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THE METHODOLOGY FOR SUBSTANTIATING THE MATERIALS HANDLING EQUIPMENT OF A UNIT LOAD WAREHOUSING SYSTEM

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Abstract: *The most important objectives of a warehouse system organization design's to substantiate the structure of the materials handling equipment fleet, which directly determines the quality of functioning of the warehouse system in the supply network of industrial enterprises. The complexity of the above objective's preconditioned not only by the existing variety of handling equipment models, but also by a large number of factors affecting the efficiency of the equipment fleet, being determined by the specifics of cargo flows and the space-planning solution of a warehouse. This paper studies the problem of substantiating the optimal number of materials handling equipment units in the composition of various technological groups in a unit load warehouse system. Methodology implies iterative optimization of the equipment quantity according to a criterion of minimization of total aggregate costs caused by equipment maintenance or downtime of transport vehicles with various values of the number of service channels for transport vehicles.*

Keywords: *industrial enterprise, warehouse system, materials handling equipment, technological group, service channel, handling queue, handling capacity, aggregate costs.*

1. Introduction

The conditions where industrial enterprises are evolving today imply that advance information technology is intensively developing and getting introduced into production processes to ensure their better flexibility and adaptiveness to the changing external environment. So the issues related to substantiating the warehousing process characteristics in the relevant supply chains are of special importance. This circumstance is preconditioned, on the one hand, by the need to minimize the total aggregate costs in terms of the entire process of customer needs satisfaction in order to ensure the competitiveness of new generation production systems (Leventsov et al., 2017), and, on the other hand, by a high proportion of costs related to stock-keeping of products in the structure of the total logistic expenses in the supply chains of industrial enterprises. Herewith, one of the most important objectives (from the positions of minimizing the enterprises' logistic costs) is to substantiate the characteristics of the materials handling equipment fleet (MHE) which directly ensures the implementation of the materials handling process and, consequently, considerably affects the

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efficiency indicators of the operating supply chains of industrial enterprises (Ahmad, 2006; Ertuğrul & Güneş, 2007). The problem is also complex because the warehouse performance indicators (including traffic capacity and operating costs) depend both on the quantity of the MHE and on its technical characteristics (Shymchenko et al., 2017; Zobacheva et al., 2017)

This circumstance has determined the need to carry out research aimed at developing some tools for substantiating the characteristics of the MHE fleet and a unit load warehouse system (Aiello et al., 2002; Bhattacharya et al., 2002). It is important to note that the methodology to be created must consider various specific features of the warehousing technological process, such as:

- parallel handling of the elements of incoming and outgoing cargo flows entering and leaving the warehousing system – unit loads (ULs) corresponding to individual transport vehicles (TVs);
- technological specialization of the structural elements of the MHE fleet – presence of the so-called technological groups of machinery, with each of them performing a certain set of cargo handling operations;
- non-linear dependence of the equipment performance on its quantity, preconditioned by a negative impact of some factors, such as limitations of the working area and the presence of certain discipline of the premises and cargo withdrawal from the main storage area.

The MHE fleet, as a rule, includes standard models of machinery produced by well-known manufacturers and having concrete values of technical characteristics (Alekseev et al., 2017). So the priority objective of the research is to develop methodology for substantiating the quantity of MHE with specified technical characteristics (i.e. identical to each other units of equipment) in the context of technological groups (Roy et al., 2016). In the next phases of the research, the practical application of this methodology will allow sophisticating the objective by considering various models of equipment in the context of technological groups (Choudhury et al., 2013).

It is also important to note that in order to ensure its practical applicability (in terms of real enterprises), the methodology must be implementable with the usage of such standard computational algorithms as "Microsoft Excel", "Mathcad", "MatLab" etc.

This paper is organized as follows. Section 2 presents the review and analysis of the results of scientific papers substantiating the characteristics of the MHE fleet in warehouse systems (Glukhov et al., 2016; Ismagilova et al., 2017). Section 3 includes the problem definition which concerns substantiation of the MHE quantity for a unit load warehousing system. Section 4 contains a description of the problem solving methodology. Section 5 describes the procedure for applying the developed methodology to a practical example. Section 6 includes the analysis of the obtained results. Section 7 presents the conclusions and directions for further research.

2. Literature review

In the initial phases of research, some relevant scientific papers were reviewed. The results obtained are presented below.

In quite a few papers (including those written by (Abramov et al., 2012; Bowersox & Closs, 1996; Grishchenko et al., 2016 Melovic et al., 2015), substantiation of the MHE fleet is one of the logistic problems tackled in the context of functional storage area. However, no methodological solutions or tools are proposed by them. In papers by (Dybskaya, 2005; Jacyna et al., 2015) different approaches are suggested for solving the problem of forming a MHE fleet for the warehousing processes of materials handling (as a rule, no toolboxes are described) and some relevant practical guidelines are formulated.

A more detailed description of the procedure for substantiating the MHE fleet in the context of warehousing systems is presented in research studies by (Gadzhinskiy, 2005; Malikov, 2005; Mamaev & Osipov, 1974; Nikolov & Kazakov, 2013). In most of the above papers this procedure is described as a consequent solution of two constituent sub-problems:

1) The most preferable option is chosen by using analytical models of multi-criterion selection (Gadzhinskiy 2005; Nikolov & Kazakov, 2013).
2) The required quantity of the equipment is determined for the chosen option by using analytical models based on the preset intensity and average length of a cycle (Malikov, 2005), operational productivity (Mamaev & Osipov, 1974) and running time of the equipment (Gadzhinskiy, 2005). The drawback of this approach – consequent (time-phased) solving of individual sub-problems – is the difficulty in fining out the relation between the productivity of the MHE fleet, technical characteristics and the quantity of the machines.

A comprehensive solution – simultaneous substantiation of the quantity and characteristics of the machinery incorporated in the MHE fleet – with the usage of optimization and simulation modeling was looked into by (Radaev, 2015). In the research study the author also suggested a consolidated structure of a MHE fleet, including classes, technological groups and examples of equipment and substantiated functional dependences of a unit of equipment (of certain classes) on its technical characteristics (Khannan et al., 2016).

In some papers determining the characteristics of the warehousing MHE fleet is presented as an element of comprehensive problems for substantiating the structure of technological process (Kłodawski et al., 2017) and formation of a space and planning solution (Borovinsek et al., 2016; Cao & Zhang, 2017; Lerher, 2017; Marchet et al., 2012; Pekarcíková et al., 2014; Zou et al., 2016). Herewith, in order to solve the problems above, it is recommended to use graph analytic methods (Kłodawski et al., 2017; Marchet et al., 2012, Pekarcíková et al., 2014) mathematical optimization methods (Borovinsek et al., 2016) and simulation modelling (Cao & Zhang, 2017; Lerher, 2017; Zou et al., 2016). The quantity and characteristics of the equipment are presented in the composition of the relevant initial data. However, they can be determined by setting problems inverse in relation to the above-mentioned.

Research studies by (Pyza et al., 2017; Shchekutin et al., 2016) are dedicated to developing indicator systems for assessing the operating efficiency of warehouse equipment. The stipulated systems of indicators can be used as selection criteria for choosing the most preferable option (from the list of the preformed alternative variants) of the the machinery fleet structure in the phase when the operation of a warehousing system is organized (Klochkov et al., 2018).

According to the results of the analyzed research papers mentioned above, the following conclusions are made:

- in the majority of the above publications the processes of materials handling at a warehouse are looked into at a large scale. The specifics of the corresponding technological process (parallel work of various groups of equipment, interaction of machinery units in a restricted working area, etc.), parameters of the used MHE units (speeds of working mechanisms during operation of a machine when

loaded and not loaded, nominal lifting height of a UL and residual lift capacity, etc.) and costs related to ensuring the operation of a warehousing system (including maintenance costs of the MHE and additional losses caused by limited storage capacity) are not considered.
- in the scientific papers, which contain detailed description of the technological process of materials handling at a warehouse, the proposed toolbox provides a solution to the problem of substantiating the MHE fleet characteristics either indirectly (by setting and solving an inverse problem), or has a limited applicability in the context of the space planning solution (only most common technological schemes are considered). Moreover, the toolbox is hard to adapt and apply (Leoro et al., 2017).

Thus, none of the above scientific research results consider a large number of factors which affect the efficiency of the MHE fleet in terms of a warehousing system (Montoya et al., 2016). So they are only efficient in the context of large-scale organizational design of warehousing divisions of enterprises. This circumstance proves that this research is really topical.

3. Problem definition

This section of the article describes the consolidated statement of the problem related to substantiation of the MHE quantity of a load unit warehousing system in terms of general provisions, initial data and unknown variables.

The main provisions of the problem are the following ones:

- the research object is a warehousing system where palleted ULs are accepted, temporarily stored and shipped without re-kitting by using technological equipment for motor vehicles handling, ULs and MHE (means of floor trackless transport equipped with fork load handling devices that ensure handling of just one UL at a time) are stored;
- the spatial planning solution of the warehousing system includes the following technological areas: the main storage area, one or several loading and unloading fronts (LUFs), one or several intermediate storage areas, corresponding to LUFs (Figure 1); in the common case, the main storage area is fitted out with racking equipment, ensuring that a UL stays there for a long period between the time of arrival at and departure from the warehousing system; each LUF represents a technological area having equipment for TV unloading or loading (receiving gates, dock levelers, etc.) with certain characteristics – body dimensions, load carrying capacity, etc.; every intermediate storage area represents, as a rule, a one-level site, where ULs are temporarily accumulated while they are unloaded from the body of a TV and further transferred to the main storage area or withdrawn from the main storage area and further loaded to the body of a TV;
- cargoes are accepted and shipped from the warehouse for a limited number of suppliers and consumers, correspondingly; in addition, every contract agent is serviced by using identical transport vehicles; the characteristics of flows of suppliers' and consumers' TVs and the single flow of TVs (for unloading and for loading) satisfy the main statements of the queuing theory (i.e. they have such qualities as stationarity, lack of after-action, ordinariness);

- the structure of the MHE fleet in a warehousing system includes various technological groups of machinery; every group includes equipment units identical to each other, corresponding to a certain class and ensuring movement of ULs between a concrete pair of adjacent technological area, i.e. between a LUF and the intermediate storage area or between the intermediate and main storage areas; the process of movement of a UL performed by a LUF unit in the composition of an individual technological group represents a technological cycle, i.e. sequence of such operations as acquisition, transportation and shipment of a UL; the technological handling cycle of UL in terms of an individual LUF is executed only by one technological group of MHE; the combination of technological cycles implemented subsequently over every UL in the composition of a set handled during its acceptance or shipment represents a technological procedure (Figure 1);
- the operational productivity of every MHE unit in the composition of a technological group reduces with a rise in the number of machinery units in the group due to the limited width of working passes during parallel operation of equipment; thus a non-linear dependence is assumed between the productivity of a technological group of MHE and the quantity of the relevant units of machinery;

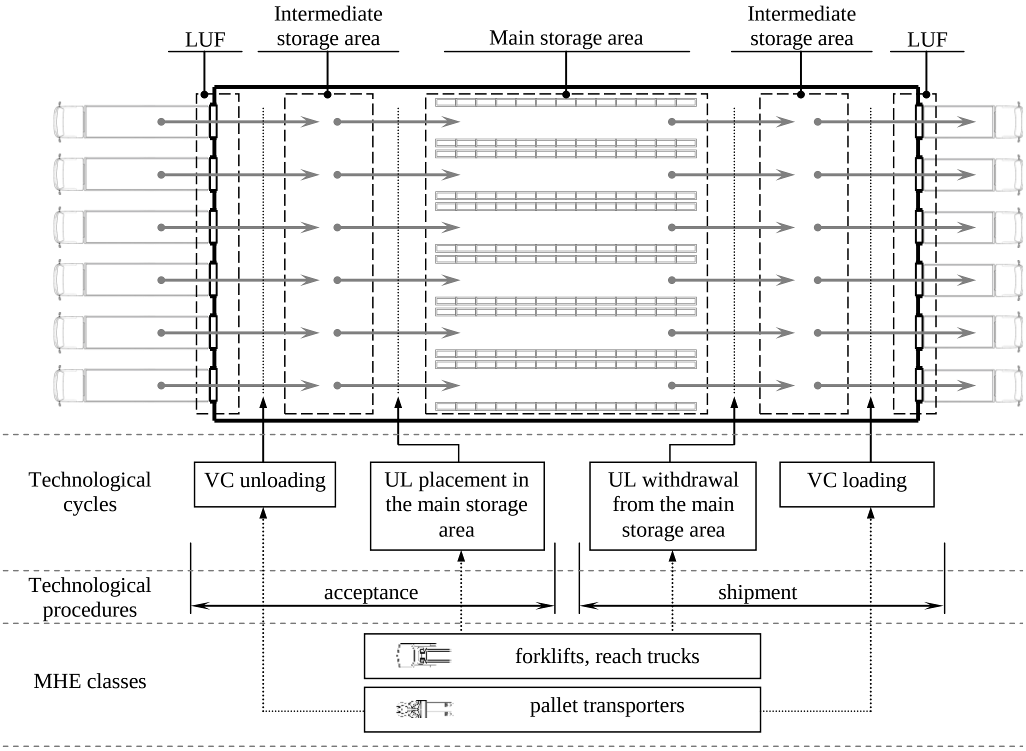
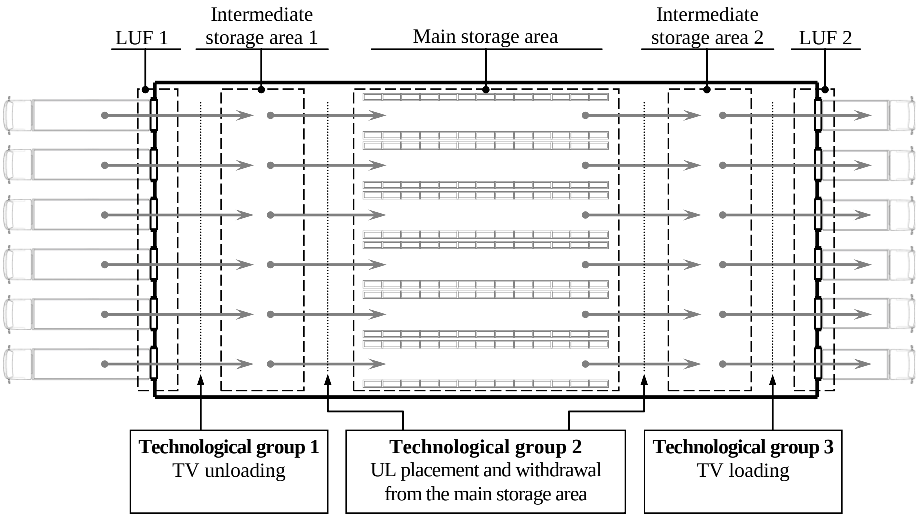


Figure 1. Relationship between the structural elements of in and out flows of cargoes, spatial-planning solution of the warehouse, implemented technological process and used MHE fleet.

- the spatial-planning solution of the warehousing system ensures simultaneous implementation of in and out technological procedures of UL sets corresponding to individual TVs in terms of various LUFs; in addition every technological group of MHE can simultaneously handle cargo flows in terms of several LUFs; depending on the correspondence of MHE to the stipulated technological procedures, the following technological schemes are marked out:
- a full-fledged scheme, implying that every technological procedure of accepting and shipping ULs is implemented by using a separate LUF (Figure 2);



Index of the technological group of MHE d	Correspondence indicator $y_{df}^{\text{in(out)}}$ for LUF index f in terms of the technological procedure			
	acceptance (<u>in</u>)		shipment (<u>out</u>)	
	1	2	1	2
1	1	0	0	0
2	1	0	0	1
3	0	0	0	1

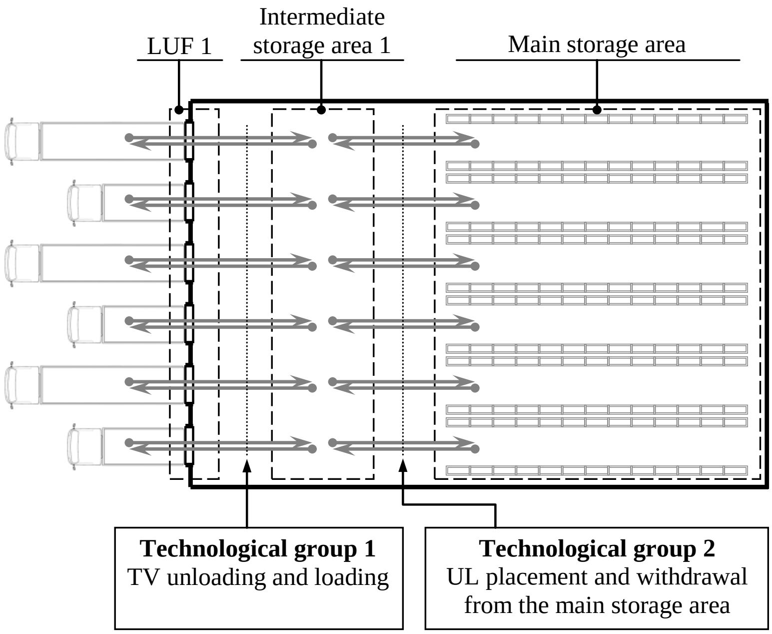
matrix Y^{in} matrix Y^{out}

Index of the technological group of MHE d	Ordinal number of technological operation $o_{df}^{\text{in(out)}}$ for LUF index f in terms of the procedure			
	acceptance (<u>in</u>)		shipment (<u>out</u>)	
	1	2	1	2
1	1	-	-	-
2	2	-	-	1
3	-	-	-	2

matrix O^{in} matrix O^{out}

Figure 2. Description of interrelation between MHE technological groups, executed by UL treatment cycles and by in and out procedures for a consolidated variant of the warehouse layout, corresponding to a detailed technological scheme

- an integrated scheme, implying that there is a single LUF to implement technological procedures of accepting and shipping ULs (Figure 3);



Index of the technological group of MHE d	Correspondence indicator $y_{df}^{\text{in(out)}}$ for LUF index f in terms of the technological procedure	
	acceptance (<u>in</u>)	shipment (<u>out</u>)
	1	1
1	1	1
2	1	1

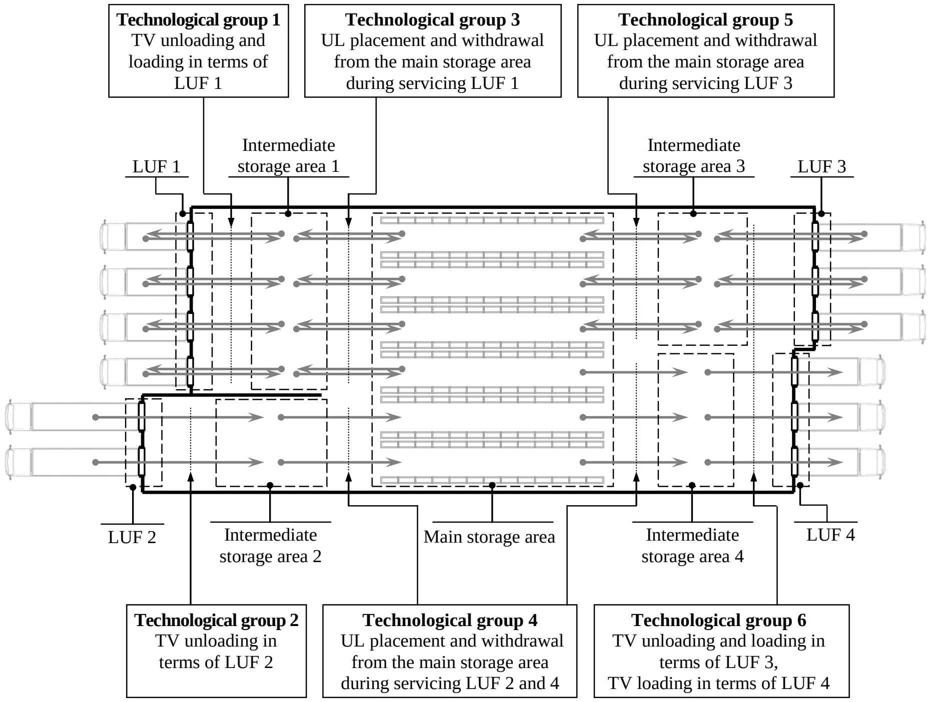
matrix Y^{in} matrix Y^{out}

Index of the technological group of MHE d	Ordinal number of technological operation $o_{df}^{\text{in(out)}}$ for LUF index f in terms of the procedure	
	acceptance (<u>in</u>)	shipment (<u>out</u>)
	1	1
1	1	2
2	2	1

matrix O^{in} matrix O^{out}

Figure 3. Interrelation between technological groups of MHE, executed by UL treatment cycles and by in and out procedures for a consolidated variant of the warehouse layout, corresponding to an integrated technological scheme

- a combined scheme, including elements of each of the above technological schemes (Figure 4);



Index of the technological group of MHE *d*	Correspondence indicator $y_{df}^{in(out)}$ for LUF index *f* in terms of the technological procedure							
	acceptance (in)				shipment (out)			
	1	2	3	4	1	2	3	4
1	1	0	0	0	1	0	0	0
2	0	1	0	0	0	0	0	0
3	1	0	0	0	1	0	0	0
4	0	1	0	0	0	0	0	1
5	0	0	1	0	0	0	1	0
6	0	0	1	0	0	0	1	1

matrix Y^{in} matrix Y^{out}

Index of the technological group of MHE *d*	Ordinal number of technological operation $o_{df}^{in(out)}$ for LUF index *f* in terms of the procedure							
	acceptance (in)				shipment (out)			
	1	2	3	4	1	2	3	4
1	1	-	-	-	2	-	-	-
2	-	1	-	-	-	-	-	-
3	2	-	-	-	1	-	-	-
4	-	2	-	-	-	-	-	1
5	-	-	2	-	-	-	1	-
6	-	-	1	-	-	-	2	2

matrix O^{in} matrix O^{out}

Figure 4. Interrelation between technological groups of MHE, executed by UL treatment cycles and by in and out procedures for a consolidated variant of the warehouse layout, corresponding to an integrated technological scheme

- the totality of the elements of the spatial-planning solution that are used to handle an individual set of ULs represents a physical service channel; the number of physical service channels, as a rule, corresponds to the number of receiving gates of a specific LUF (Figure 5);
- the totality of MHE units (in terms of different technological groups) ensuring handling of an individual set of ULs during acceptance or shipment represents an organizational service channel; such service channels, the same as physical ones, correspond to a specific LUF. The number of organizational service channels cannot exceed the quantity of physical service channels (Figure 5);
- distribution of LUF units of a separate technological group by organizational service channels ensures that the productivity of technological operations conducted in terms of every service channel is the same (Figure 5);

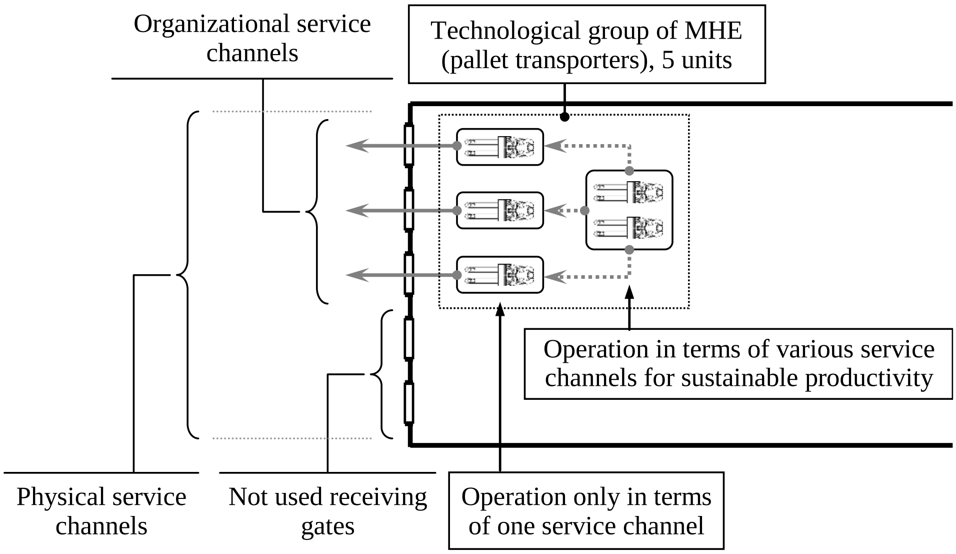


Figure 5. Principles of MHE units distribution in the compositions of a technological group by organizational service channels (illustrated by a special example)

- the process of handling a consignment of ULs in terms of an individual technological group of MHE has a property of rhythmicity. Herewith, the average time interval between the termination of handling for chronologically related ULs is inversely proportional to the number of MHE units in the group (Figure 6);
- the productivity of UL handling by the further (in the structure of the technological process) technological group of MHE cannot exceed the comparable value for the previous group of machinery; the difference in the productivity of the contiguous technological groups of MHE makes ULs accumulate in the intermediate technological area (Figure 6);

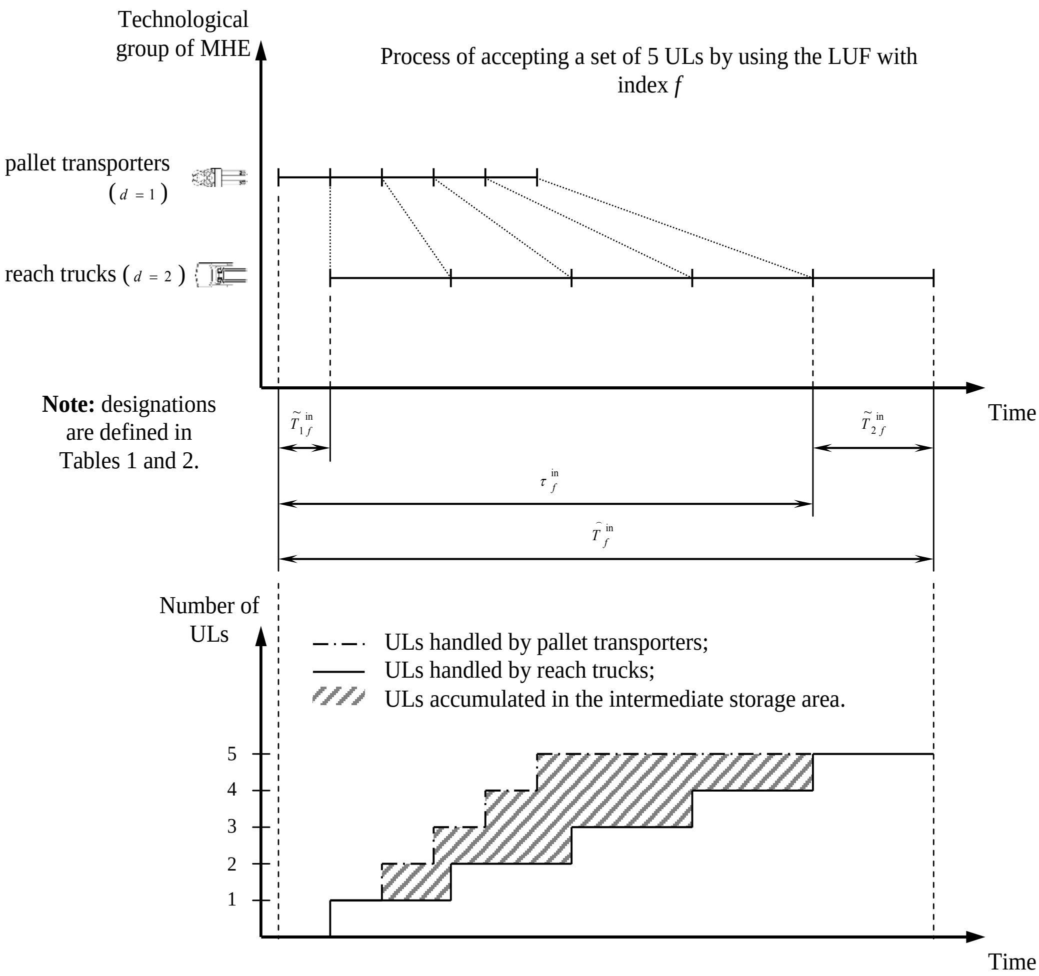


Figure 6. Interrelation between the time characteristics of ULs handled with the equipment of different technological groups and the number of ULs accumulated in the intermediate storage area (illustrated by a special example)

- it is necessary to determine the quantity of MHE units in the composition of every technological group. This quantity must ensure that the warehouse operates with minimal aggregate costs spent on equipment maintenance and downtime of TVs in a service queue when meeting the requirements set for carrying capacity. The carrying capacity is described by such indicators as the queue length of TVs which expect unloading or loading, the time TVs stay in queue, etc.

The initial data and unknown variables for solving the problem are presented in Table 1.

Table 1. Initial data and unknown variables for solving the problem at issue

Item No.	Name of the parameter / variable	Designation / expression	Measurement unit
1	**Initial data**		
1.1	**General parameters of the warehousing system**		
1.1.1	Number of suppliers being serviced	m^{S}	units
1.1.2	Index of the supplier being serviced	$i = 1, 2, ..., m^{S}$	-
1.1.3	Number of consumers being serviced	m^{C}	units
1.1.4	Index of the consumer being serviced	$j = 1, 2, ..., m^{C}$	-
1.1.5	Number of the LUFs	F	units
1.1.6	Index of the LUF	$f = 1, 2, ..., F$	-
1.1.7	Number of the technological groups of MHE	D	units
1.1.8	Index of the technological group of MHE	$d = 1, 2, ..., D$	-
1.1.9	Matrices of logical parameters defining correspondence of the technological groups of MHE to the LUFs being serviced during acceptance (<u>in</u>) and shipment (<u>out</u>) of ULs*	$Y^{\text{in(out)}}$	-
1.1.10	Matrices of the whole-numbered parameters, determining the ordinal numbers of the technological operations, implemented by individual MHE groups when servicing the LUF during in and out procedures of ULs**	$O^{\text{in(out)}}$	-
1.1.11	Duration of the base period	T^{Σ}	workdays/pd
1.1.12	Duration of the business day	T^{sh}	h/workday
1.2	**Parameters of each LUF** ***f***		
1.2.1	Number of receiving gates	N_{f}	units
1.2.2	Actual capacity of the intermediate storage area	$[\Delta K_{f}]$	pcs
1.2.3	Additional average duration of servicing one TV	$[\tau_{f}^{0}]$	min/unit
1.2.4	Admissible average quantity of TVs in a service queue	$[z_{f}^{0}]$	units

Table 1. Initial data and unknown variables for solving the problem at issue (continued)

Item No.	Name of the parameter / variable	Designation / expression	Measurement unit
1.3	**Parameters of the flows of cargoes handled in terms of every LUF *f*, from every supplier *i* and consumer *j***		
1.3.1	TV body capacity	$r_{i(j)}$	pcs/unit
1.3.2	Losses from one hour downtime of one TV in a service queue	$C^{\mathrm{q}}_{i(j)}$	\$/(unit·h)
1.3.3	Expected intensity of arriving TVs	$\lambda_{i(j)f}$	units/day
1.4	**Parameters of every technological group of the MHE *d***		
1.4.1	Approximate value of a MHE unit	C^{ε}_{d}	\$/unit
1.2.4	Technical maintenance costs per a MHE unit	$C^{\varepsilon\mathrm{t}}_{d}$	$\frac{\$}{\text{unit·month}}$
1.3.4	Period of the value-added usage of equipment	T^{ε}_{d}	workdays
1.4.4	Productivity reduction coefficient of a MHE unit	k^{P}_{d}	-
1.5	**Parameters of the technological process carried out by every technological group of MHE *d* in terms of every LUF *f*** ***		
1.5.1	Average duration of the technological handling cycle of one UL in terms of the acceptance (<u>in</u>) and shipment (<u>out</u>) procedure	$T^{\mathrm{in(out)}}_{df}$	s/pc
1.5.2	Maximal quantity of MHE units in terms of an organizational service channel	$\varepsilon^{\mathrm{C\ max}}_{df}$	units

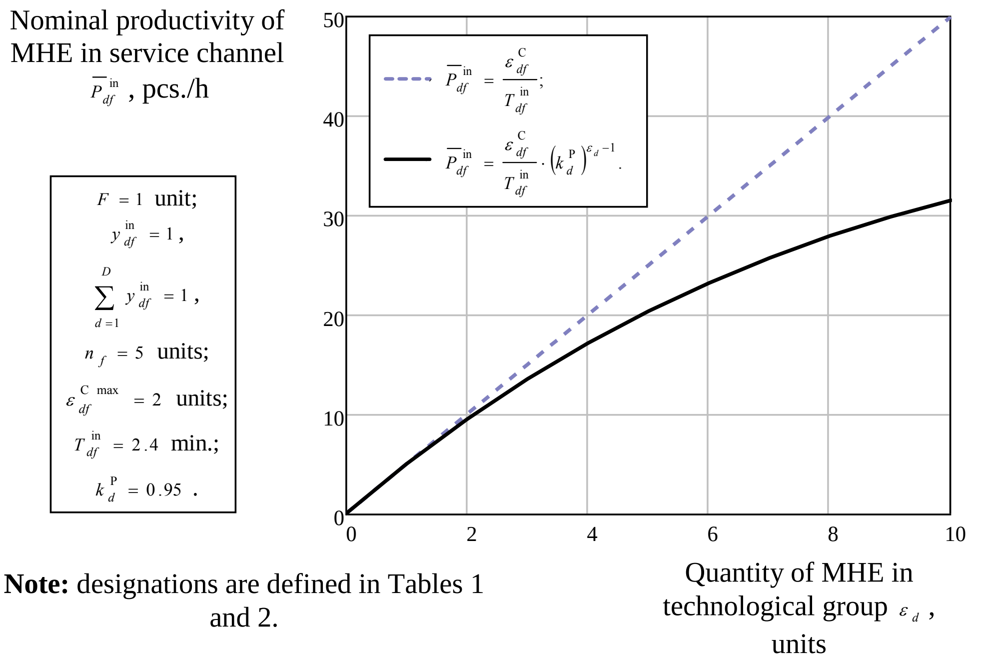
Note:

* every matrix $Y^{\mathrm{in(out)}}$ includes parameters $\{y^{\mathrm{in(out)}}_{df}\}$, with each of them being equal to 1, if the technological group of MHE *d* services the LUF *f* during acceptance (shipment) of a UL, and it is equal to 0 otherwise; examples of matrices $Y^{\mathrm{in(out)}}$ for various options of cargo handling technological schemes are presented in Figures 2–4;

** each matrix $O^{\mathrm{in(out)}}$ includes whole-numbered parameters $\{o^{\mathrm{in(out)}}_{df}\}$. Parameter $o^{\mathrm{in(out)}}_{df}$ is equal to 1 for the first (in the structure of the cargo handling process) technological cycle implemented by the technological group of MHE *d* during servicing the LUF *f* in terms of UL in (out) procedures; parameter $o^{\mathrm{in(out)}}_{df}$ is equal to 2 for the second cycle, etc.; if the technological group of MHE *d* does not take part in servicing the LUF *f* in terms of UL in (out) procedures, the parameter $o^{\mathrm{in(out)}}_{df}$ has no value (equals null); examples of matrices $O^{\mathrm{in(out)}}$ for various options of cargo handling technological schemes are presented in Figures 2–4;

***parameters are of importance only in case the following condition is fulfilled $y^{\mathrm{in(out)}}_{df} = 1$. In order to consider the non-linear character of the dependence between the productivity of a technological group of MHE and the number of equipment units in the problem we use the so-called productivity reduction coefficient, usually set in the range of 0.9…0.95. The effect of this coefficient on the calculated characteristics of productivity is illustrated in Figure 7.

It is important to note that in this problem the required quantity of MHE units in every technological group is determined at the same time as the number of organizational service chambers are substantiated in terms of the LUF. This circumstance is preconditioned because both of the above characteristics significantly influence the carrying capacity indicators of the warehousing system. Herewith, organization of any quantity of organizational service channels generally does not imply that additional money should be spent.



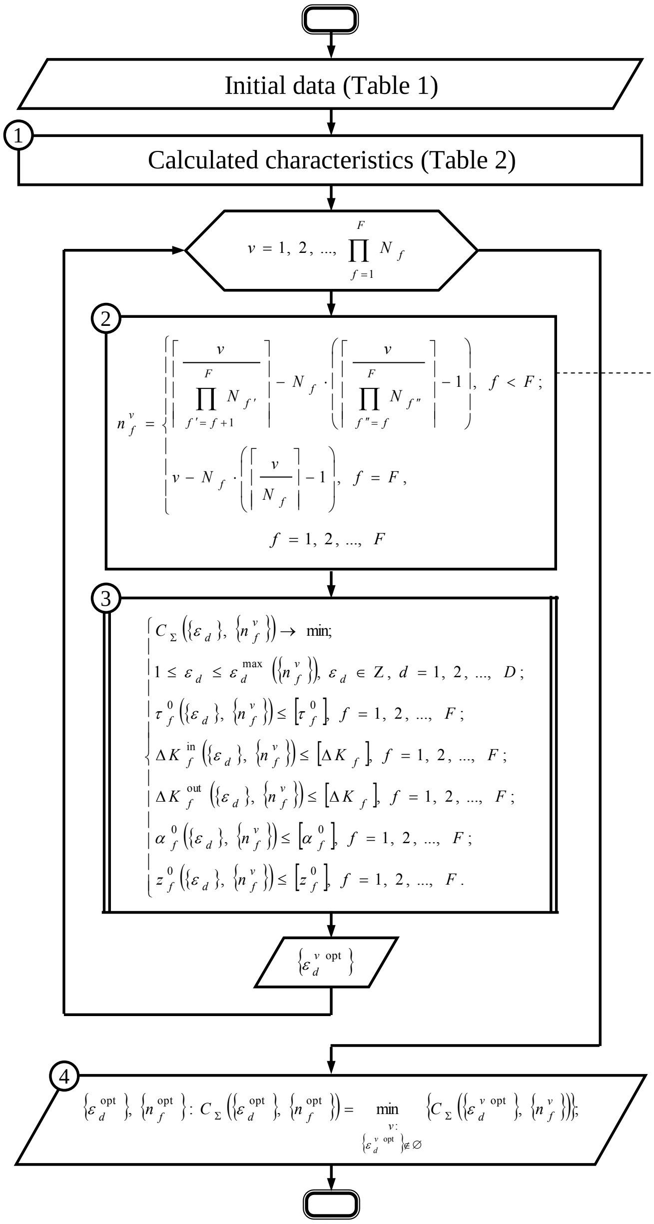
Note: designations are defined in Tables 1 and 2.

Figure 7. The effect of the productivity reduction coefficient on the operational efficiency of a technological group of MHE (illustrated by a special example)

4. Description of the Problem Solving Methodology

The methodology for substantiating the number of MHE in terms of a unit load warehousing system is described by a sequence of certain implementation phases (Figure 8) which are stated in detail below.

In the initial (first) phase of methodology implementation, the calculated characteristics are formed for the optimization model used in further phases of the methodology. These characteristics are described in Table 2. It is important to note that this table includes: characteristics dependent on both groups of unknown variables $\{\varepsilon_d\}$ and $\{n_f\}$ (with numbers 1.1–1.4, 2.9–2.23, 3.2, 4.3, 4.4); characteristics, dependent only on the variables $\{\varepsilon_d\}$ (4.1, 4.2) and on the variables $\{n_f\}$ (3.1); characteristics, independent on the unknown variables (2.1–2.8).



Calculation example

Ordinal number of combination v	Number of organizational service channels n_f^v for LUF f			
	1	2	3	4
1	1	1	1	1
2	1	1	1	2
3	1	1	1	3
4	1	1	2	1
5	1	1	2	2
6	1	1	2	3
7	1	2	1	1
…	…	…	…	…
71	3	4	2	2
72	3	4	2	3
Number of receiving gates N_f	3	4	2	3

Additional designations

$\lceil ... \rceil$ – result of rounding the value to the nearest larger integer value;
Z – a set of integer numbers;
$\varnothing$ – void set.

Figure 8. The structure of the methodology implementation procedure for substantiating the quantity of materials handling equipment for a unit load warehousing system.

Table 2. The calculated characteristics of the optimization model implemented in the solution of the problem.

Item No.	Name of the characteristic	Measurement unit	Formula
1	**Characteristics of the technological process*, implemented by every technological group of MHE d in terms of every LUF f**		
1.1	Average quantity of MHE units in terms of an organizational service channel**	units	$\varepsilon_{df}^{\mathrm{C}} = \frac{\varepsilon_d}{n_f} \cdot \frac{\varepsilon_{df}^{\mathrm{C\ max}}}{\sum_{f=1}^{F} \varepsilon_{df}^{\mathrm{C\ max}}}$
1.2	Nominal average productivity of handling a set of ULs per shift during acceptance (in) and shipment (out)***	pcs h	$\overline{P}_{df}^{\mathrm{in(out)}} = \frac{\varepsilon_{df}^{\mathrm{C}}}{T_{df}^{\mathrm{in(out)}}} \cdot \left(k_d^P\right)^{\varepsilon_d - 1}$
2.11	Consolidated average duration of handling a set of ULs	min. unit	$\widehat{T}_f^{0} = \frac{\widehat{T}_f^{\mathrm{in}} \cdot \lambda_f^{\mathrm{in}} + \widehat{T}_f^{\mathrm{out}} \cdot \lambda_f^{\mathrm{out}}}{\lambda_f^{\Sigma}}$
2.12	Maximum carrying capacity of the warehouse during UL acceptance (in) and shipment (out)	pcs h	$\widehat{P}_f^{\mathrm{in(out)}} = n_f \cdot \frac{r_f^{\mathrm{in(out)}}}{\widehat{T}_f^{\mathrm{in(out)}}}$
2.13	Average duration of servicing one TV during UL acceptance (in) and shipment (out)****	min. unit	$\tau_f^{\mathrm{in(out)}} = \widehat{T}_f^{\mathrm{in(out)}} - \widetilde{T}_{d^*f}^{\mathrm{in(out)}}$, $d^* : o_{d^*f}^{\mathrm{in}} = 1 \left(o_{d^*f}^{\mathrm{out}} = \max_{d:\, o_{df}^{\mathrm{out}} \neq \mathbf{null}} \left\{ o_{df}^{\mathrm{out}} \right\} \right)$
2.14	Average duration of servicing one TV for supplier i and consumer j		$\tau_{i(j)} = \tau_f^{\mathrm{in(out)}} \cdot \frac{\lambda_{i(j)f}}{\lambda_f^{\mathrm{in(out)}}}$
2.15	Consolidated additional average duration of servicing one TV	min. unit	$\tau_f^{0} = \frac{\tau_f^{\mathrm{in}} \cdot \lambda_f^{\mathrm{in}} + \tau_f^{\mathrm{out}} \cdot \lambda_f^{\mathrm{out}}}{\lambda_f^{\Sigma}}$
2.16	Average quantity of busy organizational service channels during UL acceptance (in) and shipment (out)	units	$\alpha_f^{\mathrm{in(out)}} = \lambda_f^{\mathrm{in(out)}} \cdot \tau_f^{\mathrm{in(out)}}$
2.17	Consolidated average quantity of busy organizational service channels	units	$\alpha_f^{0} = \lambda_f^{\Sigma} \cdot \tau_f^{0}$
2.18	Probability of downtime for all organizational service channels during UL acceptance (in) and shipment (out)	units	$\rho_f^{\mathrm{in(out)}} = \frac{1}{\sum_{k=0}^{n_f} \frac{\left(\alpha_f^{\mathrm{in(out)}}\right)^k}{k!} + \frac{\left(\alpha_f^{\mathrm{in(out)}}\right)^{n_f+1}}{n_f! \cdot \left(n_f - \alpha_f^{\mathrm{in(out)}}\right)}}$

2.19	Consolidated probability of downtime for all organizational service channels	-	$\rho_f^0 = \dfrac{1}{\sum_{k=0}^{n_f} \dfrac{(\alpha_f^0)^k}{k!} + \dfrac{(\alpha_f^0)^{n_f+1}}{n_f! \cdot (n_f - \alpha_f^0)}}$
2.20	Average number of TV in a handling queue during UL acceptance (in) and shipment (out)	units	$z_f^{\text{in(out)}} = \dfrac{(\alpha_f^{\text{in(out)}})^{n_f+1} \cdot \rho_f^{\text{in(out)}}}{n_f \cdot n_f! \cdot \left(1 - \dfrac{\alpha_f^{\text{in(out)}}}{n_f}\right)^2}$
2.21	Consolidated admissible average quantity of TVs in a service queue	units	$z_f^0 = \dfrac{(\alpha_f^0)^{n_f+1} \cdot \rho_f^0}{n_f \cdot n_f! \cdot \left(1 - \dfrac{\alpha_f^0}{n_f}\right)^2}$
2.22	Average duration TVs stay in a handling queue during UL acceptance (in) and shipment (out)	min. unit	$T_f^{\text{q in(out)}} = \dfrac{z_f^{\text{in(out)}}}{\lambda_f^{\text{in(out)}}}$
2.23	Consolidated average duration a TV stays in a service queue	min. unit	$T_f^{\text{q }0} = \dfrac{z_f^0}{\lambda_f^0}$
3	**Characteristics of every technological group of MHE *d***		
3.1	Maximum quantity of equipment units	units	$\varepsilon_d^{\max} = \sum_{f:\, y_{df}^{\text{in(out)}}=1} \varepsilon_{df}^{\text{C max}} \cdot n_f$
3.2	Average coefficient of usage	$\dfrac{\text{units}}{\text{workday}}$	$k_d^{\text{sh}} = \dfrac{\sum_{f:\, y_{df}^{\text{in}}=1} \lambda_f^{\text{in}} \cdot \dfrac{\alpha_f^{\text{in}}}{n_f} \cdot \dfrac{P_{df}^{\text{in}}}{\overline{P}_{df}^{\text{in}}} + \sum_{f:\, y_{df}^{\text{out}}=1} \lambda_f^{\text{out}} \cdot \dfrac{\alpha_f^{\text{out}}}{n_f} \cdot \dfrac{P_{df}^{\text{out}}}{\overline{P}_{df}^{\text{out}}}}{\sum_{f:\, y_{df}^{\text{in}}=1} \lambda_f^{\text{in}} + \sum_{f:\, y_{df}^{\text{out}}=1} \lambda_f^{\text{out}}}$
4	**Operational characteristics of MHE fleet**		
4.1	Cumulative costs for MHE purchase	$	$C_\Sigma^{\varepsilon} = \sum_{d=1}^{D} C_d^{\varepsilon} \cdot \varepsilon_d$
4.2	Cumulative costs for MHE maintenance for the calculation period	$\dfrac{\$}{\text{pd}}$	$C_\Sigma^{\varepsilon\text{t}} = \sum_{d=1}^{D} \left(\dfrac{C_d^{\varepsilon} \cdot T^{\Sigma}}{T_d^{\varepsilon}} + C_d^{\varepsilon\text{t}} \right) \cdot \varepsilon_d$
4.3	Cumulative losses from one hour downtime of a TV in a service queue for the calculation period	$\dfrac{\$}{\text{pd}}$	$C_\Sigma^{\text{q}} = T^{\Sigma} \cdot T^{\text{sh}} \cdot \sum_{f=1}^{F} C_f^{\text{q }0} \cdot z_f^0$
4.4	Total aggregate losses	$\dfrac{\$}{\text{pd}}$	$C_\Sigma = C_\Sigma^{\varepsilon\text{t}} + C_\Sigma^{\text{q}}$

Note:

* formulas to calculate characteristics 1.1–1.4 are true provided the following conditions are fulfilled $y_{df}^{\mathrm{in(out)}} = 1$; otherwise the calculation is not to be made;

**the principle of calculating the characteristic is illustrated by Figure 5;

*** the dependence of the characteristic on the quantity of MHE units with other set parameters is shown in Figure 7;

****the principle of calculating the characteristic is illustrated by Figure 6.

Further implementation stages of the methodology are illustrated by the flow chart shown in Figure 2. It is neither possible to calculate all unknown variables in terms of the problem that is being reviewed by building a single optimization model nor implement it by using standard calculation methods (due to a large number of dissimilar variables). So, in terms of the methodology it is supposed that some variables should be optimized. They are the ones that correspond to the number of MHE units in technological groups with fixed values of variables which determine the quantity of organizational service channels in the context of the LUF.

In terms of the next (second) stage of the methodology, all alternative combinations of variable values are formed to describe the number of organizational service channels for the LUF. At this the total number of combinations will correspond to the product of the number of physical service channels of all LUFs.

Implementation of the next (third) stage of the methodology implies optimization of the quantity of MHE units in all technological groups in terms of the reviewed warehousing system according to the minimization criterion of total aggregate costs related to MHE maintenance and downtime of TVs expecting servicing for the calculation period under the following functional limitations:

- limitation by the number of MHE units in every technological group (determined by the limited working area of the warehouse premises)
- the average number of organizational service channels does not exceed the number of physical service channels (which ensures that there is no perpetually growing queue);
- limitation by the consolidated average quantity of TVs in the service queue (preconditioned by the layout of the area adjacent to the warehouse);
- limitation by the consolidated average duration of servicing one TV (determined by the technological process procedure at the warehouse).

It is important to note that the above structure of the optimization model, depending on the specifics of the problem to be solved, can be changed by altering the composition of the calculated characteristics (Table 2) in the content of the target function and functional limitations.

According to the results of the implemented optimization model for every individual combination of the quantity of organizational service channels in the composition of a LUF, the optimal numbers of MHE units are fixed in technological groups. Otherwise, the lack of optimal solution is recognized due to the impossibility to execute the set limitations.

In the last (fourth) phase of the methodology implementation, the most preferable combination is chosen for the values of the quantities of organizational service channels in the composition of a LUF from the list of alternative combinations by the minimum criterion of total aggregate costs, related to MHE servicing and downtime of TVs waiting to be serviced for the calculation period with optimal values of MHE quantity in technological groups.

Thus, the proposed methodology implies an iterative implementation of the mathematical model of non-linear whole-numbered optimization. In order to carry out the above procedure it is proposed that genetic algorithms should be used. They are available in terms of widely used computer programs, including "Microsoft Excel".

5. Implementing the methodology by a practical example

The developed methodology was applied to a practical example in order to solve the problem of defining the number of MHE units in terms of a unit load warehouse with a set spatial-planning solution corresponding to the integrated technological scheme (Figure 3). TVs were unloaded and loaded by using pallet transporters, whereas ULs were placed and withdrawn from the rack area by using reach trucks. The calculation period was considered as one month given that the warehouse works round the clock. The layout of the warehousing system is presented in Figure 9.

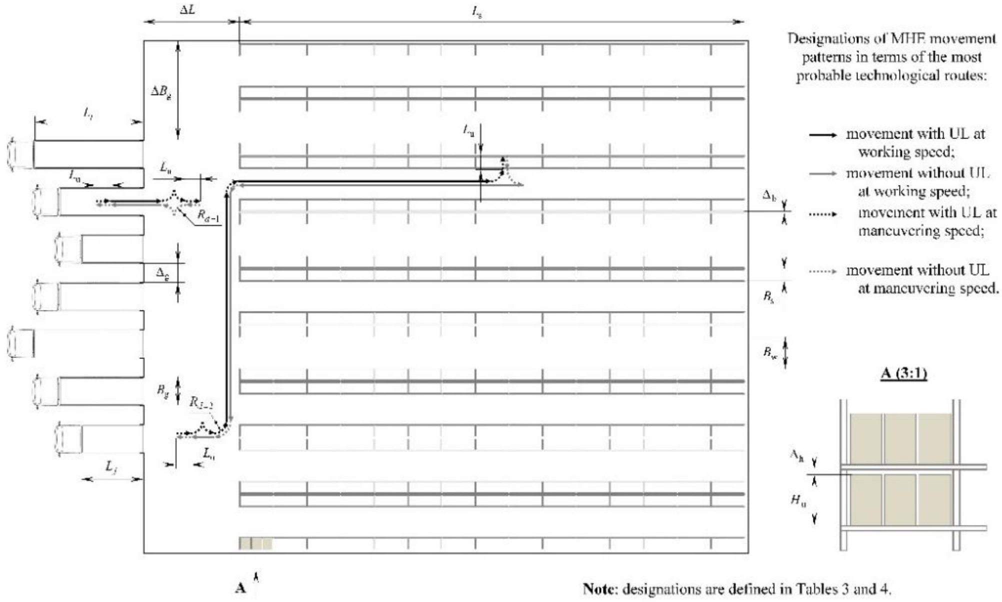


Figure 9. The layout of the warehousing system showing most probable travel routes for MHE in terms of technological groups.

The initial data for solving the applied problem is presented in Tables 3–5. It is important to note that in the tables, apart from the parameters listed in section 3, there is additional initial data (in the rows numbered 1.7–1.21 in Table 3, in the third column (on the left), Table 4, in the rows numbered 1.1, 1.2, 1.8–1.21, Table 5). It is used for calculating (directly before going through the main phases of the proposed methodology) the average duration of the technological cycle of one UL handled by the equipment belonging to different technological groups. In order to carry out the above-mentioned calculation, the most probable (based on averaged spacial parameters of the warehouse premises and serviced TVs) technological travel routes of MHE units were formed in terms of technological groups during carrying out the procedures of ULs acceptance and shipment.

Table 3. Initial parameters of the warehousing system and LUF for solving the practical problem at issue

Item No.	Name of the parameter	Designation	Measure-ment unit	Value
1	**General parameters of the warehousing system**			
1.1	Number of suppliers being serviced	m^{S}	units	5
1.2	Number of consumers being serviced	m^{C}	units	5
1.3	Number of LUFs	F	units	1
1.4	Number of MHE technological groups	D	units	2
1.5	Duration of the base period	T^{Σ}	workdays/pd	30
1.6	Duration of a business day	T^{sh}	h/workday	8
1.7	Length of a UL	L_{u}	m	1.2
1.8	Length of a UL	B_{u}	m	1
1.9	Height of a UL	H_{u}	m	1.65
1.10	Mass of a UL with cargo*	G_{u}	kg	1200
1.11	Width of the receiving gate	B_{g}	m	3
1.12	Distance from the wall edge to the receiving gate	ΔB_{g}	m	10.5
1.13	Distance between the gates of the LUF	Δ_{g}	m	2
1.14	Transverse clearance between a rack post and a wall of the warehouse	Δ_{b}	m	0.25
1.15	Vertical clearance between a pallet and a rack structure	Δ_{h}	m	0.15
1.16	Number of inter-rack passages	N_{w}	units	9
1.17	Width of an inter-rack passage	B_{w}	m	3.25
1.18	Length of a rack row	L_{s}	m	52.6
1.19	Depth of a rack row	B_{s}	m	1.2
1.20	Height of a rack row	H_{s}	m	5.7
1.21	Length of the intermediate storage area	ΔL	m	10
2	**LUF parameters ($f = F = 1$)**			
2.1	Number of receiving gates	N_{f}	units	7
2.2	Additional average duration of servicing one TV	$[\tau_{f}^{0}]$	$\frac{\text{min.}}{\text{unit}}$	10
2.3	Admissible average quantity of TVs in a service queue	$[z_{f}^{0}]$	units	10

Note: *the parameter is part of reference information and is not used for calculation

Table 4. Initial parameters of incoming and outgoing cargo flows for solving the practical problem at issue

Counter-agent type	Item No. $i \mid j$	Longitudinal dimension of the body, m $L_i \mid L_j$	Capacity of the TV body, pcs/unit $r_i \mid r_j$	Expected intensity of TVs arriving to the LUF $f = F = 1$, units/workday $\lambda_{if} \mid \lambda_{jf}$	Losses from one hour downtime of one TV in service queue, $/h $C_i^q \mid C_j^q$
Supplier	1	11.2	20	2.82	16.96
	2	10.16	18	6.75	17.86
	3	13.2	24	1.39	13.39
	4	18.2	16	20.79	13.39
	5	22.4	20	1.04	8.93
Consumer	1	2.4	4	34.17	7.14
	2	3.7	6	19.17	5.36
	3	3.1	5	30.00	5.36
	4	2.45	4	20.83	7.14
	5	2.4	4	20.00	5.36

Table 5. Initial parameters of technological groups of MHE for solving the practical problem at issue

Item No.	Name of the parameter	Designa-tion	Measure-ment unit	Value for the technological group of MHE *d*	
				1	2
1.1	Name of the producer*	-	-	Still	Still
1.2	Name of the model*	-	-	ECU-SF-20	FM-X 12
1.3	Approximate value of a MHE unit	C_d^{ε}	$\frac{\$}{\text{unit}}$	8035	40180
1.4	Technical maintenance costs per a MHE unit	$C_d^{\varepsilon t}$	$\frac{\$}{\text{unit}\cdot\text{month}}$	180	395
1.5	Value-added usage period of equipment	T_d^{ε}	days	1825	1825
1.6	Productivity reduction coefficient of a MHE unit	k_d^{P}	-	0.95	0.95
1.7	Maximal quantity of MHE units in terms of an organizational service channel for the LUF ($f = F = 1$)	$\varepsilon_{df}^{C\max}$	units	2	3
1.8	Load bearing capacity*	G_d	kg	2000	1200

Table 5. Initial parameters of technological groups of MHE for solving the practical problem at issue (continued)

Item No.	Name of the characteristic*		Designa-tion	Meas. unit	Value for the technological group of MHE d	
					1	2
1.9	Travel speed	with load	υ_d^{m+}	$\frac{km}{h}$	7.5	14
1.10		without load	υ_d^{m-}		6	14
1.12	Load lifting height*		H_d	m	0.135	5.75
1.13	Lifting rate of the load-handling device	with load	υ_d^{lf+}	$\frac{m}{s}$	0.034	0.47
1.14		without load	υ_d^{lf-}		0.045	0.7
1.15	Lowering rate of the load-handling device	with load	υ_d^{lw+}	$\frac{m}{s}$	0.045	0.5
1.16		without load	υ_d^{lw-}		0.045	0.56
1.17	Turning radius		R_d	m	1.904	1.54
1.19	Width of a working passage		B_d^w	m	2.718	2.745
1.20	Shunting to working speed ratio		Δ_d^{υ}	-	0.35	0.25
1.21	Minimal lifting height of a UL during handling (at the beginning of the cycle)		Δh_d^{min}	m	0.12	0.12
1.22	Number of turns by 90° in terms of the technological route of UL handling during acceptance by using the LUF $f = F = 1$	with load	N_{df}^{r+}	units	2	5
1.23		without load	N_{df}^{r-}	units	2	3

Note:
*the parameter is part of reference information and is not used for calculation

In order to ensure the adequacy of the calculated values of durations of technological cycles, the operation of equipment was considered with two categories of travel speed – working and maneuvering ones, connected between each other with a pre-set average ratio (determined by revising a large variety of machinery of a certain class). The first category of speed was used to describe the movement of machinery against a straightforward pattern, the second one to describe the movement of a MHE unit against curvilinear patterns and during UL capture and shipment. The configuration of the most probable technological routes for MHE movement is presented in Figure 9. The main formulas and calculation results of route characteristics and average duration of the technological cycle for handling one UL in terms of various technological groups of MHE are presented in Table 6.

Table 6. The main formulas and results of calculating the route characteristics and average duration of the technological cycle for handling one UL in terms of various technological groups of MHE

Item No.	Name of the characteristic*		Design a-tion	Meas. unit	Value for the technological group of MHE *d*	
					1	2
1	Travel length at the working speed**	with load	$L_{df}^{\mathrm{m1}+}$	m	3.95	44.12
2		without load	$L_{df}^{\mathrm{m1}-}$		3.95	50.28
3	Travel length at the maneuvering speed**	with load	$L_{df}^{\mathrm{m2}+}$	m	8.38	14.50
4		without load	$L_{df}^{\mathrm{m2}-}$		8.38	9.66
5	Load lifting height**	when engaging a UL	H_{df}^{gr}	m	0.12	0.12
6		when shipping a UL	H_{df}^{dr}		0.12	2.01
7	Average duration of the technological cycle of handling one UL	during acceptance	T_{df}^{in}	s	42.52	57.45
8		during shipment	T_{df}^{out}		40.79	56.42
9	Actual capacity of the intermediate storage area***		$[\Delta K_f]$	pcs	15	

Item No.	Formula
1, 2	$L_{df}^{\mathrm{m1}+(-)} = \begin{cases} \dfrac{\sum_{i=1}^{m^{\mathrm{S}}} L_i \cdot \lambda_{if} + \sum_{j=1}^{m^{\mathrm{C}}} L_j \cdot \lambda_{jf}}{\lambda_f^{\Sigma}} + \dfrac{\Delta L}{2} - N_{df}^{\mathrm{r}+(-)} \cdot R_d, \quad d = 1; \\ \dfrac{\Delta L}{2} + \dfrac{N_{\mathrm{w}} - 1}{2} \cdot (B_{\mathrm{w}} + 2 \cdot B_{\mathrm{s}} + \Delta_{\mathrm{b}}) + \dfrac{L_{\mathrm{s}}}{2} - \overline{N}_{df}^{\mathrm{r}+(-)} \cdot R_d, \quad d = 2, \qquad \overline{N}_{df}^{\mathrm{r}+} = N_{df}^{\mathrm{r}+} + 2;\ \overline{N}_{df}^{\mathrm{r}-} = N_{df}^{\mathrm{r}-}. \end{cases}$
3, 4	$L_{df}^{\mathrm{m2}+(-)} = N_{df}^{\mathrm{r}+(-)} \cdot \pi \cdot \dfrac{R_d}{2} + 2 \cdot L_{\mathrm{u}}$
5	$H_{df}^{\mathrm{gr}} = \Delta h_d^{\min}$
6	$H_{df}^{\mathrm{dr}} = \begin{cases} \Delta h_d^{\min}, \ d = 1; \\ H_{\mathrm{s}} - H_{\mathrm{u}} - \Delta_{\mathrm{h}} + \Delta h_d^{\min}, \ d = 2. \end{cases}$
7, 8	$T_{df}^{\mathrm{in(out)}} = \dfrac{L_{df}^{\mathrm{m1}+(-)}}{\upsilon_d^{\mathrm{m1}+}} + \dfrac{L_{df}^{\mathrm{m2}+(-)}}{\upsilon_d^{\mathrm{m1}+} \cdot \Delta_d^{\upsilon}} + \dfrac{L_{df}^{\mathrm{m1}-(+)}}{\upsilon_d^{\mathrm{m1}-}} + \dfrac{L_{df}^{\mathrm{m2}-(+)}}{\upsilon_d^{\mathrm{m1}-} \cdot \Delta_d^{\upsilon}} + \left(H_{df}^{\mathrm{gr}} + H_{df}^{\mathrm{dr}}\right) \cdot \left(\dfrac{1}{\upsilon_d^{\mathrm{lf}+(-)}} + \dfrac{1}{\upsilon_d^{\mathrm{lw}-(+)}}\right)$
9	$[\Delta K_f] = \left\lfloor \dfrac{\Delta L - \sum_{d=1}^{D} B_d^{\mathrm{w}}}{L_{\mathrm{u}}} \right\rfloor \cdot \left\lfloor \dfrac{B_{\mathrm{g}} + \Delta_{\mathrm{g}}}{B_{\mathrm{u}}} \right\rfloor$

Note:

* the formulas for calculating the characteristics are true provided that ;

** the formulas correspond to the technological procedure of UL acceptance;

*** designation in the formula means the result of rounding the value to the nearest lower integer number.

The warehousing system under consideration has only one LUF including 7 receiving gates. So during implementation of the methodology 7 alternative variants were formed for the number of organizational service channels in terms of the LUF. For each of these variants the optimization model was executed. It is described in section 4, by using “Solver” add-in in “Microsoft Excel” program. The relevant results are presented as diagrams in Figures 10 and 11 (see Appendix).

Thus, the results obtained when solving the applied problem adequately describe the specifics of technological processes in terms of unit load warehousing systems and bear evidence that the developed methodology has a high practical value.

Diagrams show that with the set intensity of incoming and outgoing cargo flows the warehousing system is ensured with the required carrying capacity indicators even if there is just 1 organizational service channel. However, there are no reserves for increasing the quantity of MHE. Thus the indicators of the average number of TVs in a service queue and the average duration of TVs staying in a queue precondition relatively high financial losses.

In case of two organizational service channels the optimal composition of the MHE fleet grows both in terms of pallet transporters (per 1 unit) and reach trucks (per 2 units), which ensures a considerable reduction in the characteristics of the queue and, consequently, a decrease in the total aggregate costs over the period. This trend is also observed when the number of service channels increases from 2 to 5. At this, the optimal composition of the MHE fleet does not change since there are reserves in the functional limitations of the optimization model. The increased optimal quantity of MHE in case of further growth in the number of organizational service channels is preconditioned by the limitation related to the average duration of servicing a TV, which implies that a certain average quantity of equipment units is provided in each service channels. It is also important to note that the efficiency of handling a set of TVs as a whole reduces if the number of organizational service channels grows (it is shown by a growth in the average duration of handling a set of UL and servicing one TV and by a reduced probability of downtime for all service channels). However, the maximal carrying capacity of the warehousing system increases due to a larger nominal quantity of the simultaneously handled sets of ULs. Minimal total aggregate costs are ensured when 3 pallet transporters and 4 reach trucks operate in terms of 5 service channels (i.e. it is not feasible to use 2 out of 7 receiving gates in terms of the LUF).

6. Conclusions and directions for further research

This paper discusses in detail the issues related to substantiating the quantity characteristics of materials handling equipment for a unit load warehousing system. A conclusion is made about the topicality of the considered problematic area according to the reviewed scientific papers in the relevant subject. The problem is stated, the main provisions, initial data and unknown variables are defined. Methodology for solving the above-mentioned problem is proposed. It is based on iterative implementation of the mathematical problem of non-linear whole-numbered optimization in the quantity of equipment units with a fixed number of organizational service channels. The above model can be efficiently applied by utilizing standard computing programs, but at the same time has the following drawbacks:

- when modeling the operation of MHE, it is not considered (in explicit form) that the machinery productivity reduces due to the need for individual equipment units to move between various organizational service channels and between various LUFs (if there is a time interval between when an equipment unit completes the previous technological cycle and begins the next one);
- the required quantity of MHE is substantiated without considering the reliability factor (possible machinery failure) and without the specifics of energy supply to machinery (which determines the limitations of the time intervals for continuous operation of MHE, the need to use chargers, etc.).
- The above drawbacks are to be eliminated at the next stages of research by improving the methodology in terms of the utilized optimization model. When modernizing the latter one, it is supposed that the presence of various (according their technical specifications) MHE models should be considered in the composition of technological groups.

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Appendix:

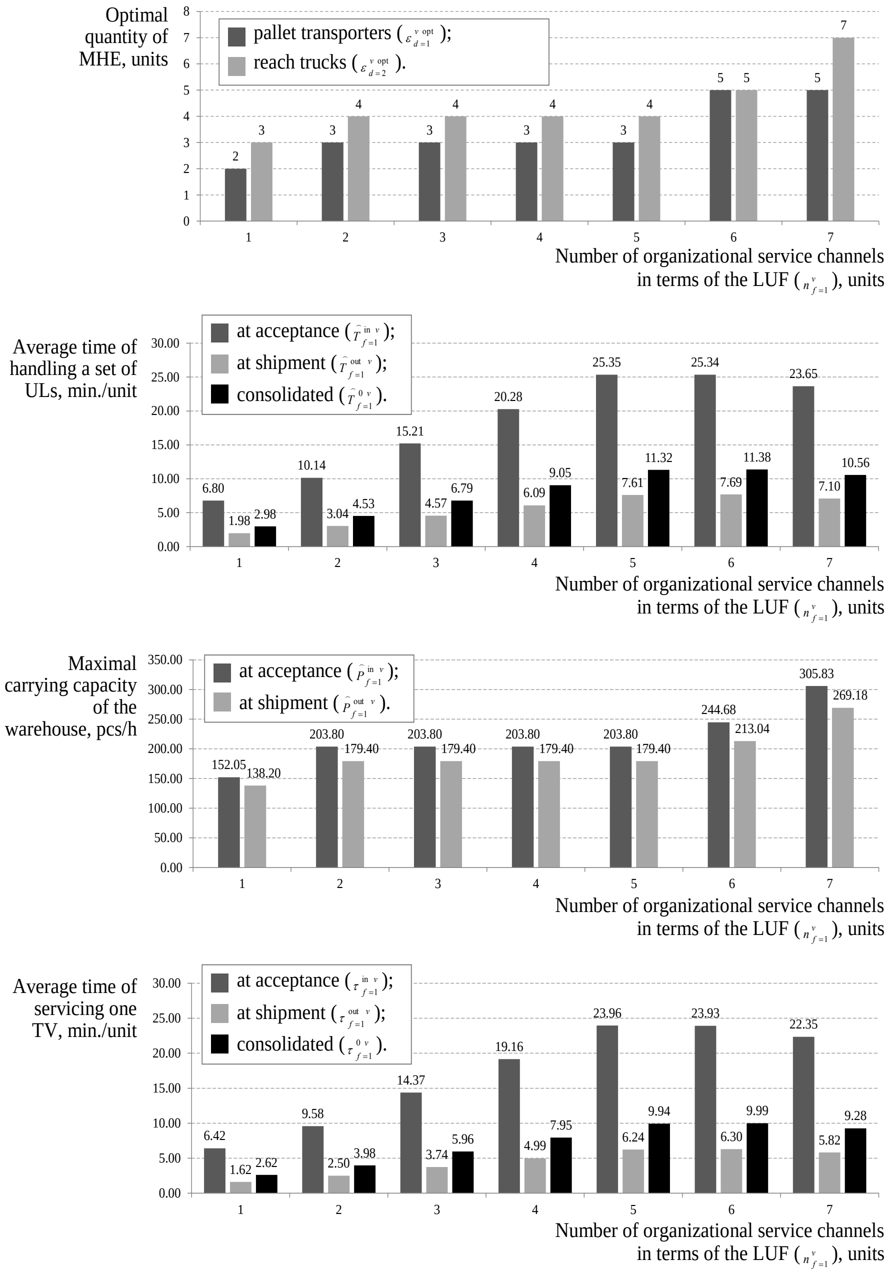

Figure 10. Results of iterative optimization of the quantity of MHE units (in the context of technological groups) with different values of the number of organizational service channels in the composition of the LUF

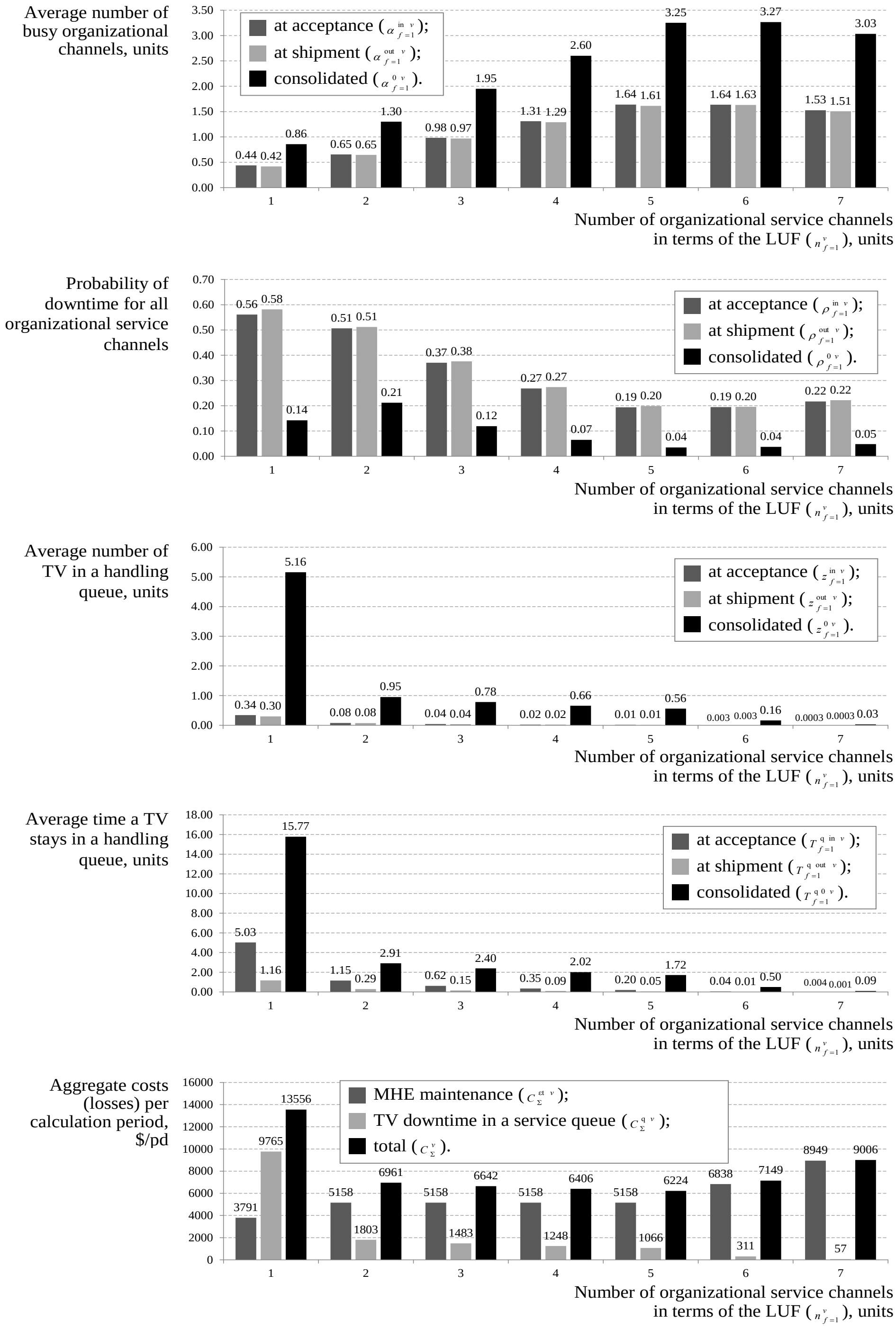

Figure 11. Results of iterative optimization of the quantity of MHE units (in the context of technological groups) with different values of the number of organizational service channels in the composition of the LUF (continuation)