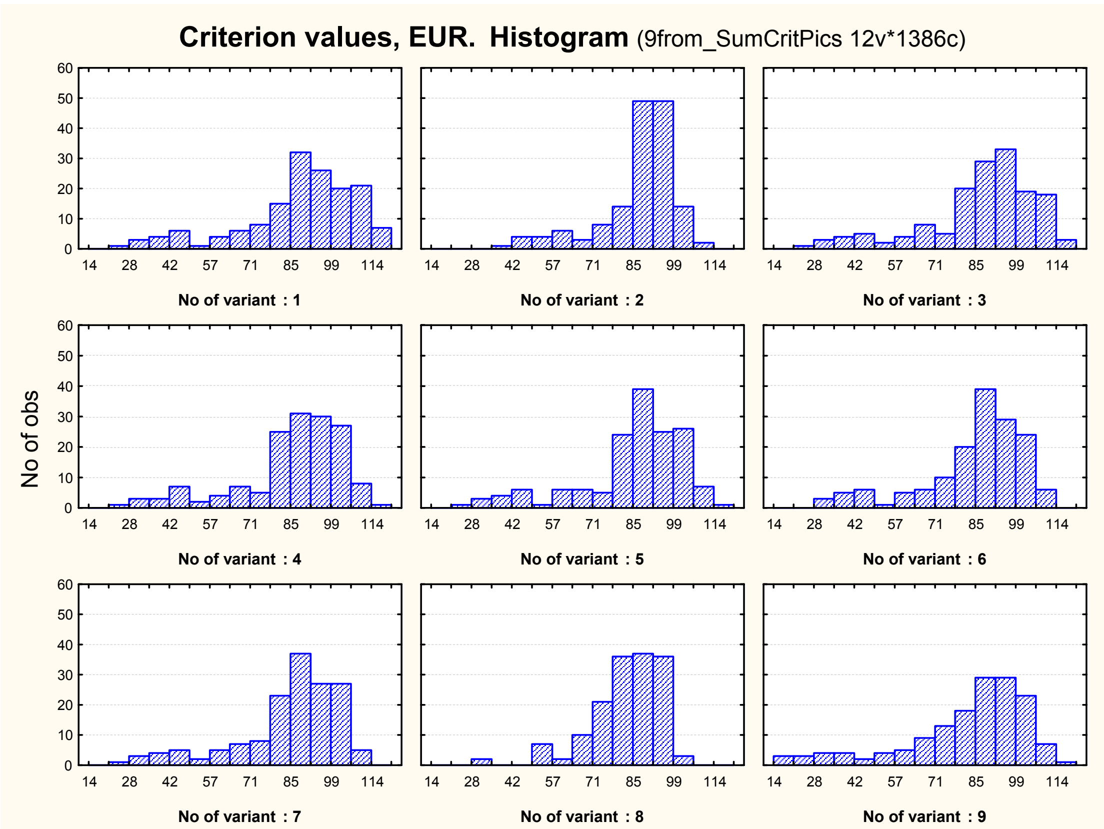


FIGURE 5.19. Casewise histograms of nine combinations of resources leading to highest economic efficiency values.

All the histograms are clearly asymmetric, with no signs of normality which leaves us no possibility to apply analysis tools based on normality assumption. The minor discrepancies in mathematical expectations are significantly smaller than respective range of dispersion, which makes making final decision difficult.

Since the type of distribution is neither normal nor is known to us, we have to use non-parametric research methods. One has to take decision whether the discrepancies in average values of economic efficiency for different combinations of resources are significant or follow a random order caused by the limited size of the sample. In order to identify that, we will apply the Mann-Whitney U-test (Zaks, 1976). Let us make a paired comparison of the samples of the first combination (maximum average value) and the remaining 8 combinations using the U-test. The results are presented in the table below.

TABLE 5.8. Mann-Whitney U-test for nine most efficient resource combinations

Mann-Whitney U Test (9from_SumCritPics)
Comparing two groups: Group 1 with the first rank and 2 rank Group 2
Marked tests are significant at p <.05002

Criterion	Rank Sum Group 1	Rank Sum Group *i*	U	Z	p-level	Valid N group 1	Valid N group *i*	REM
Comparing the 1 variant with variant i=2	24925	22661	10726	1.449	0.147	154	154	
Comparing the 1 variant with variant i=3	24366	23220	11285	0.733	0.463	154	154	
Comparing the 1 variant with variant i=4	25025	22561	10626	1.577	0.115	154	154	
Comparing the 1 variant with variant i=5	25253	22333	10398	1.868	0.062	154	154	
Comparing the 1 variant with variant i=6	25533	22053	10118	**2.227**	**0.026**	154	154	*test is significant*
Comparing the 1 variant with variant i=7	25544	22042	10107	**2.241**	**0.025**	154	154	*test is significant*
Comparing the 1 variant with variant i=8	27171	20415	8480	**4.323**	**0.000**	154	154	*test is significant*
Comparing the 1 variant with variant i=9	25787	21799	9864	**2.552**	**0.011**	154	154	*test is significant*

As a result, we might exclude four last combinations whereas the first five combinations are statistically identical, and in order to make a choice we have to analyze secondary information beyond the U-test.

Let us concentrate on the seemingly statistically identical first five combinations with the highest economic efficiency values.

There are only four-truck brigades in the table, therefore let us analyze the behaviour of criterion of efficiency for combinations featuring four tractors.

TABLE 5.9. Parameters of the five most efficient resource combinations.

Combination No.	Number of trucks	Tq_set	Ty_set	Resource description	Average efficiency value, EUR
1	4	80	80	Tr=4, QC80, YC80	**88**
2	4	98	110	Tr=4, QC98, YC110	**87**
3	4	90	80	Tr=4, QC90, YC80	**87**
4	4	90	90	Tr=4, QC90, YC90	**86**
5	4	80	90	Tr=4, QC80, YC90	**85**

In FIGURE 5.20. the x-scale marks values of resource operational cycles (values of 80, 90, and 98 seconds) for quay cranes **QC1**, **QC2**, and **QC3** respectively. The y-scale represents values of yard crane operational cycles **Ty_set** (80, 90, and 110 seconds) for respective yard cranes **YC1**, **YC2**, and **YC3**. The z-scale marks criterion of efficiency denominated in EUR.

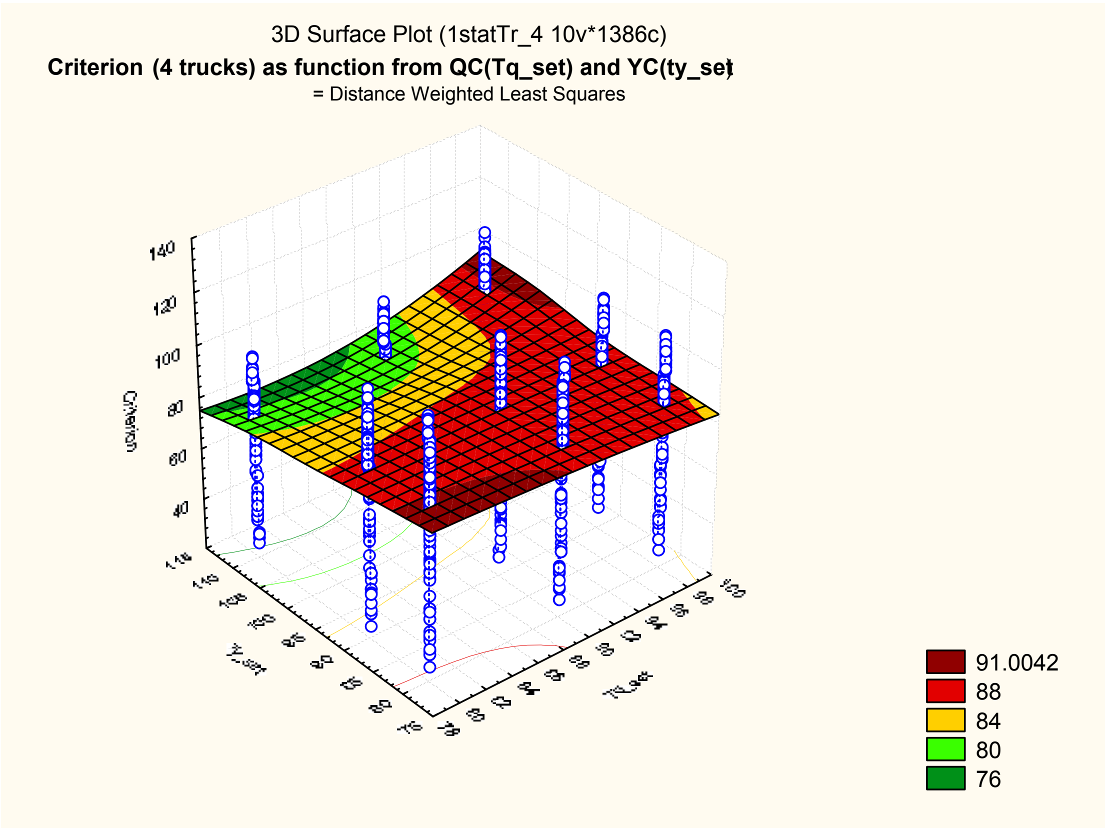


FIGURE 5.20. 3D surface of average values of criterion of economic efficiency for the workgroup of 4 tractors plotted on the set of observations of the economic efficiency criterion (original data plotted as rows).

As it follows from the graph, the following pairs of cranes yielding maximum economic efficiency: **QC1**+**YC1**, **QC3**+**YC3**, **QC2**+**YC1**, **QC2**+**YC2**, **QC1**+**YC2**. Thus, we have arrived at most efficient case for one type of resources: workgroup of 4 trucks with nominal productivity of **NP**=33 and cost of EUR 166’700.

For the final choice of the pair of cranes among the remaining combinations let us see the compilation table below. Parenthesis indicate percentage of maximum value of EUR 21'415 for combination **QC1 +YC2**. The crane names include respective productivities in parenthesis.

TABLE 5.10. Resource cost and economic efficiency

Тип		YC1 (45)	YC2 (40)	YC3 (33)
	Цена, EUR	**875'000**	**820'000**	**770'000**
QC1 (45)	**1'000'000**	21'307 (99%), EffCrit = EUR 88	21'415 (100%), EffCrit=EUR 85	
QC2 (40)	**920'000**	20'632 (96%), EffCrit=EUR 87	20'233 (94%), EffCrit =EUR 86	
QC3 (37)	**870'000**			**18'851(88%), EffCrit = EUR 87**

Leaving other considerations aside, the optimal choice of equipment will be the one with the smallest relative cost.

The choice of the cheapest and consequently, most unproductive resources **QC3 +YC3** is the optimal choice in the task considered. So, the optimal choice is workgroup of four trucks, quay crane **QC3** (allowing 37 moves per hour), and yard crane **YC3** (allowing 33 moves per hour).

The average value of economic efficiency of such pool of resources is EUR 87 at average productivity **NP**= 27 moves/hour (see TABLE 5.10.). The chosen combination of cranes also allows some productivity slack (productivity data for respective crane are 37 moves/hour for quay crane **QC3** and 33 moves/hour for yard crane **YC3**) of ca. 20%.

The breakdown of associated costs for the preferable combination of **QC3 +YC3+4Tr** is illustrated in FIGURE 5.21. below.

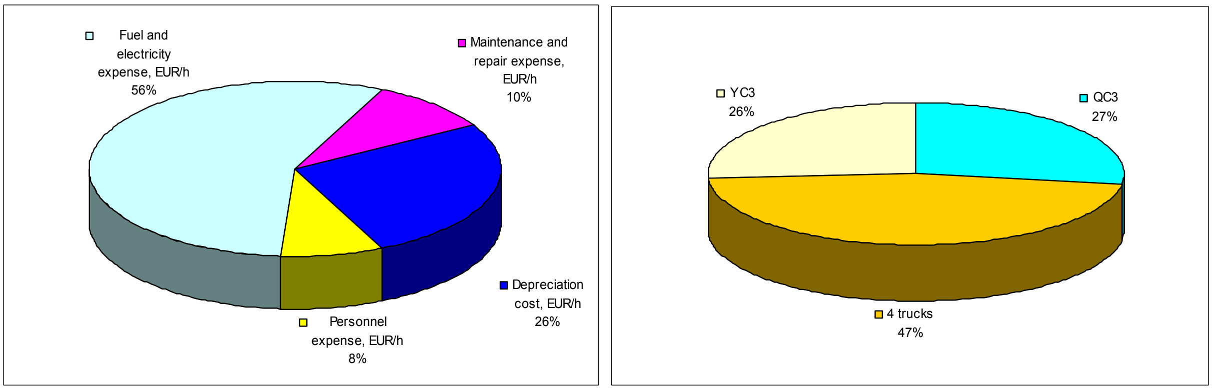


FIGURE 5.21. Resource cost structure for **QC3 +YC3**+**4Tr** (left-hand side) and total cost breakdown by resource type (right-hand side).

As it follows from the graph above, the most important components are the running fuel and electricity expenses, accounting for more than a half of total cost, and depreciation costs accruing a quarter of total expenses. Cost breakdown by type of resources is uneven with around a half attributed for truck expenses and below 30% each for the two gantry cranes.

5.2.7. 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. There arises a logical question: *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$\boldsymbol{i}$ + Tr$\boldsymbol{j}$ + YC$\boldsymbol{k}$ cannot exceed productivity of the slowest link, i.e. the lowest of (NPtr, NPqc, NPyc):

$$\text{NP}min(\boldsymbol{i,j,k}) = \min(\text{NPqc}\boldsymbol{i}, \text{NPtr}\boldsymbol{j}, \text{NPyc}\boldsymbol{k}) \qquad (5.7)$$

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

Now in order to calculate economic efficiency (5.5.) we have to use the minimum productivity value NP*min(* ***i,j,k****)* to sum up all associated resource costs at given productivity level:

$$\text{CRITERION}\mathit{min}\,(\boldsymbol{i,j,k}) = \mathbf{SSS}\boldsymbol{ijk}\,(\text{NP}\mathit{min}(\boldsymbol{i,j,k})) \tag{5.8}$$

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 **QC2**+**Tr5**+**YC2**, where **NP(QC2)**=40, **NP(Tr5)** = 41.9, **NP(YC2)**=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(QC2)**=**NP(YC2)**=40 (the productivity of the least productive element of the whole chain).

FIGURE 5.23. illustrates influence of 10% statistical deviation of the elements of logistics chain consisting of **QC2**, **Tr5**, **YC2** on the highest attainable performance of the whole chain in accordance with the straightforward slowest link approach). The figure features net productivity histograms based on 2’000 observations and the distribution statistics of the least productive element in each combination of feasible element. The average value of the productivity data is 39.967 with square deviation of 0.0481 which falls in line with the previously found value of 40.

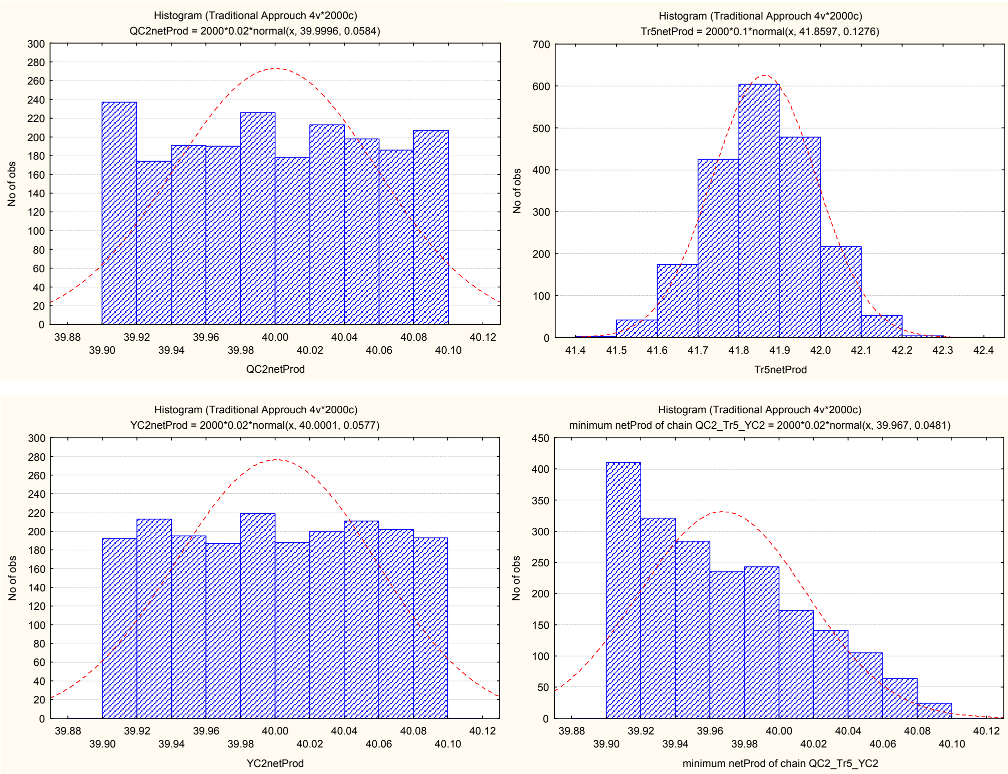


FIGURE 5.23. Sample of modelling results portraying histograms for **QC2+Tr5+YC2** set of resources. The upper panes and left-hand side lower pane show histograms for each separate resource unit, whereas the right-hand side histogram lower histogram stands for combination of resources.

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

Let us analyze the productivity values of all the feasible resource combinations and comparing them to the productivity values observed for the same combinations obtained from the simulation model runs thus comparing the traditional *'slowest link'* approach to micro-simulation approach.

TABLE 5.11. below features net productivity data for all possible combinations calculated using traditional *'slowest link'* approach (row labeled **Min(NPtr, NPqc, NPyc)**) and simulation-modelled data (row labeled **NP average from model**).

TABLE 5.11. Net productivity values of feasible combinations of resources

Min (NPtr, NPqc, NPyc)		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**
Trucks = 3	**25.1**	Min (NPtr, NPqc, NPyc)			NP average from model			(NPmin-NPaver)/NPaver, %		
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 (NPtr, NPqc, NPyc)		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**
Trucks = 4	**33.5**	Min (NPtr, NPqc, NPyc)			NP average from model			(NPmin-NPaver)/NPaver, %		
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 (NPtr, NPqc, NPyc)		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**
Trucks = 5	**41.9**	Min (NPtr, NPqc, NPyc)			NP average from model			(NPmin-NPaver)/NPaver, %		
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 (NPtr, NPqc, NPyc)		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**
Trucks = 6	**50.2**	Min (NPtr, NPqc, NPyc)			NP average from model			(NPmin-NPaver)/NPaver, %		
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 both data rows, comparing values of traditional approach **min(NPqc*i*, NPtr*j*, NPyc*k*)** along the x-scale and **NP** values obtained through simulation modelling of respective combinations of resources along the y-scale (FIGURE 5.24.).

From FIGURE 5.24. it might be inferred that the assumption of the logistics chain performance being equal to the performance of the slowest element does not hold. The calculation error increases proportionally to the net productivity increase and in the considered productivity range (from **NP**=20 to **NP**=40) the error reaches 25% which is insufficient for determining a combination of resource whose own productivity data deviate in the range of 15%-25%.

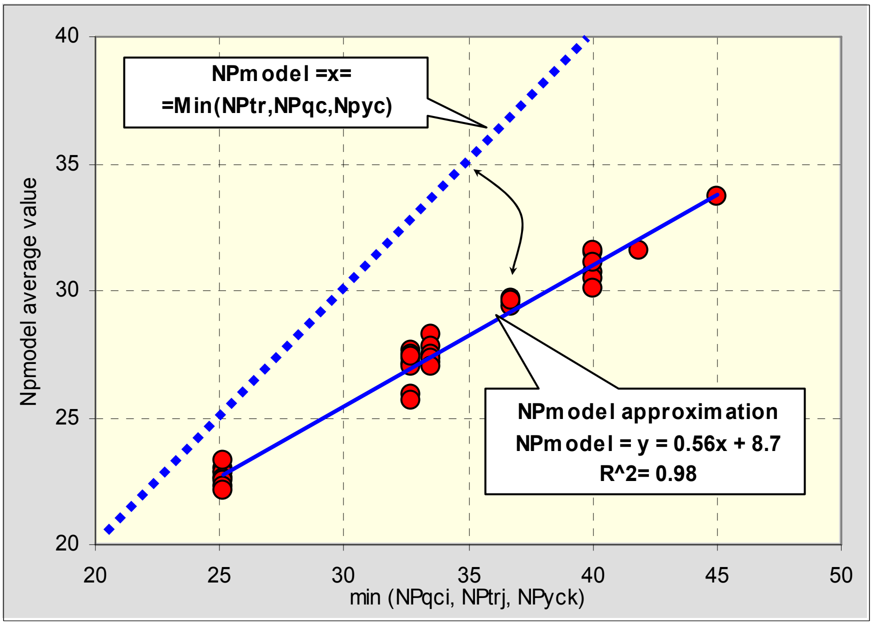


FIGURE 5.24. Dependance of the resource net productivities in the stochastical simulation model (Y-scale) and slowest link method assuming NPmin(**i,j,k)** = = min (NPqc**i**, NPtr**j**, NPyck) along Y-scale.

Let us now take a look at application of the slowest link method for economic analysis discussed above. FIGURE 5.25. portrays the economic efficiency estimates obtained both for the average values of the productivity of the simulation model and the results of *'slowest link'* approach as per expression (5.8.).

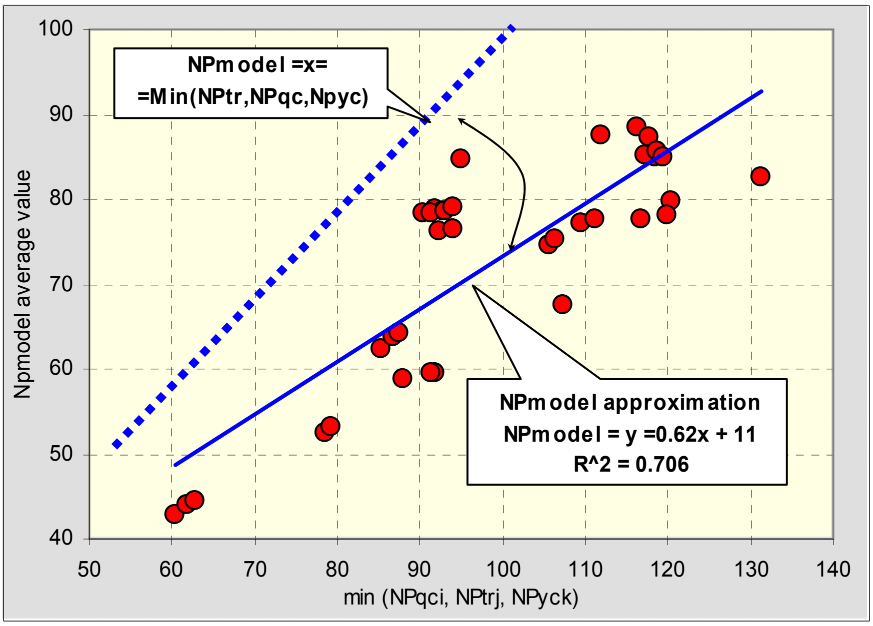


FIGURE 5.25. Stochastical interdependence of economic efficiency criterion values for simulation-based (y-scale) and traditional *'slowest link'*(x-scale) methods for choosing pool of resources.

The discrepancy in efficiency estimates through the two methods described above constitutes a solid difference of up to 25% with even higher discrepancy (R^2=0.706).

From the above-mentioned it can be inferred that the more simple method of *'slowest link'* does not provide the degree of calculation reliability necessary for making investment decisions. Despite its complexity, the more precise method of simulation modelling is preferred.

5.3. CONCLUSIONS

The present chapter has illustrated several applications of the simulation model for performance and cost-efficiency analysis. Thus, the following tasks have been successfully solved:

- 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 variations in productivity values of NP(3)real = 24 +/- 1, +/- 2, +/- 3, NP(4)real = 30 +/- 1, +/- 2, +/- 3, NP(5)real =32 +/- 1, +/- 2, +/- 3.
- 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.

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 calls for more precise tools like stochastical modelling methods which nowadays gain on popularity in estimation of business projects.

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. A choice of a single most efficient set of resources with similar technical characteristics often becomes statistically impossibly even in relatively uncomplicated logistics chains featuring stochastic element interaction.

The chapter has also illustrated the practical value of the simulation model as a software usable by external parties. As a result, the simulation model is used by management of the Baltic Container Terminal as decision-support and personnel training tool for different tasks of workload planning (see recommendation letter in APPENDIX V).

6. 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. The approach is presented in **2.2.1. Hierarchically integrated BCT models**.
- 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. Several applications of the approach are presented in CHAPTER 5. PRACTICAL APPLICATIONS OF SIMULATION MODEL.

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. The simulation model is used by management of the Baltic Container Terminal as decision-support and personnel training tool for workload planning (see respective recommendation letter in APPENDIX V.

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

7. REFERENCE LIST

1. Akbay, K. S. 1996. Using Simulation Optimization to Find the Best Solution. IIE Solutions, May issue, 24-29.
2. Alrefaei, M. H. and S. Andradottir. 1995. A New Search Algorithm for Discrete Stochastic Optimization, *Proceedings of the 1995 Winter Simulation Conference*, 236-241.
3. Andradottir, S. 1990. A New Algorithm for Stochastic Optimization, *Proceedings of the 1990 Winter Simulation Conference*, 364-366.
4. Avriel, M., Penn, M., Shpirer, N., Witteboon, S. 1998. Stowage planning for container ships to reduce the number of shifts. Annals of Operations Research 76: 55-71.
5. Azadivar, F. 1992. A Tutorial on Simulation Optimization, *Proceedings of the 1992 Winter Simulation Conference,* 198-204.
6. Azadivar, F. and Y. H. Lee. 1988. Optimization of Discrete Variable Stochastic Systems by Computer Simulation, *Mathematics and Computers in Simulation*, 30, 331-345.
7. Barton, R. R., and J. S. Ivey. 1991. Modifications of the Nelder-Mead Simplex Method for Stochastic Simulation Response Optimization, *Proceedings of the 1991 Winter Simulation Conference,* 945-953.
8. Biles, W. E. 1974. A Gradient Regression Search Procedure for Simulation Experimentation, *Proceedings of the 1974 Winter Simulation*
9. Boyes, J. R. C. (ed). 2000. Containerisation international yearbook, ranking of container ports of the world. National Magazin, London
10. Boyes, J. R. C. (ed). 2003. Containerisation international yearbook, ranking of container ports of the world. National Magazin, London
11. Bruzzone, A, Signorile, R. 1998. Simulation and genetic algorithms for ship planning and shipyard layout. Simulation 71: 74—83
12. Cao, B., Uebe, G. 1995. Solving transportation problems with nonlinear side constraints with tabu search. Computers & Operations Research 22: 593-603.
13. Carson, Y., Maria, A. 1997. Simulation optimization: methods and applications. Proceedings of the 1997 Winter Simulation Conference, ed. S. Andadottir, K. J. Healy, D. H. Withers, and B. L. Nelson.
14. Chen, T. 1999. Yard operations in the container terminal - a study in the 'unproductive moves'. Maritime Policy and Management 26: 27-38.
15. Cheung, R. K., Li, C.-L., Lin, W. 2002. Interblock crane deployment in container terminals. Transportation Science 36(1): 79-93
16. Cochran W.G., Cox G.M, 1962. Experimental Designs, John Wiley & Sons, New York.
17. Daganzo, C. F. 1989. The crane scheduling problem. Transportation Research-B23B(3): 159-175.
18. Daugherty, A. F. and M. A. Turnquist. 1980. Simulation Optimization Using

Responses Surfaces Based on Spline Approximations, *Proceedings of the 1980 Winter Simulation Conference*, 183-193.

19. De Souza, P. S. and Talukdar, S. N. 1991. Genetic Algorithms in Asynchronous Teams, *Proceedings of the 4th International Conference on Genetic Algorithms,* 392-397.
20. Dennis J.E., Woods D.J., 1987. Optimization on Microcomputers: The Nelder-Mead Simplex Algorithm. In: Wouk A., New Computing Environments: Microcomputers in Large Scale Computing, SIAM, Philadelphia, pp.116-122.
21. Desrochers, M., Lenstra, J. K., Savelsbergh, M. W. P. 1990. A classification scheme for vehicle routing and scheduling problems. European Journal of Operational Research 46: 322-332
22. Donohue, J. M., E. C. Houck, and R. H. Myers. 1990. Some Optimal Simulation Designs for Estimating Quadratic Response Surface Functions, *Proceedings of the 1990 Winter Simulation Conference,* 337-343.
23. Dubrovsky, O., Levitin, G., Penn, M. 2002. A genetic algorithm with a compact solution encoding for the container ship stowage problem. Journal of Heuristics 8: 585-599.
24. Fagerholt, K. 2000. Evaluating the trade-off between the level of costumer service and transportation costs in a ship scheduling problem. Maritime Policy and Management 27(2): 145-153.
25. Fleischer, M. 1995. Simulated Annealing: Past, Present, and Future, *Proceedings of the 1995 Winter Simulation Conference*, 155-161.
26. Free J.W., Parkinson A.R., Bryce G.R., Balling R.J., 1987. Approximation of Computationally Expensive and Noisy Functions for Constrained Nonlinear Optimizations. Transactions of the American Society of Mechanical Engineers 109, 528-532.
27. Fu M.C., 1994. Optimization via Simulation: A Review. Annals of Operations Research 53, 199-247.
28. Gademann, A. J. R. M., van de Velde, S. L. 2000. Positioning automated guided vehicles in a loop layout. European Journal of Operational Research 127(3): 565-573.
29. Gambardella, L. M., Bontempi, G., Taillard, E., Romanengo, D., Raso, G., Piermari, P. 1996. Simulation and forecasting in intermodal container terminal. In: A.G. Bruzzone, JH. Kerckhoffs (eds.), *Simulation in Industry, 8th European Simulation Symposium*, 1996. Genoa: Society for Computer Simulation International.
30. Gambardella, L. M., Rizzoli, A. E., Zaffalon, M. 1998. Simulation and planning of an intermodal container terminal. Simulation 71(2): 107-116
31. Glover, F. 1989. Tabu Search - Part I, *ORSA Journal on Computing*, Vol. 1, No. 3, Summer 1989.
32. Glover, F. 1990. Tabu Search - Part II, *ORSA Journal on Computing*, Vol. 2, No. 1, Winter 1990
33. Glynn, P. W. 1989a. Likelihood Ratio Derivative Estimators for Stochastic Systems, *Proceedings of the 1989 Winter Simulation Conference*, 374-380.

34. Glynn, P. W. 1989b. Optimization of Stochastic Systems Via Simulation, *Proceedings of the 1989 Winter Simulation Conference,* 90-105.

35. Goldsman, L. and B. Nelson. 1990. Batch-Size on Simulation Optimization Using Multiple Comparisons with the Best, *Proceedings of the 1990 Winter Simulation Conference,* 288-293.

36. Gupta, S. S. and S. Panchapakesan. 1979. *Multiple-Decision Procedures - Theory and Methodology of Selecting and Ranking Populations,* John Wiley.

37. Gurkan, G., A. Y. Ozge, and S. Robinson. 1994. Sample-Path Optimization in Simulation, *Proceedings of the 1994 Winter Simulation Conference*, 247-254.

38. Gutenschwager, K., Niklaus, C., Voss, S. 2004. Dispatching of an electric monorail system: applying meta-heuristics to an online pickup and delivery problem. Transportation Science

39. Haghani, A., Kaisar, E. I. 2001. A model for designing container loading plans for container ships. Working paper, University of Maryland, presented at Transportation Research Board 2001 Annual Meeting.

40. Hall, J. D. and R. O. Bowden. 1997. Simulation Optimization by Direct Search: a Comparative Study, *Proceedings of the Sixth International Industrial Engineering Research Conference.*

41. Hanafi, S., Jesus, J., Semet, F. 2003. The container assignment problem: a case study on the port of Lille. Working paper, University of Valenciennes, presented at ODYSSEUS2003

42. Hartmann, S. 2004. A general framework for scheduling equipment and manpower on container terminals. OR Spectrum 26: 51-74.

43. Henesey, L., 2005. "A Simulation Model for Analysing Terminal Management Operations", Proceeding of the 4th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT '05), May 8-11, Hamburg, Germany

44. Hoffarth, L., Voss, S. 1994. Liegeplatzdisposition auf einem Containerterminal-Ansaetze zur Entwicklung eines entscheidungsunterstuetzenden Systems. In: Dyck-hoff H, Derigs U, Salomon M, Tijms H (eds) Operations Research Proceedings 1993, pp. 89-95. Springer, Berlin Heidelberg New York.

45. Holland, J. H. 1992. Genetic Algorithms, *Scientific American*, July, 66-72.

46. Hsu, J. C. and B. L. Nelson. 1988. Optimization over a Finite Number of System Designs with One-Stage Sampling and Multiple Comparisons with the Best, *Proceedings of the 1988 Winter Simulation Conference*, 451-457.

47. Hulten, L. A. R. 1997. Container logistics and its management. PhD thesis, Chalmers University of Technology: Department of Transportation and Logistics.

48. Ioannou, P. A., Kosmatopoulos, E. B., Jula, H., Collinge, A., Liu C.-I., Asef-Vaziri, A., Dougherty, Jr. E. 2000. Cargo handling technologies. Final Report, University of Southern California.

49. Ioannou, P. A., Jula, H., Liu, C.-I., Vukadinovic, K., Pourmohammadi, H., Dougherty Jr. E. 2001. Advanced material handling: automated guided vehicles in agile ports. Final Report, University of Southern California,

50. Ioannou, P., Chassiakos, A., Zhang, J., Kanaris, A., Unglaub, R. 2002. Automated container transport system between inland port and terminals. Project Report, University of Southern California.

51. Kim, K. H. 1997. Evaluation of the number of rehandles in container yards. Computers& Industrial Engineering 32: 701-711.

52. Kim, K. H., Bae, J. W. 1998. Re-marshaling export containers in port container terminals. Computers & Industrial Engineering 35: 655-658.

53. Kim, K. H., Kim, K. Y. 1999. Routing straddle carriers for the loading operation of containers using a beam search algorithm. Computers & Industrial Engineering 36:106-136.

54. Kim, K. H., Lee, K. M., Hwang, H. 2003. Sequencing delivery and receiving operations for yard cranes in port container terminals. International Journal of Production Economics 84(3): 283-292.

55. Kim, K. H., Park, K. T. 2003. A note on a dynamic space-allocation method for outbound containers. European Journal of Operational Research 148(1): 92-101.

56. Kim, K. H., Park, Y. M., Ryu, K.-R. 2000. Deriving decision rules to locate export containers in container yards. European Journal of Operational Research 124: 89-101.

57. Kim, K. Y., Kim, K. H. 2003. Heuristic algorithms for routing yard-side equipment for minimizing loading times in container terminals. Naval Research Logistics 50: 498-514

58. Kleijnen, J.P.C., 1997. Experimental Design for Sensitivity Analysis, Optimization, and Validation of Simulation models. In: Banks, J., Handbook of Simulation: Principles, Methodology, Advances, Applications and Practice. John Wiley & Sons, New York, pp.173-223.

59. Koch, J. 1997. Die Entwicklung des Kombinierten Verkehrs. Gabler, Deutscher Uni-versitats-Verlag, Wiesbaden.

60. Konings, J. W. 1996. Integrated centres for the transshipment, storage, collection and distribution of goods: a survey of the possibilities for a high-quality intermodal transport concept. Transport Policy 3(1-2): 3-11.

61. Kozan, E. 2000. Optimising container transfers at multimodal terminals. Mathematical and Computer Modelling 31: 235-243

62. Kozan, E., Preston, P. 1999. Genetic algorithms to schedule container transfers at multimodal terminals. International Transactions of Operational Research 6: 311-329.

63. L'Ecuyer, P. 1991. An Overview of Derivative Estimation, *Proceedings of the 1991 Winter Simulation Conference,* 207-217.

64. Legato, P., Mazza, R. M. 2001.Berth planning and resources optimisation at a container terminal via discrete event simulation. European Journal of Operational Research 133: 537-547

65. Lemper, B. 2003. Containerschifffahrt und Welthandel - eine 'Symbiose'.http://www.gdv.de/download/VortragLemper,pdf – last check of address: July 17, 2006

66. Leung, Y. T. and R. Suri. 1990. Finite-Time Behavior of Two Simulation Optimization Algorithms, *Proceedings of the 1990 Winter Simulation Conference,* 372-376.

67. Li C.-L., Cai, X., Lee, C.-Y. 1998. Scheduling with multiple-job-on-one-processor pattern. IIE Transactions 30: 433-445.

68. Li, C.-L., Vairaktarakis, G. L. 2001. Loading and unloading operations in container terminals. Technical Memorandum 745, Case Western Reserve University, Weatherhead School of Management, Department of Operations.

69. Lim, A. 1998. The berth planning problem. Operations Research Letters 22: 105-110.

70. Liu, C.-I., Jula, H., Ioannou, P. A. 2002. Design, simulation, and evaluation of automated container terminals. IEEE Transactions on Intelligent Transportation Systems 3(1): 12-26

71. Mahoney, J. H. 1985. Intermodal freight transportation. Eno Foundation for Transportation, Westport, CN.

72. Meersmans, P. J. M., Dekker, R. 2001. Operations research supports container handling. Technical Report El 2001-22, Erasmus University Rotterdam, Econometric Institute.

73. Merkuryev, Y., Bardachenko, V., Solomennikov, A., and Kamperman, F. 2002. Multi-level simulation of logistics processes at the Baltic Container Teminal. *International Workshops on Harbour, Maritime and Multimodal Logistics Modelling & Simulation, HMS2002, and Modelling and Applied Simulation, MAS2002. October 3–5, 2002, Bergeggi, Italy.* Ed. by Agostino G. Bruzzone, Yuri Merkuryev, Roberto Mosca. Genoa, pp. 78–83.

74. Merkuryev, Y., Bardachenko, V., Solomennikov, A., and Kamperman, F. 2003. Multi-level simulation of logistics processes at the Baltic Container Terminal: Calibration study. *Modelling and Simulation of Business Systems. Proceedings of the International Conference. May 13–14, 2003, Vilnius, Lithuania.* Ed. by H. Pranevicius, E. Zavadskas and B. Rapp. Kaunas: Technologija, pp. 274–278.

75. Merkuryev, Y., Bardachenko, V., Solomennikov, A., and Kamperman, F. 2003. Simulation of logistics processes at the Baltic Container Terminal: Model validation and application. *Proceedings of the International Workshop on Harbour, Maritime and Multimodal Logistics Modelling and Simulation. HMS2003. September 18–20, 2003, Riga, Latvia.* Ed. by Yuri Merkuryev, Agostino G. Bruzzone, Galina Merkuryeva, Leonid Novitsky and Edward Williams. Riga: RTU, pp. 294–302.

76. Merkuryev, Y., Bardachenko, V., Solomennikov, A., and Kamperman, F. 2003. The Baltic Container Terminal Simulation System. In: *Applications of Simulation and Its Solutions in the Baltic Port Areas of the Associated Candidate Countries.* Ed. by E. Blumel. Riga: JUMI Ltd., pp. 47–83.

77. Merkuryev, Y., Bardachenko, V., Solomennikov, A., and Kamperman, F. 2004. Simulation-based resource pooling at the Baltic Container Terminal. *Proceedings of International Workshops on Harbour, Maritime and Multimodal Logistics Modelling and Simulation, and Applied Modelling and Simulation. HMS2004 & AMS2004. September 16–18, 2004, Rio de Janeiro, Brazil.* Ed. by Agostino G. Bruzzone, Gerson Gomes Cunha, Luiz Landau and Yuri Merkuryev. Universidade Federal do Rio de Janeiro, pp. 16–24.

78. Merkuryev, Y., Bardachenko, V., Solomennikov, A., and Kamperman, F. 2005. 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, pp. 91–95.

79. Morrice, D. J., and L. W. Schruben. 1989. Simulation Sensitivity Analysis Using Frequency Domain Experiments, *Proceedings of the 1989 Winter Simulation Conference*, 367-373.

80. Muller, G. 1995. Intermodal freight transportation, 3rd edn. Eno Foundation for Transportation, Westport, CN.

81. Murty, K. G., Liu J., Wan, Y.-W., Linn, R. J. 2003. A DSS (Decision Support System) for operations in a container terminal. Working paper, University of Michigan, USA

82. Myers, R.H., Montgomery, D.C., 1995. Response Surface Methodology: Process and Product Optimization Using Designed Experiments, John Wiley & Sons, New York.

83. Nam, K.-C., Ha, W.-I. 2001. Evaluation of handling systems for container terminals. Journal of Waterway, Port, Coastal and Ocean Engineering 127(3): 171-175

84. Neddermeijer, H. G., N. Piersma, G. J. van Oortmarssen, J. D. F. Habbema, and R. Dekker (1999). Comparison of Response Surface Methodology and the Nelder and Mead Simplex Method for Optimization in Microsimulation Models. Econometric Institute Report EI-9924/A, Erasmus Universiteit Rotterdam, The Netherlands.

85. Nelson L.S., 1985. Nelder-Mead Simplex Method. In: Kotz S. and Johnson N.L. (Eds.). Encyclopedia of Statistical Sciences, John Wiley & Sons, New York, pp. 178-181.

86. Nishimura, E., Imai, A., Papadimitriou, S. 2001. Berth allocation planning in the public berth system by genetic algorithms. European Journal of Operational Research 131: 282-292.

87. NKM Noell Special Cranes. Crane construction, http://www.nkmnoell.com/ – last check of address: April 27, 2006

88. Orient Overseas Container Line – World's Top 50 Container Ports 2002 vs 2001. http://www.oocl.com/trade-news/20030715.htm – last check of address: March 23, 2006

89. Osman, I. H. 1993. Metastrategy Simulated Annealing and Tabu Search Algorithms for the Vehicle Routing Problem, *Annals of Operations Research*, 41, 421-451.

90. Park, Y.-M., Kim, K. H. 2003. A scheduling method for berth and quay cranes. OR Spectrum 25: 1-23

91. Peterkofsky, R. I., Daganzo, C. F. 1990. A branch and bound solution method for the crane scheduling problem. Transportation Research-B 24B: 159-172.

92. Pflug, G. Ch., 1996. Optimization of Stochastic Models: The Interface Between Simulation and Optimization, Kluwer Academic Publishers, Boston.

93. Preston, P., Kozan, E. 2001. An approach to determine storage locations of containers at seaport terminals. Computers & Operations Research 28: 983-995.

94. Reiman, M. I. and A. Weiss. 1986. Sensitivity Analysis Via Likelihood Ratios, *Proceedings of the 1986 Winter Simulation Conference,* 285-289.

95. Reklaitis, G. V., A. Ravindran, and K. M. Ragsdell.1983. *Engineering Optimization Methods and Applications*, John Wiley.

96. Roach, P. A., Wilson, I. D. 2002. A genetic algorithm approach to strategic stowage planning for container-ships. Working paper, University of Glamorgan, UK.

97. Saanen, Y., van Meel, J., Verbraeck, A. 2003. The next generation automated container terminals. Technical Report, TBA Nederland/Delft University of Technology

98. Schwefel, H. P. 1995. *Evolution and Optimum Seeking*, John Wiley.

99. Shahabuddin, P. 1995. Rare Event Simulation in Stochastic Models, *Proceedings of the 1995 Winter Simulation Conference,* 178-185.

100. Shapiro, A. 1996. Simulation Based Optimization, *Proceedings of the 1996 Winter Simulation Conference*, 332-336.

101. Sideris, A., Boile, M. P., Spasovic, L. N. 2002. Using on-line information to estimate container movements for day-to-day marine terminal operation. Working Paper, New Jersey Institute of Technology.

102. Smith D.E., 1979. Automatic Optimum-Seeking Program for Digital Simulation. Simulation 27, 27-32.

103. Solomennikov, A., Bardachenko, V., Merkuryev, Y., and Kamperman, F. 2003. Analysis of resource cycles in marine container terminals. *The International Conference "Reliability and Statistics in Transportation and Communication" (RelStat'03). 16–17 October 2003. Riga, Latvia. Programme and Abstracts.* Ed. by Igor V. Kabashkin. Riga, p. 20.

104. Solomennikov, A., Bardachenko, V., Merkuryev, Y., and Kamperman, F. 2004. Analysis of resource cycles in marine container terminals. *The International Conference "Reliability and Statistics in Transportation and Communication" (RelStat'03). 16–17 October 2003. Riga, Latvia. Proceedings.* Volume 1. Riga, pp. 19–27.

105. Steenken, D. 1992. Fahrwegoptimierung am Containerterminal unter Echtzeitbedingungen. OR Spectrum 14: 161-168.

106. Steenken, D. 1999. Latest operational experience with satellite based container positioning systems. In: Proceedings IIR-Conference on 'Container Handling, Automation and Technology', IIR, London.

107. Steenken, D. 2003. Optimised vehicle routing at a seaport container terminal. ORbit4: 8-14

108. Steenken, D., Henning, A., Freigang S., Voss, S. 1993. Routing of straddle carriers ata container terminal with the special aspect of internal moves. OR Spectrum 15: 167-172.

109. Steenken, D., Voss, S., and Stahlbock, R. 2004. Container terminal operation and operations research - a classification and literature review. OR Spectrum 26: 117-135.

110. Taleb-Ibrahimi, M., de Castilho, B., Daganzo, C. F. 1993. Storage space vs handling work in container terminals. Transportation Research-B 27B: 13-32.

111. Toth, P., Vigo, D. (eds). 2002. The vehicle routing problem. Society for Industrial &Applied Mathematics, SIAM, Philadelphia

112. Tseng, P. Fortified-descent simplical search method: a general approach. Department of Mathematics, University of Washington, Seattle, 1998.

113. UNCTAD Review of Maritime Transport, Report of UNCTAD secretariat. 2003. UNITED NATIONS New York and Geneva.

114. van der Heijden, M., Ebben, M., Gademann, N., van Harten, A. 2002. Scheduling vehicles in automated transportation systems: algorithms and case study. OR Spectrum 24: 31-58.

115. Vis, I. F. A., de Koster, R. 2003. Transshipment of containers at a container terminal: an overview. European Journal of Operational Research 147: 1-16

116. Volk, B. 2002. Growth factors in container shipping. http://maritimebusiness.amc.edu.au/papers/AMC3_GRO.pdf - last check of address: August 15, 2006

117. Voss, S., Bose, J. W. 2000. Innovationsentscheidungen bei logistischen Dienstleistern -Praktische Erfahrungen in der Seeverkehrswirtschaft. In: Dangelmaier W, Felser W(eds) Das reagible Unternehmen, pp. 253-282. HNI, Paderborn.

118. Wilson, I. D, Roach, P. A. 2000. Container stowage planning: a methodology for generating computerised solutions. Journal of the Operational Research Society 51: 1248-1255

119. Большев, Л. Н., Смирнов, Н. В. 1983. Таблицы математической статистики. Издание третье. Москва «Наука», главная редакция физико-математической литературы, pp. 81-87.

120. Закс, Л. С. 1976. Статистическое оценивание. Москва «Статистика»., 598 c, pp. 270-283.

121. Королюк, В. С., Портенко Н. И., Скороход, А. В., Турбин, А. Ф. 1978. Справочник по теории вероятностей и математической статистике. Киев «Наукова думка».

122. Меркурьев, Ю. А., Бардаченко, В. В., Соломенников, А. В., Камперман, Ф. 2004. Выбор оптимального набора ресурсов с помощью имитационного моделирования. *Информационные технологии и вычислительные системы*. Москва: Российская Академия Наук, No. 4, с. 104–118.

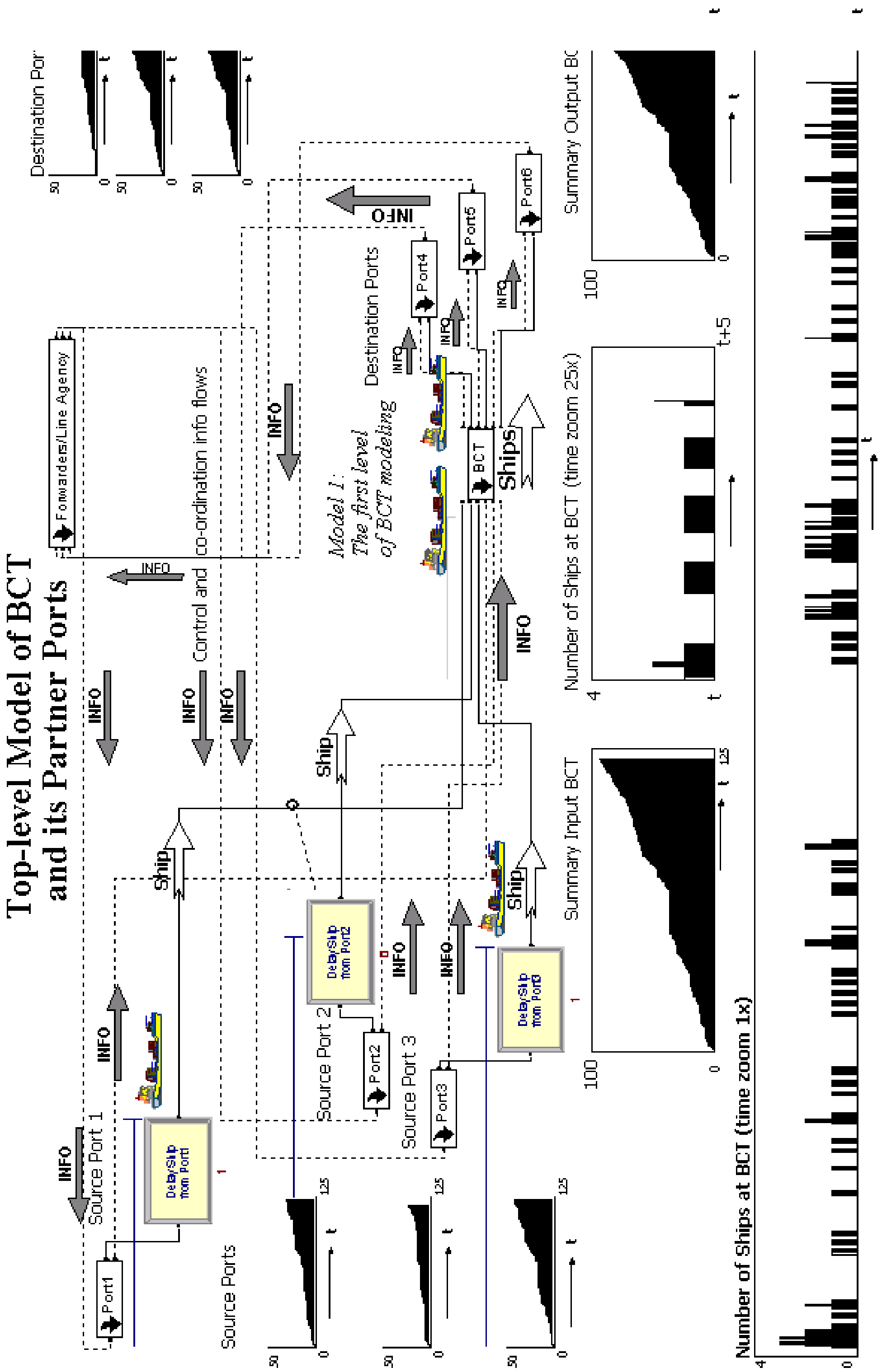
123. Меркурьев, Ю. А., Бардаченко, В. В., Соломенников, А. В., Камперман, Ф. 2005. Выбор оптимального набора ресурсов на Балтийском контейнерном терминале с помощью имитационного моделирования. *Transport and Telecommunication*. Riga: Institute of Transport of Telecommunication, Vol. 6, No. 4, pp. 4–29.

124. Смирнов, Н. В. 1970. Теория вероятностей и математическая статистика. Избранные труды. Москва «Наука», pp. 73-115.

8. Appendix

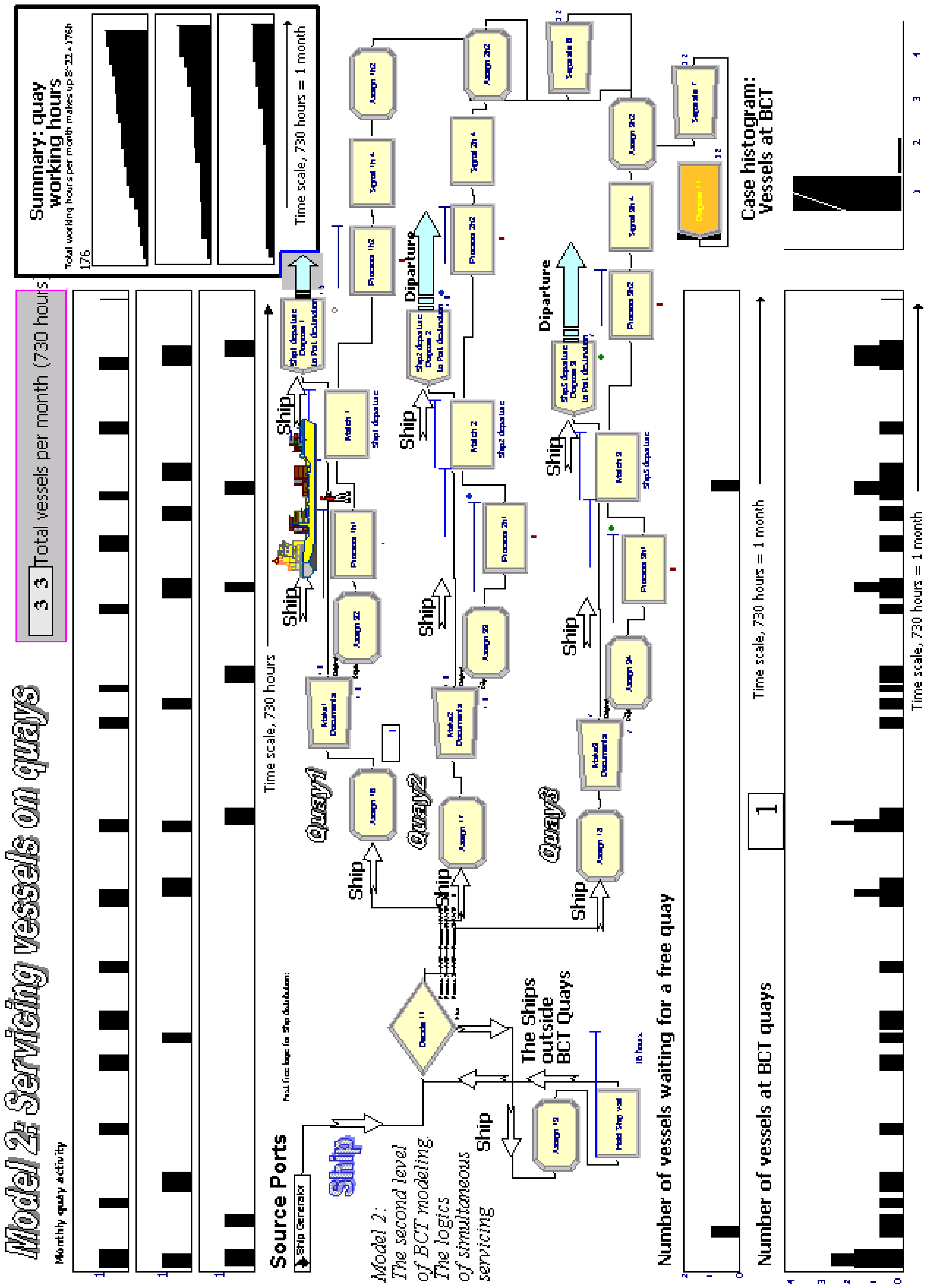
8.1. Appendix I

Model 1: The top level of BCT model featuring BCT and partner ports.



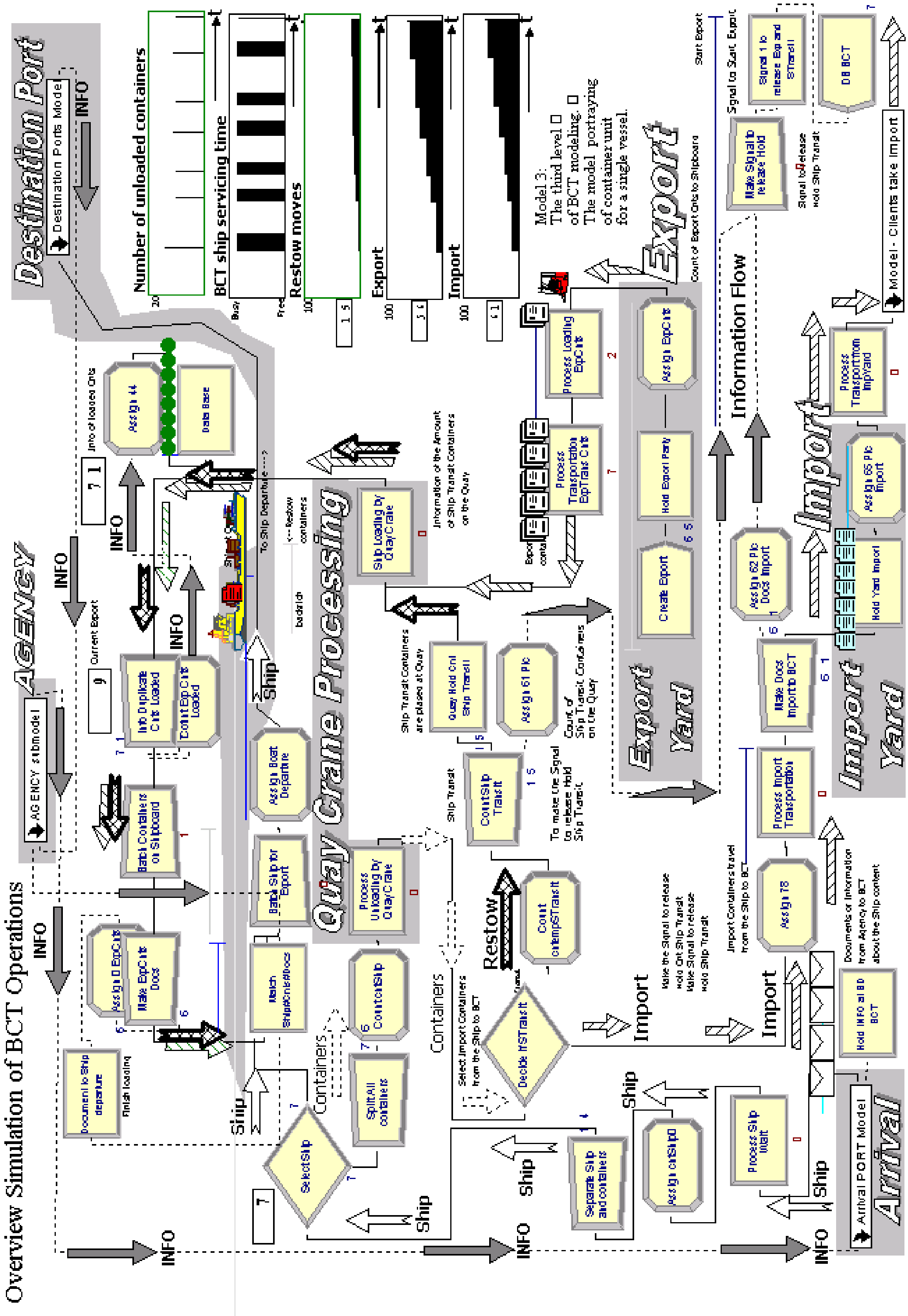
8.2. Appendix II

Model 2 estimates the influence of diverse algorithms of work teams on the vessel servicing times.



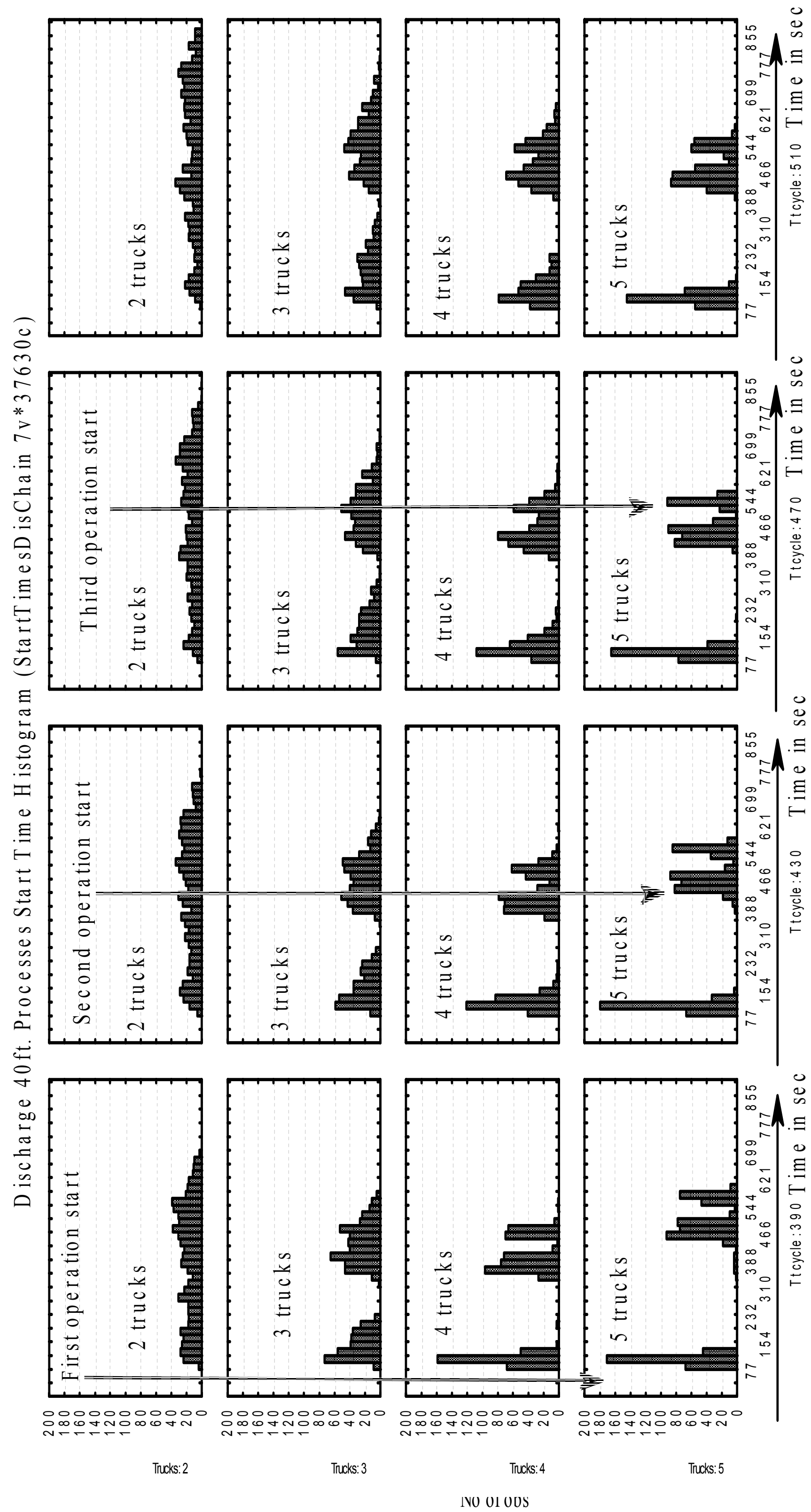
8.3. Appendix III

Model 3 allows further analysis of vessel loading and discharge processes along one berth.



8.4. APPENDIX IV

Case-wise histograms of operation start times on discharging 40ft containers as functions of truck operational cycle (350, 430, 470, 510 sec) and the number of trucks (2, 3, 4, 5 trucks).



8.5. APPENDIX V

Recommendation letter from BCT confirming practical application of the simulation model.

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TO WHOM IT MAY CONCERN

29. 05. 2006. Nr. 01-15/282

LETTER OF RECOMMENDATION

Andrey Solomennikov was participating in the Baltports-IT project "Simulation and IT-solutions: Applications in the Baltic ports' areas of the newly associated states" of the 5th Framework Programme of the European Commission during the whole project life time since 2001 to 2003. After completion of the project, Andrey continued developing and improving the methodology of simulation modelling of maritime container terminals that resulted in preparing a promotional work (Doctoral thesis). For the time being I see the methodology presented in his thesis as a complex approach to a variety of tasks, related to operation of container terminals.

The promotion work offers a new methodology to modelling maritime container terminals, the most important points being:

- creation of a logical structure of the terminal model
- adequate visualization and animation of micro-processes of the structural model
- aggregation of parameters of the structural model into resource cycles
- aggregation of parameters of micro-operations and allowing tight monitoring of modelled processes
- visualization of the aggregated model
- adjustment of parameters of the aggregated structural model based on minimization of discrepancy between model outputs and the real observed data

The practical result of the work was implemented in an operationable model of the Baltic Container terminal (BCT) that was developed using the Arena simulation environment. The following should be noted concerning the model:

- logic of the model recreates the logic of terminal operation (at the required level of details)
- adjustment of the parameters of the model has been performed using real observed data
- parameters of the adjusted model correspond to real parameters of the terminal
- the model is used by the managers for playing scenarios in non-standard situations, as well as for demonstrational and educational purposes

Finally, I recommend Andrey Solomennikov for the Doctoral degree in *Telematics and Logistics* and wish him a good luck in his career.

Frederik Kamperman
Terminal Manager, Baltic Container Terminal

Kamperman