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Simulation modeling in heterogeneous distributed computing environments to support decisions making in warehouse logistics

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Abstract

We address an important problem of automation in simulation modeling of logistics warehouses. An effective solution for such a large-scale problem is difficult to obtain without high-performance computing. To this end, we propose a new approach for adjusting management system parameters of the warehouse in its production use. It is based on the integration of conceptual, wireframe, and service-oriented programming used to develop parameter sweep applications and data analysis in simulation modeling in heterogeneous distributed computing environments. We design a toolkit to support modeling of warehouse logistics. Using this toolkit, we develop a parameter sweep application and solve three optimization tasks for adjusting parameters of a warehouse management system. The practical experiments are focused on the refrigerated warehouse. The developed applications demonstrate high efficiency and scalability capabilities to optimize nine criteria to cope with different production demands.

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Keywords: simulation modeling; queue systems; toolkit; distributed computing; parameter sweep applications

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1. Introduction

A study of complex technical and economic systems at different stages of their design and functioning is one of the important problems in simulation modeling. Often, effective modeling of the systems for manufacturing, material handling, transportation, storing, communication, information processing and other more processes are based on using a queuing systems theory.

An important class of queuing systems are Logistics Warehouses (LWs). These systems are oriented to the management of large-capacity cargo traffic, distribution of goods, etc. The functioning of modern LWs is associated with complex operation processes of the aforementioned queuing systems, taking into account their important role in the economic sphere. In this regard, the most important problems in warehouse management are functional and organizational structure analysis and optimization. To a certain extent, these problems can be solved by Warehouse Management Systems (WMS) that provide automation of a business process and support for decision making [1].

The trends of modern LWs include improvement of technologies, communication systems, expansion of a set of warehouse and logistic operations, increasing operational complexity, designing efficient logistic decisions, optimization tools, etc. Simulation modeling is one of the most effective approaches for LWs' functioning analysis [2]. It allows observing the behavior of LWs over time to identify parameters that influence their warehousing processes, and predict their behavior in the future.

A simulation modeling methodology gives users the ability to examine operational schemes and their parameters, and test effects of these alternatives without experimenting in a real environment, which is often too costly or impossible. It simplifies the optimization of control parameters for LWs operational schemes [3]. A process of the LW study implies a development of simulation program of warehouse operations, and its execution with a parameter sweep. In the parameter sweep, users adjust the values of parameters by sweeping their values in defined ranges. These experiments provide a low-cost method to determine the optimal parameters for operations.

The efficiency of results directly depends on the problem-oriented knowledge usage [4]. For example, Felice and Petrillo [5] present a successful application of simulation modeling based on problem-oriented knowledge in the decision-making process for the manufacturing system. Gwynne [6] discusses how to operate an efficient and cost-effective warehouse. Unfortunately, often, they do not take into account unpredictable factors and production uncertainties [7, 8], and do not have tools for solving various unexpected problems of warehouse management.

Efficient management includes:

- Modeling logistic operations to determine their time and cost parameters, taking into account service delays and risks associated with a human factor;
- Developing equipment maintenance plans considering random failures;
- Analysis of customer service levels and prediction of the possible financial results for different periods.

High-performance computing (HPC) seems to be an essential part of large-scale mathematical modeling. It provides significant computational speedup based on the parallel processes execution. The scale in number of computational elements and complexity of systems is increasing dramatically. Applications also need to scale upwards to address this challenge by improving performance. Problem-solving time should decrease with increase in a number of the nodes. Thus, it is essential to design special tools for development of simulation programs that are parallel and scalable.

Law [9] notes that the simulation program design, which adequately reflects the studied system, is a non-trivial problem and requires high mathematical and programming skills, especially, when parallel and distributed programs are developed [10]. Thus, to automate this process, there is a need for high-level tools that reveal the potential of HPC and support a complex technological process from the problem formulation to model creation.

An analysis of recent publications in the field of simulation modeling of queue systems shows that managers may choose from available simulation tools that differ in the accuracy of real-world representation and performance [11-14]. However, many tools do not use HPC power, and do not consider all details of subject domains [15]. Services and their delivery for users are also important components for interfaces of modern simulation tools [16].

In this paper, we propose tools for simulation modeling of warehouse logistics processes in a heterogeneous distributed computing environment. These tools provide additional opportunities for a warehouse manager to adjust parameters of the WMS.

2. Warehouse management

The goal of logistics systems is to coordinate activities of the company to optimize processes related to acquiring, moving, storing, and delivering products in all stages of flow of goods, and provisioning information and services.

An important goal is to maintain cost-effective solutions and improve customer service. As an inherent element of logistics systems, warehousing plays an important role in ensuring a satisfactory level of customer service at the lowest possible expenditure on it. A warehouse is used for the storage of both, raw materials and finished goods during all stages of a logistics process.

The LW is a distribution center, where input flows are converted into output flows. It performs the following major logistics operations: transportation, loading/unloading, receiving/dispatching, identifying, sorting, packaging, warehousing, pre-assembly, cargo processing, collection of returnable waste, item distribution, pricing, etc. Figure 1 shows the logical and information interconnections of basic operations. Material and information flows define the relationships between them. The warehouse manager uses the WMS to automate business processes related to material, financial, and information flows.

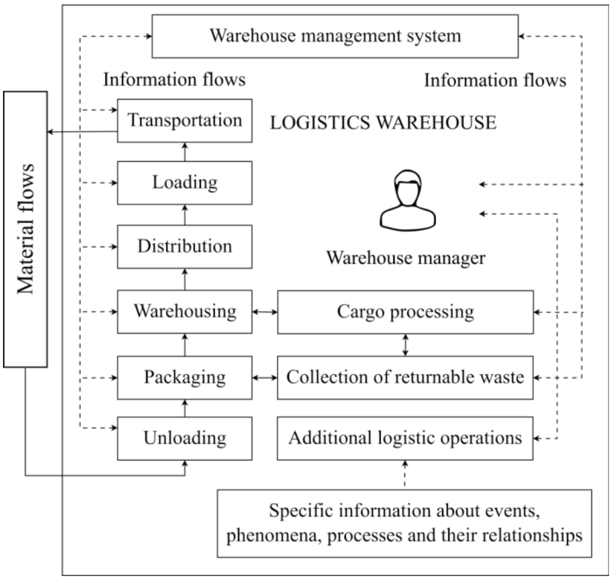

Fig. 1. Operations of a logistics warehouse.

The WMS has the capabilities to help the warehouse manager to study process details required to handle major and minor warehouse tasks. These tasks include control and validation of each operation stage, inventory of status changes, movement of goods, and recording information into databases. The additional operations are applied to information flows. For example, they include scheduling operations, predicting equipment failures, allocation of resources, analysis of operations efficiency, etc.

The LW model includes single-channel and multi-channel services. A customer request queue is processed according to the First-Come-First-Served (FCFS) policy with resource reservation. The reservation is included in a servicing schedule. In general, the customer service is multi-phase service. The simulation model has to take into account possible service faults. Flows of customer requests and service faults have the properties of stochasticity, discreteness, dynamics, non-ordinariness, non-stationarity, heterogeneity, and lack of feedback. An appearance of requests and faults is performed according to different probability distributions.

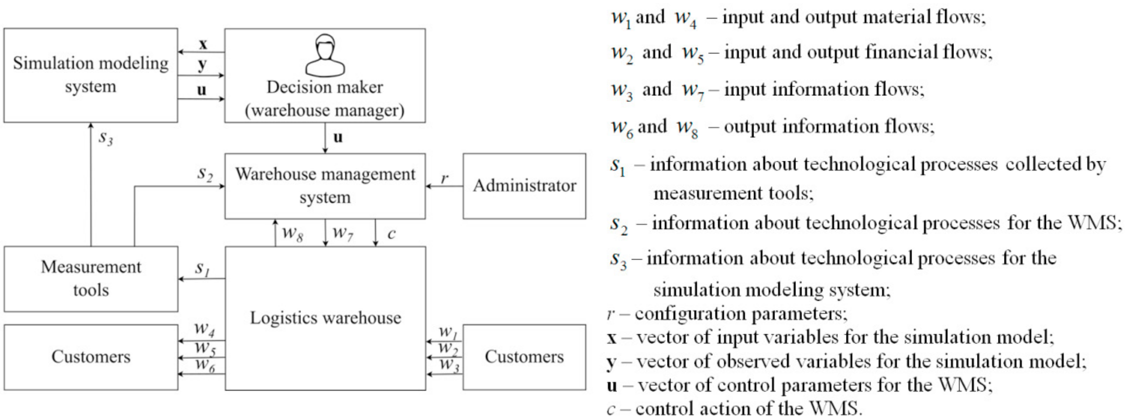

Fig. 2. Block diagram of the warehouse management.

Figure 2 shows a block diagram of the warehouse management model. We use simulation modeling to solve the following problem:

$$y_i(\mathbf{x}) \to \min(\max)\,, \tag{1}$$

$$y_i^{\min} \le y_i \le y_i^{\max}\,,\ i = \overline{1,m}\,. \tag{2}$$

The problem described by (1) and (2) is solved using the parameter sweep for the vector $\mathbf{x}$, and further multi-criteria selection for the vector $\mathbf{y}$. Elements of the vector $\mathbf{u}$ are associated with sweep elements of the vector $\mathbf{x}$ that have values corresponding to the selected variant of values of the vector $\mathbf{y}$.

The decision maker (warehouse manager) adjusts a range of the control parameters for the WMS using the vector $\mathbf{u}$ as the result of simulation modeling. The following parameters are adjusted: standards, expenses and cost for the logistics operations, cost structure, categories of customers, levels of their service, etc. The simulation modeling of the LW is initiated by the decision maker in a given time frame.

3. Toolkit SIRIUS II

We develop the toolkit SIRIUS II for the simulation modeling of the LWs (Figure 3).

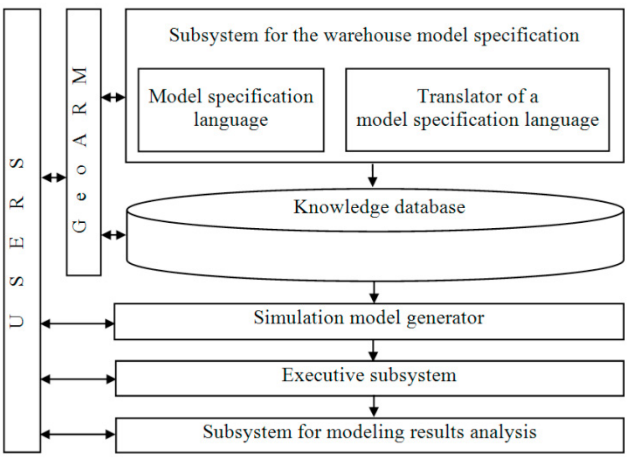

Fig. 3. Toolkit architecture.

The toolkit is based on an integrated use of conceptual, wireframe, and service-oriented programming, parameter sweep and data analysis. It includes the following main components: user interface; subsystems for warehouse model specifications, simulation model design, model execution in distributed computing environment, and analysis of modeling results; and knowledge database.

The developer describes a model structure on a special language and translates it in terms of SQL for constructing the knowledge database scheme (Figure 4). User interface is implemented with the GUI toolkit GeoARM [17]. Unlike known systems for creating database applications, the GeoARM provides automated extraction of information about the database structure, and then, formalizes this knowledge. The GeoARM uses algorithms for access to the database tables, their modification, dynamic creation of the user interface, additional manual configuration of its design, and interaction with external software systems.

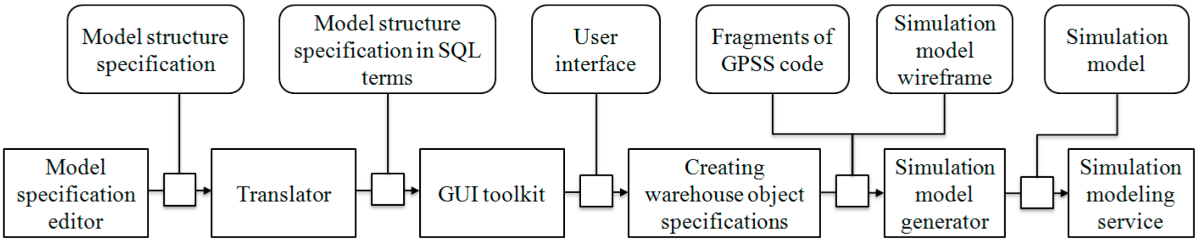

Fig. 4. Simulation model creating process.

The simulation model generator creates models based on wireframe approach to programming using prepared fragments of GPSS code (Figure 4). These fragments model a behavior of subject domain objects.

The conceptual model description is implemented using the first subsystem. The initial conceptual model description (database schema) includes a set of build-in system components: classes, attributes, and types. A specification language targets to describing objects of subject domain, attributes, and relations between objects.

The conceptual model of the warehouse is represented by the structure $S = <O, A, R, C, P>$, where the sets O, A, R, C and P represent respectively the warehouse objects, their attributes, relations between objects, constraints for these relations, and warehouse processes. It is based on the approach to conceptual modeling proposed by Bychkov et al. [18]. Two subsets of object attributes (parameters) are related to the warehouse process: input and output. The process defines output parameters depending on input parameters.

The scheme of the warehouse functioning processes is created with elements of the set P that define the sequence $f = (p_1, p_2, ..., p_r)$. Figure 5(a-c) shows examples of various schemes of the warehouse functioning processes. The processes of unloading, warehousing, loading, transporting and packaging goods, collecting returnable waste and cargo processing are represented by the elements p_1, p_2, p_3, p_4, p_5, p_6 and p_7 respectively.

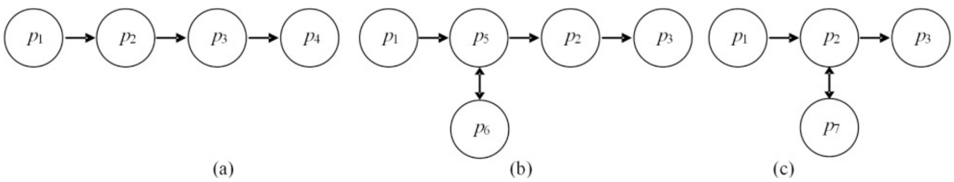

Fig. 5. Schemes of unloading, warehousing and loading goods with additional operations of transportation (a), packaging goods and collecting returnable waste (b), and cargo processing (c).

The set $Q \subset C$ defines constraints represented in (2). Components of the vector $\mathbf{y}$ represent object attributes from the set A. We use procedural and non-procedural problem formulations for the scheme creation that have the forms "Perform f with the set Q of constraints" and "Calculate Z using D with the set Q of constraints", where $D \subset A$ and $Z \subset A$. Elements of the subset D correspond to elements of the vector $\mathbf{x}$ in Figure 2.

In non-procedural formulation of the problem, the sequence f is formed automatically using relations between the subsets D and Z that are described in the model. Otherwise, the information planning is implemented and subsets D and Z are formed for the known sequence f. In general, a set of schemes can be created for each non-procedural problem formulation.

The conceptual model description is translated to the SQL language to record it in the database. Such properties of the model as the completeness, correctness, and integrity are identified in the model translation process. The model specification language belongs to ontology description languages. The model specification tools provide facility for development of fragments in parallel by different users and their aggregation.

Fragment of the simulation model are developed with the GPSS language for each process $p \in P$. The needed additional analytical models are implemented in C language, and called using the PLUS language built into GPSS. The simulation model is generated automatically according to the scheme of the logistics warehouse functioning processes. We use wireframe programming for the simulation model construction. Different variants of the model realize various schemes.

The subsystems for the simulation experiment design, case study, and analysis of simulation results are represented by the distributed service-oriented computing environment [19]. The service-oriented environment uses resources of the Center of collective usage “Irkutsk Supercomputer Center of SB RAS” [20].

We design the simulation model as the parameter sweep application that generates a large number of independent jobs [21]. Each job runs the model with a variant of values of input variables. After execution of all jobs, the environment services provide the collection of simulation results (variants of the vector $\mathbf{y}$). We apply multi-criteria selection of the results to form the vector $\mathbf{u}$ with evaluation of components of the vector $\mathbf{y}$ using the conditions represented in (1) and (2). Users assign an extremum for these components before task solving.

4. Experimental analysis

The proposed approach to adjust parameters of warehouse management systems is applied in the refrigerated warehouse of the Co Ltd “Irkutsk Khladokombinat”. At present, this dynamic, expanding enterprise includes a warehouse of the class A, several warehouses of the class B, and a refrigerated warehouse. The refrigerated warehouse is the second in terms of storage volume in Russia, from the Urals to the Far East. In this regard, it attracts special attention. The refrigerated warehouse has the following characteristics:

- 6 floors, 8 freight elevators and ramps for road and rail transport,
- 42 storage units with the total storage capacity of 20000 tones and several temperature regimes,
- Storage conditions include a safekeeping and storage rent,
- 8 commodity groups, various categories of customers who differ by the required volume and conditions of the storage, type of goods, turnover intensity, type of transport used, customer loyalty, etc.,
- Additional objects of commercial real estate that include offices, back offices, garages, and services of cargo processing that can be used for other purposes after their re-equipment depending on customer demand.

We address three optimization tasks that take into account the elevators usage, temperature regimes of storages, and equipment failures and risks associated with human factors.

3.1. Task formulations

Task 1: Improvement of loading and unloading processes, including returnable waste processing. The refrigerated warehouse provides loading and unloading operations for input and output material flows in accordance with planned and random requests. The planned requests contain an information about the time of receiving and dispatching goods, time of request servicing, goods volume, and required resources to carry out necessary operations. It is necessary to determine control actions of the process to improve the following criteria: loader efficiency, average time of loading and unloading operations, profit from returnable waste, and average time of returnable waste collection.

We use these four criteria as observed variables of the simulation model. Sweep parameters (a part of the model input) include number of loaders, electric loaders, loader teams, storekeepers, and schedule of the loader teams’ work, maintenance schedule of electric loaders, cargo unit, and schedule of planned requests.

Task 2: Restructuring of customer service. The refrigerated warehouse provides services to various categories of customers. Hence, it is necessary to determine the control action to parameters of the customer service to improve the following criteria: warehouse filling, average profit from loading and unloading operations, number of storekeepers, and number of elevator calls.

We use these four criteria as observed variables. Sweep parameters include cost of loading and unloading, cost of storage, rent price, level of customer service, one-time cargo volume of the client, timeliness of payment, sensitivity to changes of the service cost, solvency, storage duration, frequency of arrival, lack of own warehouses, assortment of goods, and frequency of shipment.

Restructuring of the customer service includes customer categorization based on the qualitative and quantitative characteristics of customers, service level determination for different customer categories, and operation standards selection. In the refrigerated warehouse, there are four customer categories: A, B, C and D. Different volumes of goods turnover per month characterize these categories: up to 50 tons (D), from 50 to 200 tons (C), from 200 to 600 tons (B), and over 600 tons (A).

Task 3: Re-equipment and rent out of additional objects of commercial real estate. The refrigerated warehouse implements the project related to re-equipment and rent out of additional objects of a commercial real estate. It is necessary to determine the control actions to parameters of the re-equipment process to improve the following criteria: incomes and spending of commercial real estate.

We use these two criteria as the observed variables of the simulation model. Sweep parameters include category of objects and predicted demand for objects during a certain period of time. In this task, the target criterion is a profit from additional objects of commercial real estate.

3.2. Performance evaluation

In this section, we evaluate our toolkit by designing parameter sweep application. Experiments include the following stages: selecting sweep parameters and observed variables of a model, preparing and carrying out an experiment, collecting simulation results, selecting values of the observed variables, and forming the control actions.

Sweep parameters and observed variables of a model for each task were considered above.

We prepared experiments based on task formulations. The simulated period of warehouse work was one year. This was decided due to the fact that various goods turnover and customer service demands differ in different quarters of the year. Value ranges had from 2 to 24 levels for different sweep parameters. Full factorial experiments included 3583944, 6291456 и 518400 variants of input data in the tasks 1-3 respectively. To solve the tasks in the allotted time of a computational resources use, we carried out partial factorial experiments. A model run number for one data variant in the tasks changed from 100 to 200. It provides an error for average values of observed variables, which is not more than 0.05.

The service-oriented environment provides an automated support of generating variants of input data, model runs, and collecting simulation results. After completion of computations, we conduct a comprehensive performance evaluation study. In order to provide effective guidance in selecting the best parameters (model inputs), we perform a joint analysis of task criteria according to multi-criteria optimization.

Let us denote by $V=\{v_1,v_2,...,v_n\}$ a finite set of variants of calculated values for the vector $\mathbf{y}$. The elements y_i represent criteria defined in a task and ordered by the LW manager in accordance with their importance, $i\in\overline{1,m}$. Also, denote by y_{ij} a value of the *i*th criterion in the *j*th variant. For each criterion y_i, values y_{ij} are ordered and indexed by ascending or descending order in accordance to the defined in (1) extremum for the *i*th criterion, $j=\overline{1,n}$. Equal values are assigned the same index. Indexes of the values y_{ij} are used as their estimates $\hat{y}_{ij}$.

We use the following lexicographic rule for a selection of the optimal variant v_o:

$$v_o\in V:(\forall v_k\in V\ \exists p:(\hat{y}_{1,o}=\hat{y}_{1,k})\wedge...\wedge(\hat{y}_{p,o}=\hat{y}_{p,k})\wedge(\hat{y}_{p+1,o}>\hat{y}_{p+1,k})),\ p\in\overline{1,m-1},\ k,o\in\overline{1,n},\ k\neq 0\,.$$

The existence of a hierarchy among criteria allows us to solve the selection problem sequentially, step-step, optimizing each of the following criteria. In practice, a solution is quickly found. In the particular case, if there are several variants equal to v_o , then the final selection can be made based on the expert evaluation of the LW manager. At the final stage, values of model inputs (sweep parameters of the vector $\mathbf{x}$) that correspond to the selected variant v_o are assigned to the elements of the vector $\mathbf{u}$ and used for the WMS parameter adjustment.

When we examine the overall performance of the warehouse with real data, we find that our tools for model design and parameter adjustment perform well even if they do not take into account all details of real warehouse.

Using results from solving the first two tasks, the LW manager determines the optimal schedules of loader team works, electric loader maintenance, planned requests, and other parameters for the used WMS. His control actions balanced the goods turnover and increased the loader efficiency due to reduction in loader idle time and selection of more efficient schemes of the customer service. Despite the greater turnover caused by the increase in warehouse filling, Figure 6(a) shows more balanced volumes of goods turnover in different periods of a daily working shift in comparison with similar indicators of the previous year. Increasing the efficiency of loading and unloading operations provided an opportunity for the more efficient processing returnable waste.

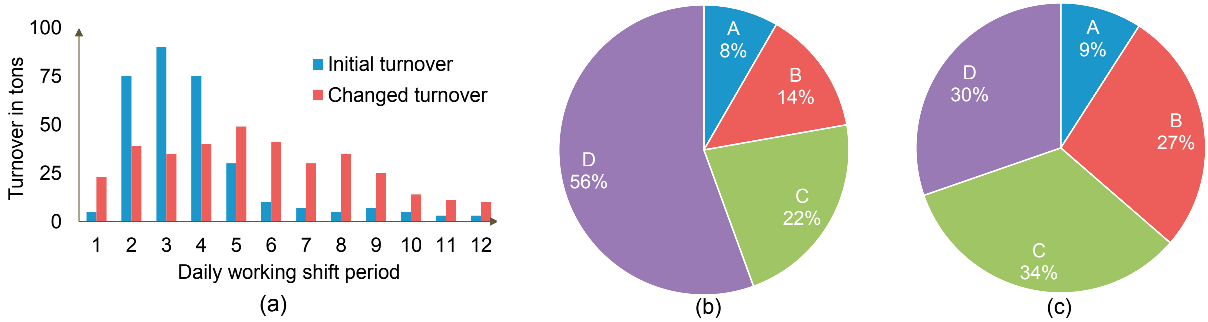

Fig. 6. WMS parameter adjustment results: turnover changing (a) and customer categories beefore (b) and after (c) restructuring.

Simulation modeling of warehouse processes for the second task showed that overheads for customer servicing grows in accordance with the decrease of their goods turnover. Especially, customer service in the category D has a negative effect on the efficiency of loading and unloading operations and their average cost. In this regard, the LW manager differentiated a service cost for customers of the categories A-D in ascending order. Figures 6(b) and 6(c) shows that the change in cost led to a reduction in the number of clients in the category D and an increase in the number of customers in the categories A-C. Control actions of the LW managers provided the increase of warehouse filling and average profit from the operations, and partially reduced the workload on technical and human resources.

Re-equipment and rent out of additional objects of commercial real estate allowed to increase incomes per month in comparison with the same periods of the previous year. Figure 7(a) shows this improvement in percentages. During the year after solving the task 3, 32 objects were re-equipped taking into account their functioning within a common scheme of the customer service, predicted demand, and available resources of the warehouse.

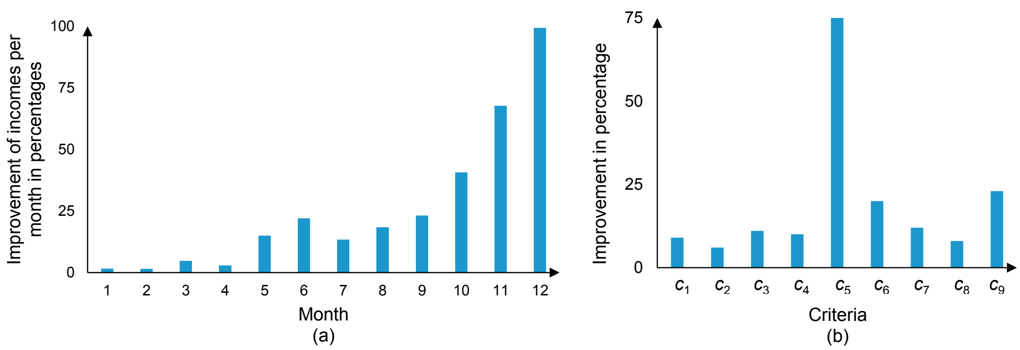

Fig. 7. Improvement of incomes per month (a) and all criteria (b).

To summarize the results of the study, Figure 7(b) shows the nine criteria improvement that varies from 6% to 75%. We compared annual values for these criteria obtained respectively before and after the WMS parameter adjustment. Loader efficiency (c_1), average profit from loading and unloading operations per month (c_3), average warehouse filling per month (c_8), total profit from returnable waste (c_5) and additional objects of commercial real estate (c_9) have been respectively increased by 9%, 11%, 8%, 75%, and 23%. In the same time, average time of loading and unloading operations (c_2), average time of the returnable waste collection (c_4), storekeeper number (c_6) and elevator calls number (c_7) have been respectively decreased by 6%, 10%, 20%, and 12%.

The designed sweep application includes three simulation models for the solved tasks. In a task-solving process, it generates independent jobs to run a model with one of value variants for its input variables. Models run in dedicated resources of the service-oriented environment using virtual machines. The multi-agent system for computations management in the environment ensures a capability to run virtual machines in queues of idle non-dedicated resources. An independence of jobs and this capability of the multi-agent management provides a high computation scalability. Figures 8(a) and 8(b) illustrate the obtained speedup and efficiency versus number of cores in comparison to the linear speedup and efficiency equal to 1 respectively. All experiments are carried out in the environment based on resources of the Center of Collective Usage "Irkutsk Supercomputer Center of SB RAS" [20].

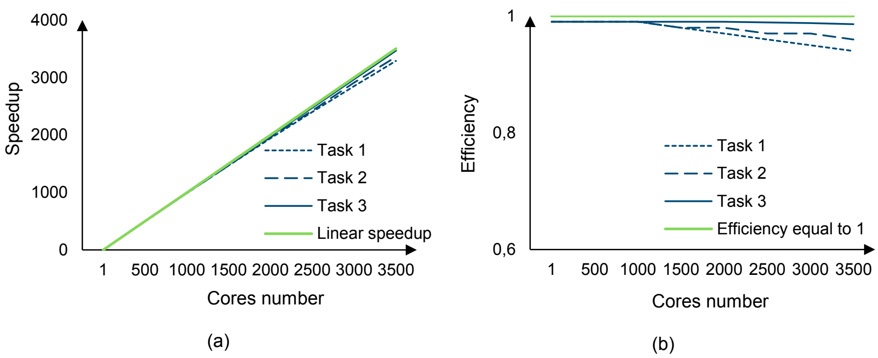

Fig. 8. Speedup (a) and efficiency (b) versus the number of cores.

4. Conclusion

In this paper, we address the problem of automation in simulation modeling of logistics warehouses based on distributed computing. Our contribution is multi-fold. We developed the toolkit named SIRIUS II for the simulation modeling of the LWs using HPC. We provided the conceptual model for planning of various schemes of logistic operations, tools for simulation model development, and distributed service-oriented computing environment for the execution of these models. We created the parameter sweep applications for the simulation modeling of the logistics warehouse and optimized refrigerated warehouse of the Co Ltd "Irkutsk Khladokombinat".

We conducted a comprehensive performance evaluation study of our tools. In order to provide effective guidance in choosing the best parameters, we performed an analysis of nine metrics for each solved task. When we examined the overall performance of the warehouse on the real data, we found that our tools for model design and parameter adjustment performed well even if they do not take into account all details of real warehouse.

The benefit of our approach is that the toolkit provides additional possibilities for warehouse managers to adjust parameters of the WMSs. We showed that parameter adjustment allows to improve the warehouse functioning from 6 to 75 percent considering nine criteria. The obtained results can be applied to an automation of computational experiments for large-scale studies based on simulation modeling and queue system theory in various problem domains. In practical experiments, we demonstrated the high scalability of the parameter sweep application developed in the toolkit SIRIUS II.

Acknowledgements

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