Toolkit for Simulation Modeling of Logistics Warehouse in Distributed Computing Environment

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Abstract

We address an important problem of an automation of logistics warehouses simulation modeling in distributed service-oriented computing environments. To this end, we propose new approach for adjusting management system parameters of real warehouse in production use. It is based on the integration of the conceptual, wireframe and service-oriented programming used to develop parameter sweep applications and data analysis in the simulation modeling process. We develop a toolkit for supporting modeling of warehouse logistics. The practical experiments are focused upon the refrigerated warehouse. The developed application demonstrates high efficiency and scalability for optimizing nine criteria to cope with different production demands.

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

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 a simulation modeling. Queuing systems are used for modeling manufacturing, material handling, transportation, communication, information processing systems, etc.

The important class of queuing systems are logistics warehouses (LWs). These systems are oriented to the management of the large capacity cargo traffic, distribution of goods, etc. Often, a functioning of the 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 of the warehouse management are functional and organizational structures analysis and optimization. In part, these problems can be solved by warehouse management systems (WMS) [1].

The trends of the modern LWs include improvement of technologies, communication systems, expansion of a set of warehouse and logistic operations, increasing operational complexity, designing efficient logistic decisions and optimization tools, etc.

The simulation modeling is one of the most effective approaches to the LWs functioning analysis [2]. It simplifies the development and optimization of operational schemes and their parameters [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, the researcher adjusts the values of parameters by sweeping their values in defined ranges. These experiments provide a low-cost method to determine the optimal parameters for the operations.

The efficiency of results directly depend on the problem-oriented knowledge usage [4]. For example, Felice and Petrillo [5] present the successful application of the simulation modeling based on the problem-oriented knowledge in the decision-making process for the manufacturing system. Gwynne [6] represent a range of the known WMSs.

Unfortunately, often, they do not take into account unpredictable factors and production uncertainties [7, 8], and do not have needed tools for solving various unexpected problems of the warehouse management. For example, efficient management needs:

- 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,
- Prediction of the possible financial results for different periods,
- Analysis of customer service levels.

High-performance computing (HPC) became an essential part of large-scale mathematical modeling. Thus, it is essential to design special tools for development of the simulation programs that are parallel and scalable.

The simulation program design, which adequately reflects the studied system, is non-trivial problem and requires the high mathematical and programming skills [9]. 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 flow from the problem formulation to model creation.

An analysis of the recent publications in a field of the simulation modeling of queue systems shows that managers may choose from a range of 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 take into account all details of subject domains [15]. Services and their delivery for users are also important components for interfaces of the modern simulation tools [16].

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

2. Warehouse management

The warehouse performs the following major logistics operations: transportation, loading/unloading, packaging, warehousing, 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 set and optimize material, financial and information flows.

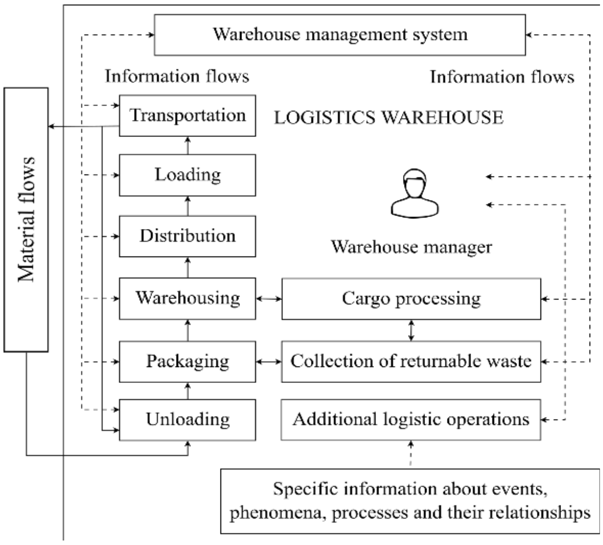

Fig. 1. Operations of a logistics warehouse.

The WMS has the capabilities to help the warehouse manager to study processes 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 the scheduling operations, predicting equipment failures, transformation of external constraints into internal constraints, allocation of resources, analysis of the operations efficiency, etc. An administrator of the WMS configures its parameters.

Figure 2 shows a block diagram of the warehouse management. The model includes single-channel and multi-channel services. The customer request queue is processed according to the First-Come-First-Served (FCFS) policy with resource reservation. The reservation is included into 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 the customer requests and service faults have the properties of stochasticity, discreteness, dynamics, extraordinariness, heterogeneity, non-stationarity, and lack of feedback. An appearance of the requests and faults is performed according to different probability distributions.

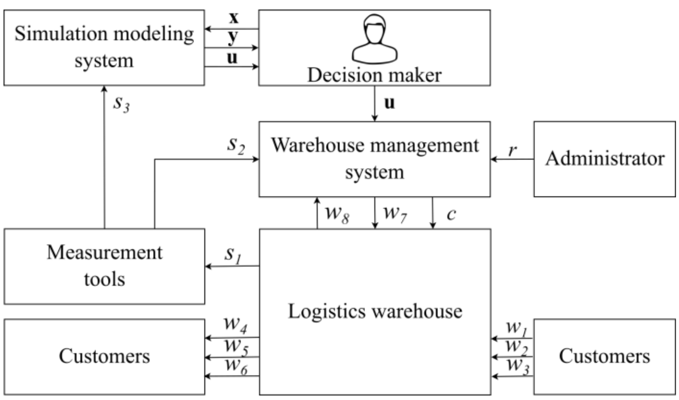

Fig. 2. Block diagram of the warehouse management.

Table 1 describes the parameters used on the block diagram of the warehouse management in Figure 2.

Table 1. Parameters description

Notation	Description
w_1	Input material flow
w_2	Input financial flow
w_3	Input information flow
w_4	Output material flow
w_5	Output financial flow
w_6	Output information flow
w_7	Output Input information flow
w_8	Output information flow
s_1	Information about technological processes collected by measurement tools
s_2	Information about technological processes for the WMS
s_3	Information about technological processes for the simulation modeling system
r	Configuration parameters
$\mathbf{x}$	Vector of input variables for the simulation model
$\mathbf{y}$	Vector of observed variables for the simulation model
$\mathbf{u}$	Vector of control parameters for the WMS
c	Control action of the WMS

We use the simulation modeling to solve the following problem:

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

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

For different components of the vector $\mathbf{y}$, the dependence of the vector $\mathbf{x}$ in (1) is representable in simulation model by functional, statistical, ambiguous, or other relations.

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

The decision maker 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.

3. Toolkit SIRIUS II

We develop the toolkit SIRIUS II for the simulation modeling of the LWs in a distributed service-oriented computing environment. The toolkit functioning is based on an integrated use of the conceptual, wireframe and service-oriented programming, parameter sweep and data analysis. The toolkit includes the user interface and the subsystems for warehouse model specifications, simulation model design, model execution in distributed computing environment, and analysis of modeling results (Figure 3).

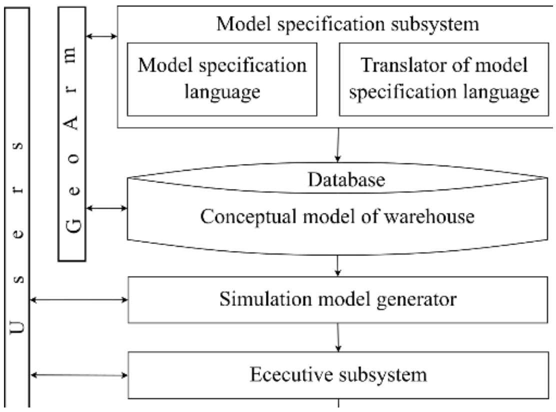

Fig. 3. Toolkit architecture.

User interface is implemented with the GeoARM system [17]. Unlike to 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, and interaction with external software systems.

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. Two subsets of object attributes (parameters) are related with the warehouse process: input and output. The process defines output parameters depending on input parameters.

The scheme h of the warehouse functioning processes is created with elements of the set P that define the sequence f:

$$f = (p_1, p_2, ..., p_m).$$

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. They have the following forms:

- Perform f with the set Q of constraints,
- 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 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 into 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 the 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 [18] provided by Irkutsk Supercomputer Center of SB RAS [19].

We create the simulation model as the parameter sweep application that generates the large number of jobs [20]. Each independent job runs the model with the single values variant of its input variables. After execution of all jobs, the environment services provide the collection of simulation results represented by 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) [21]. Users assign an extremum for each component of the vector $\mathbf{y}$ before the task solving.

4. Experiments

The proposed approach to adjusting parameters of warehouse management systems is applied in the refrigerated warehouse Co Ltd "Irkutsk Khladokombinat". The warehouse has the following characteristics:

- 6 floors, 8 freight elevators and ramps for a road and rail transport,
- 42 storages 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 that 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 the customer demand.

In this paper, we solve the following optimization problems (Task 1-3):

1. Improvement of the loading and unloading processes, including returnable waste processing.
2. Restructuring of the customer service, including the customer categorization based on the qualitative and quantitative characteristics of customers, service levels determination for different customer categories and operations standards selection.
3. Re-equipment of the additional objects of commercial real estate.

Features of these tasks are the taking into account the equipment failures and risks, associated with the human factors.

In the toolkit SIRIUS II, we describe the conceptual model, develop the simulation models for solving the aforementioned tasks, create the parameter sweep application including the developed models, planning the experiments and execute models. The experiments planning has been performed with the help of methods, proposed by Boev [22].

We conduct a comprehensive performance evaluation study of our tools. In order to provide effective guidance in choosing the best parameters, we perform a joint analysis of nine metrics (Table 2) according to multi-criteria analysis assuming different importance of each criteria. When we examine the overall performance of the warehouse on the 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. Table 2 shows the criteria improvement.

Table 2. Criteria improvement

Criteria	Improvement
Loaders efficiency	9 %
Average time of the loading and unloading operations	6 %
Average profit of the loading and unloading operations	11 %
Average time of the collection of returnable waste	10 %
Profit of the returnable waste	75 %
Storekeepers number	20 %
Elevators calls	12 %
Warehouse filling	8 %
Profit of the additional objects of commercial real estate	23 %

Figure 4 and Figure 5 demonstrate the speedup and efficiency of the computations in the task solving process versus number of cores in distributed environment. These results confirm the high scalability of the parameter sweep application developed in the toolkit SIRIUS II.

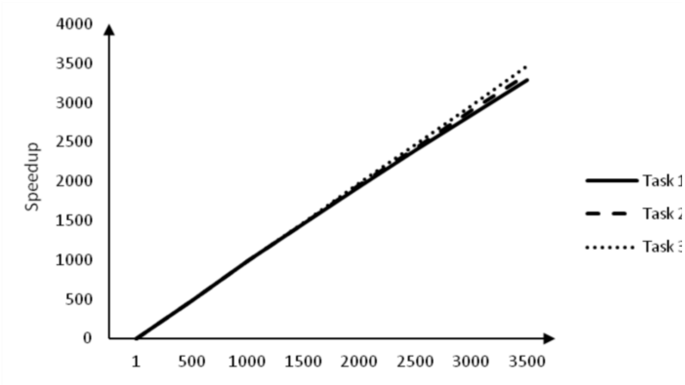

Fig. 4. Speedup versus the number of cores.

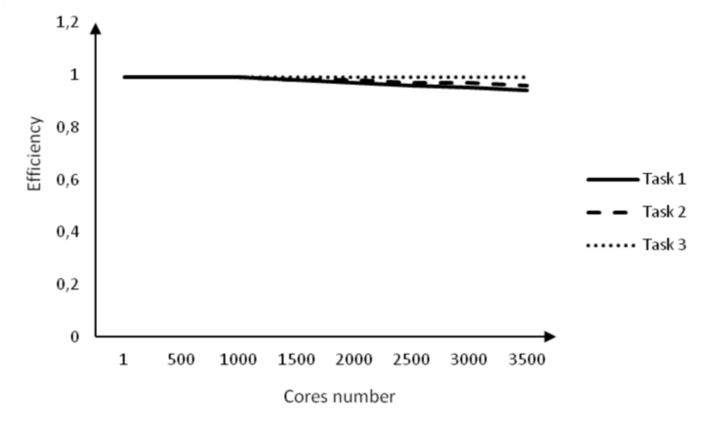

Fig. 5. Efficiency versus the number of cores.

5. Conclusion

In this paper, we address the problem of an automation of logistics warehouses simulation modeling based on distributed computing. Our contribution is multifold.

We developed the toolkit named SIRIUS II for the simulation modeling of the LWs using HPC. In this toolkit, we provide 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 solved optimization tasks for the refrigerated warehouse Co Ltd “Irkutsk Khladokombinat”.

We conduct a comprehensive performance evaluation study of our tools. In order to provide effective guidance in choosing the best parameters, we perform a joint analysis of nine metrics according to multi-criteria analysis assuming different importance of each criteria. When we examine the overall performance of the warehouse on the 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.

Practical experiments showed the high scalability of the parameter sweep applications developed in the toolkit SIRIUS II. The benefit of our approach is that the toolkit provides additional opportunities for warehouse managers to adjust parameters of the used WMSs. The parameter adjustment allows to significantly improve the warehouse functioning considering nine criteria. The obtained results can be applied to an automatization of computational experiments for large-scale studies based on the simulation modeling and queue system theory in various problem domains.

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