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OPTIMAL MACHINE CONFIGURATION OF LOGISTICS EQUIPMENT

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ABSTRACT: This article proposes an approach to ensure optimum positioning accuracy of logistics machines with cyclic operation, with respect to costs. It is based on the determination of system characteristics, adopted for the specific peculiarities of the logistics process, but ensures minimum machine cost.
KEYWORDS: logistics, logistics equipment, machine structure, optimization

INTRODUCTION

Main function of logistics systems is the spatial and temporal transformation of products. These functions are performed by the processes of transportation, handling, storage, packaging and marking [1]. There's been diligent working, in recent decades, on the product architecture as a link between the product itself and the decisions of the supply chains. This is necessitated by market competitiveness that requires a shorter life cycle for any product. This design structure is multidimensional and upgradeable. Fine [10] in 1998 established architecture of the three areas: product, process and supply and coined the term "three-dimensional concurrent engineering."

In this paper, an approach is proposed for designing a multidimensional architecture which ensures optimum transfer of cargo, with respect to cost, between logistics machines with cyclic operation. It is based on the determination of system characteristics adopted for the specific peculiarities of the logistics process, but ensures minimum machine cost. Such an approach allows simplifying system management and reducing its cost. Applied is the principle of selecting machine components according to the minimum total cost, but this condition is in contradiction with the requirement of positioning accuracy. In order to solve this problem, a methodology and algorithm are developed using corresponding computer programs. This approach is illustrated by a model of logistics system that consists of two machines processing loads of certain sizes. The required positioning accuracy of the system is determined by the specific requirements. Determination of the required system performance is achieved by optimizing the characteristics of the individual machine components such as: load grip device (LGD), metal construction, dampers, driving, suspension, etc. If possible, packaging is also included.

BASIC APPROACH

One of the main requirements for industrial facilities is the determination of their optimal architecture required by the specific circumstances under the minimum total cost criterion [3, 4, 5]. Here, this criterion is used in the construction of logistics (transport and load-handling) machines with cyclic operation. For this purpose, the modular principle of mechanical design is applied. When providing for the necessary positioning accuracy of a system with optimal machine configuration, the faultless delivery of the cargo must also be ensured. The term "machine configuration" includes not only hardware elements, but the control software too. It must be noted that the number of the key components of material handling equipment is relatively small and the required configuration can be prepared using standard methods. Moreover, there exist patterns for these machines that define the positioning errors as a function of their characteristics.

The purpose of this article is to propose an approach to build a multidimensional architecture of logistics machinery with prescribed positioning accuracy and minimum total cost, applying the method of heuristic branching [6].

The loading-unloading process could be considered as comprised of two main fragments - putting the load and taking the load i.e. it considers the zone of cargo transfer from one logistics machine to another. The following prerequisites exist:

- system configuration is specified, i.e. the type and number of machines is known. There is a first, basic variant of the components of each machine, as well as their characteristics that define the zone of cargo transfer from one logistics machine to another;
- the zone where the load is transferred is defined in the 6 dimensional surface of the coordinates of a rigid body. In other words, the required accuracy of positioning is determined by the size, allowed dimensional deviations and dynamic variations of the load, the size of the receiving load grip device and positioning accuracy of the donor and host machines, etc.;
- there is a large database of machine components and their characteristics applicable for the load-handling system;
- the prime costs of the machine components of the hoisting system are known, depending on their characteristics;
- two logistic machines are considered in their basic versions, that determine the area of cargo transfer and reception.

Let's have i number of elements in the first logistics machine, where i =1, 2, 3,..,I

Let's have j_i number of solutions (options) for each i (ways to achieve positioning accuracy) (j_i = 1,2, 3, …, J_i). Each solution is available in several variations each of which provides for different positioning inaccuracy and prime cost.

Similarly let's have n number of components in the second logistics machine, where n =1, 2, 3, …,N , and f_n number of solutions (versions), where $f_n = 1,2,\ldots, F_n$ for each n, where n = 1, 2, 3, …,N.

On this basis, the positioning inaccuracy could be expressed by the inaccuracy along the separate coordinates as $\Delta X, \Delta Y, \Delta Z, \Delta\varphi, \Delta\psi, \Delta\vartheta$.

The condition for the correct load transfer is the system of constraints

$$\left|\begin{array}{l}\Delta X < \Delta X_{\max}\\ \Delta Y < \Delta Y_{\max}\\ \Delta Z < \Delta Z_{\max}\end{array}\right. \qquad \left|\begin{array}{l}\Delta\varphi < \Delta\varphi_{\max}\\ \Delta\psi < \Delta\psi_{\max}\\ \Delta\vartheta < \Delta\vartheta_{\max}\end{array}\right. \tag{1}$$

where $|\Delta X_{\max}, \Delta Y_{\max}, \Delta Z_{\max}, \Delta\varphi_{\max}, \Delta\psi_{\max}, \Delta\vartheta_{\max}$ are the allowable inaccuracies (errors) for load transfer along each of the coordinate axes.

The abovementioned errors are based on the well-known literature approaches developed for analysing the dynamic response of load-handling machines.

The overall error is

$$\Delta\Theta = \Delta\Theta_1 + \Delta\Theta_2 \tag{2}$$

where: $\Delta\Theta_1$ is the error of the first machine, $\Delta\Theta_2$ is the error of the second machine

Then, the prime cost C^1 of the first machine and the prime cost C^2 of the second machine are:

$$C^1 = f(\Delta\Theta_1) \qquad \text{and} \qquad C^2 = f(\Delta\Theta_2) \tag{3}$$

Then the optimal cost combination of elements of the two machines $\hat{\Omega}$ is found by minimizing the functional

$$\sum_{i=1}^{I} C^p{}_{ij_i} + \sum_{n=1}^{N} C^l{}_{nf_n} \rightarrow \min \tag{4}$$

where $(p=1,2,\ldots P),(l=1,2,\ldots L)$ are the number of modifications for the following statements:

- $\sum_{i=1}^{I} C^p{}_{ij_i} + \sum_{n=1}^{N} C^l{}_{nf_n} < C$ - resource limitation where C is the available resource;
- C > 0 - resource availability;
- $\sum_{i=1}^{I} C^p{}_{ij_i} > 0$ i.e. presence of the first machine;
- $\sum_{n=1}^{N} C^l{}_{nf_n} > 0$ - presence of a second machine (equipment);
- $\sum_{i=1}^{I} C^p{}_{ij_i} + \sum_{n=1}^{N} C^l{}_{nf_n} > 0$

where c_{ij_i} is the cost of j_i-th solution of i-th component and C_{nf_n} is the cost of f_n-th solution of the n-th component of the corresponding machine.

In other words, changing the parameters (characteristics) of any combination of elements subject to (1), we look for that local $\hat{\Omega}$, where we have a minimum value of (4), i.e. varying the parameters of each component the minimum costs for the two machines have to be found. This approach is similar to the selection of the combination of components in each machine. There is a set of local solutions Ω where $\hat{\Omega} \in \Omega$. Each local solution Ω^k could be formulated as:

$$\Omega^k = \Omega_i^k + \Omega_n^k \tag{5}$$

Then, the set of solutions for each i -th component is

$$\Omega_i = \Omega_{i1}, \Omega_{i2}, \ldots, \Omega_{i,J_i} \tag{6}$$

For any c_{ij_i} there are δ_{ij_i} different local criteria Ψ_{ij_i}. Then the total number of criteria for any Ω_i is

$$\Omega_i = \begin{vmatrix} \Psi_{i1}^1 & \Psi_{i2}^1 & \ldots & \Psi_{iJ_i}^1 \\ \Psi_{i1}^2 & \Psi_{i2}^2 & \ldots & \Psi_{iJ_i}^2 \\ \ldots & \ldots & \ldots & \ldots \\ \Psi_{i1}^{\delta_{i1}} & \Psi_{i2}^{\delta_{i2}} & \ldots & \Psi_{iJ_i}^{\delta_{iJ_i}} \end{vmatrix} \tag{7}$$

The criteria for the rest of the first machine component are defined in the same way. Similarly are defined the local criteria $\Psi_{nf_n} \ \forall \ \Omega_n$ for the second machine.

CREATING A DATABASE OF THE MACHINE COMPONENTS

Based on the conventional classification of logistics equipment and the method of functional value analysis [7, 8, 9] and applying the decomposition process, a structural model could be constructed. It aims at achieving the required accuracy of positioning of the logistics machine (fig.1). It has a tree-like structure and is based on the "top-down design" principle.

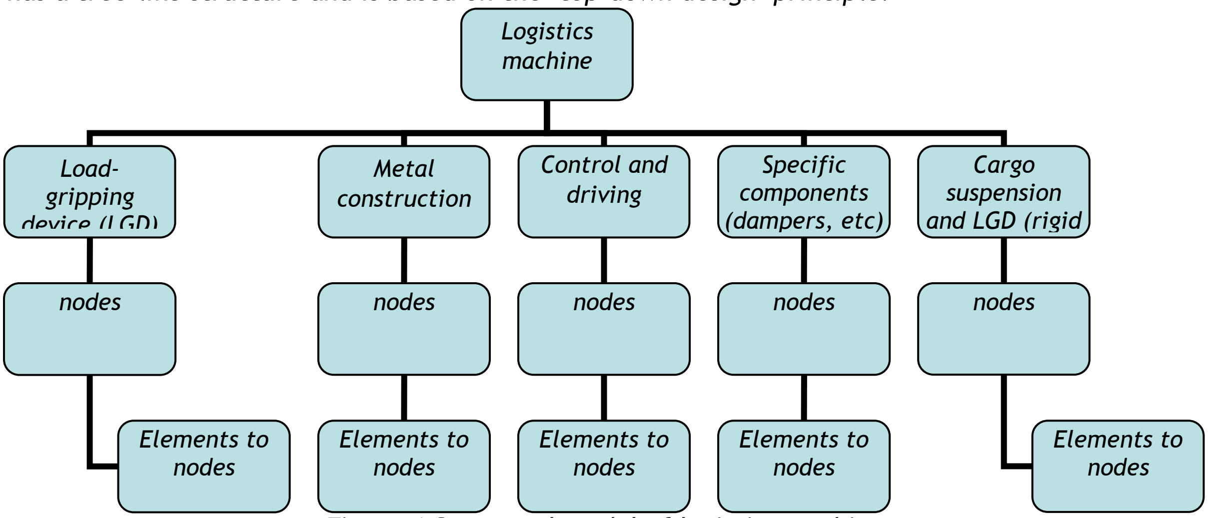

Figure.1 Structural model of logistics machine

It should be noted that this is a general structural model and there might be changes in some specific cases. Costs of individual decisions and devices for a given logistics machine are shown in Table 1.

It is assumed in this article, that each device has N number of ranges (modifications) for the corresponding cost, e.g. range 1 provides some inaccuracy for the corresponding cost C_{11}^1, range 2 provides lower inaccuracy at a higher cost $C_{11}^2 > C_{11}^1$ etc.

The methodology includes the following blocks:

1. *Block "**Contacting**". Determined are the types of contacting logistics equipment and the corresponding requirements. Determined is the area of cargo reception and transfer.*
2. *Block "**Decomposition**". Each machine system (logistics machine) is decomposed according to the elements that provide for the positioning accuracy - LGDs, suspension, metal construction, control*

and driving, other devices (dampers, etc.). Decomposition could be done according to some other scheme, depending on the case and the goals.

3. *Block "**Classification**". The ways of achieving positioning accuracy by each decomposed element are described.*
4. *Block "**Configuration**". Synthesis of possible configurations of specific solutions for each machine from a given variant following the criterion of minimum total cost of contacting equipment. This helps achieve a minimum accuracy required to transfer a load.*
5. *Block "**Ordering**". Classification of all machine configurations to achieve the desired positioning accuracy at minimum cost for a particular solution.*

Table 1. Costs of solutions and elements

Elements		Devices (solutions) increasing the positioning accuracy									
		1			2			...	N		
		Range 1	Range 2	Range N1	Range 1	Range 2	Range N2	...	Range 1	Range 2	Range NN
№	Title	value	value	value	value	value	value	...	value	value	value
1	LGD	C_{11}^{1}	C_{11}^{2}	C_{11}^{N1}	C_{12}^{1}	C_{12}^{2}	C_{12}^{N2}	...	C_{1N}^{1}	C_{1N}^{2}	C_{1N}^{NN}
2	Metal construction	C_{21}^{1}	C_{21}^{2}	C_{21}^{N1}	C_{22}^{1}	C_{22}^{2}	C_{22}^{N2}	...	C_{2N}^{1}	C_{2N}^{2}	C_{2N}^{NN}
3	Electric control and driving	C_{31}^{1}	C_{31}^{2}	C_{31}^{N1}	C_{32}^{1}	C_{32}^{2}	C_{32}^{N2}	...	C_{3N}^{1}	C_{3N}^{2}	C_{3N}^{NN}
4	Other devices	C_{41}^{1}	C_{41}^{2}	C_{41}^{N1}	C_{42}^{1}	C_{42}^{2}	C_{42}^{N2}	...	C_{4N}^{1}	C_{4N}^{2}	C_{4N}^{NN}
5	Suspension	C_{51}^{1}	C_{51}^{2}	C_{51}^{N1}	C_{52}^{1}	C_{52}^{2}	C_{52}^{N2}	...	C_{5N}^{1}	C_{5N}^{2}	C_{5N}^{NN}

The solving algorithm *is based on the "down - top design" principle, i.e. it starts from the area of load transmission and includes the following key steps (Fig.2):*

- ☐ ***Step 1***. *Determination of the required area for transshipment with the basic machine configuration according to the following two cases:*

a. *relative orientation – load-gripping device of the receiving machine is oriented according to the load orientation in the transferring machine;*

b. *absolute orientation - load-gripping device of the receiving and transferring machine are oriented in advance according to a pre-determined fixed point.*

In both cases, the area of positioning coincides with the geometric area defined by the scope of the receiving load-gripping device. In either case, this is related to the characteristics of the load and the packaging.

- ☐ ***Step 2***. *Optimization of the size of the receiving equipment by increasing its receiving area to the max possible extent defined by the material handling process. In this case, an LGD with max reach is selected from a database of all cargo handling devices. Determining the total allowable positioning error of both machines. If the condition of faultless load transition is violated, proceed to step 3.*
- ☐ ***Step 3***. *Classification and extraction from the database data about the ways to achieve positioning accuracy by each decomposed element for both logistics machines. Construct a new database with the extracted data. Compilation of Table 1.*
- ☐ ***Step 4***. *Reducing the positioning inaccuracy of the first machine. In this step, the cheaper machine configuration is replaced with a new module with greater precision of positioning. Machine synthesis is performed, i.e. the entire machine is constructed from the elements in table1. As a result, there are obtained lists of all possible machine configurations for each type of LGD.*
- ☐ ***Step 5***. *Determination, in a similar manner, of all possible configurations of the second machine. Here, the result is also in the form of lists of all possible machine configurations for each type of LGD.*
- ☐ ***Step 6***. *Formation of pairs of machines out of the two lists. The pairs include information about the positioning error that is less than or equal to the pre-defined error value as well as information about the total cost. The results form a sample in ascending order. Based on these ordered final configurations, the required positioning accuracy could be obtained along with the lowest reasonable cost of the machines.*

The algorithm could also be applied for the case in which the value of each range is more suitable than the sum of values of all elements in a specific range for each element.

The choice of the basic system is made according to the requirements of the process. In general, reducing the total cost is achieved by significantly reducing the cost of management, although the price of individual items may increase. To estimate the economic efficiency of the application of the proposed approach there could be used the method of calculating the cost of operations [2].

Figure 2 represents the accepted symbols of relationships and the steps of the algorithm. Used is the format of Table 1 for building arrays of costs.

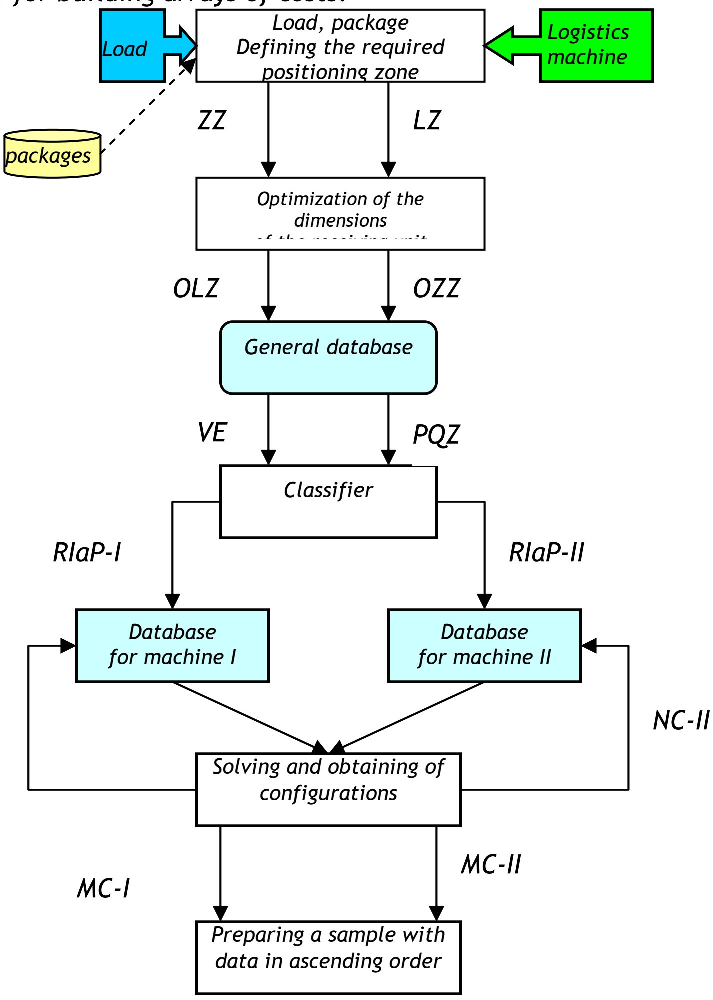

Figure 2. Solving algorithm - structural scheme

ZZ-dimensions of the zone; LZ-dimensions of the load; OZZ-optimal dimensions of the zone; OLZ-dimensions of the load; VE-type elements; POZ-parameters of the elements; RIaP-I-solutions enhancing the positioning accuracy of the first machine; RIaP-II - solutions increasing the positioning accuracy of the second machine; NC-I-a new configuration of the first machine; NC-II-a new configuration of the second machine; MC-I-mechanical configuration of the first machine; MC-II-mechanical configuration of the second machine.

Considered is the case with two machines and there exists a database of costs for each one of them. The following is accomplished in search of a solution:

- *Table 1 rows, respectively for LGD, metal structure, electric control and driving, suspension and other devices are designated as X; moreover X is an integer and varies in the interval $X \in [1;5]$;*
- *Table 1 columns (ranges) are designated as Y, where Y is an integer;*
- *values are normalized in order to generalize further reasoning [11, 12];*
- *values in rows obey the normal distribution with mean normalized to 1 and standard deviation obtained by the analysis of variance of the values from the existing database;*
- *the first machine array of costs is considered to be Z1, the second machine array of costs is considered to be Z2, and the summarized array of the costs of the two machines is assumed to be Z3; the optimum of Z3 has to be found;*

For clarity of presentation and to facilitate visualization of the results obtained it is assumed that for both of the machines Y varies in the interval $Y \in [1;4]$. As a result, two arrays with 5x4 dimensionality are obtained. It is necessary to find the optimal cost combination of elements of the two machines.

An M-file program MATLAB [13] is developed to solve the problem.

Part of the results obtained are presented in the figures below. The results obtained are analysed and part of the obtained data is given below:

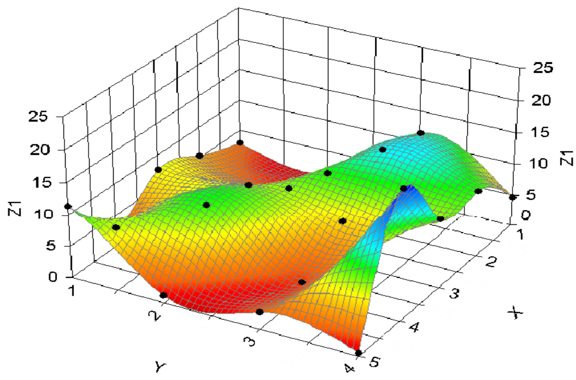

Figure. 3 Variation of Z1 for X∈[1;5] and Y∈[1;4]

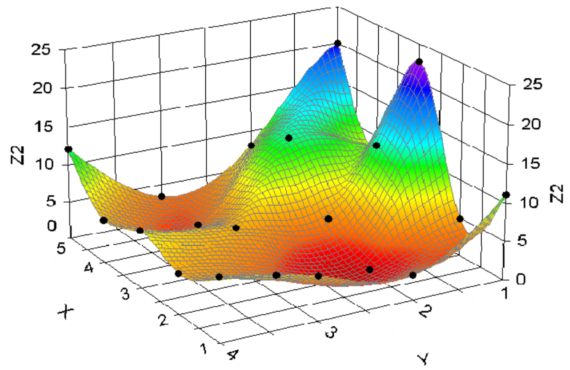

Figure. 4 Variation of Z2 for X∈[1;5] and Y∈[1;4]

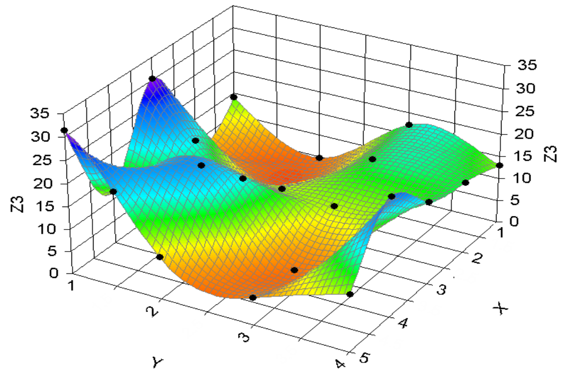

Figure. 5 Variation of Z3 for X∈[1;5] and Y∈[1;4]

sumZ1 =

Y=1	Y=2	Y=3	Y=4
30.2475	25.5444	36.4363	46.9327

sumZ2 =

Y=1	Y=2	Y=3	Y=4
67.4323	28.0331	19.5044	38.5782

sumZ3 =

Y=1	Y=2	Y=3	Y=4
97.6798	53.5775	55.9407	85.5109

where sumZi is the corresponding aggregate cost of a given combination of elements in each of the Y columns Y∈[1;4].

As shown:

- *the minimum value for the first machine is 25.5444 at Y = 2;*
- *the minimum value for the second machine is 19.5044 at Y = 3;*

But the minimum value of the general array Z3 is 53.5775 at Y = 2

Although the minimum value of the second machine is at Y = 3, then on the basis of the Z3 array, it follows that the optimal cost combination of components is at Y = 2, i.e. for range 2 of the devices increasing the positioning accuracy.

Application

The proposed approach is applied in the Factory for electric motors - Sofia. There by increasing the clamping area of the cargo handling devices in the transport system AGV-robot the overall cost of the system was substantially reduced.

CONCLUSIONS

There are proposed an approach and a methodology for determining the optimum performance of logistics machinery and a corresponding algorithm is developed. It is intended for the design of efficient transport system. It is obvious that the presented model provides plenty of opportunities for research and analysis, as well as for performing a subsequent optimization. When optimizing, further clarification is required about the laws of costs variations and the parameters must be strictly defined, so as to facilitate the selection of the most suitable option for optimization.

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