DOI: 10.2507/34th.daaam.proceedings.xxx

Choosing an Optimal Structural Variant of a Basic Size for a Size Range of Modules

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This Publication has to be referred as: Zaharinov, V[elizar]; Malakov, I[vo] & Hasansabri, H[asan] (2023). Choosing of an Optimal Structural Variant of a Basic Size of a Size Range of Modules for Driving Automatic Sliding Doors, Proceedings of the 34th DAAAM International Symposium, pp.xxxx-xxxx, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-xx-x, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/34th.daaam.proceedings.xxx

Abstract

In the present article the solution of the problem for choosing an optimal structural variant of a basic size of a size range of modules for driving automatic sliding doors is considered. For this purpose, the necessary parameters of the movement of the doors and their dimensions and mass are analysed. A functional structure of the module is built and alternative device variants are developed for the implementation of each function. The set of possible structural variants is constructed with compatibility between devices in mind. The problem of choosing the optimal structural variant is formulated. Based on an analysis of the requirements for the module, criteria for evaluating the structural variants and constraints are selected. A mathematical model of the problem for choosing an optimal structural variant is built. By means of algorithmic and software support, the formulated multi-criteria optimization problem is solved both with equal objective functions and also with different priority of some of them, with the aim of enriching the possibilities of the decision maker to find Pareto optimal solutions that best meet its requirements and limitations.

Keywords: design; optimization; size ranges; automatic doors; linear module.

1. Introduction

Automated sliding doors belong to automatic doors, which are a section of architectural systems with a large application in construction. They are used in malls, shops, offices, hotels, etc. as in practice there is hardly any public building without such type of doors installed. Apart from public buildings, automatic doors are also used in private homes, usually when it comes to large opening areas and when using heavy wings with relatively large overall dimensions.

A number of automated sliding door drive systems are available on the market. Some of the leading manufacturers are Dormakaba [1], Alumil [2], GEZE [3], etc. Dormakaba offers two types of drives for sliding doors – with a rotary electric motor and belt drive [4] and with a linear electric motor [5]. Alumil uses in its system for automated sliding doors a module with an electric drive and a toothed belt [6], converting the rotary motion of the electric motor into a linear one. Geze use, like Alumil, an electrically driven linear motion module with a toothed belt to convert rotation to translation [3]. The leading manufacturers offer a variety of typologies and functions, but the drive system, in general, is based on one main type. It is a linear motion module that is sized to drive the heaviest wings of the respective system. Thus, for

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assignments that require smaller wings, it is necessary to equip the automatic sliding door with an oversized drive, which leads to higher operating costs. The solution to this problem is the development of a size range [7], [8], [9], [10] from automatic sliding door drive modules. The first step in the development of the size range is the determination of the structure of the base variant (the main size) [8], [9], [11], [12], i.e., the structure that will be used to build the modules of the size range.

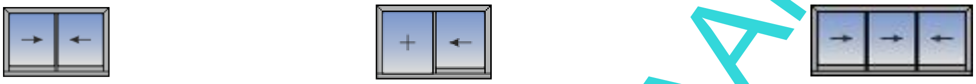
The selection of the structure of the base variant is a stage that is fundamental to the design of a size range. This is so because the technical and economic characteristics of the basic size determine the properties of the entire range (family) of sizes [8]. The results of this stage are of particular importance for the development of the size ranges, since the errors made here are multiplied in the other elements of the range. Therefore, the choosing of an optimal structural variant of a module for driving automatic sliding doors is a prerequisite for the effective development of a size range of modules.

The purpose of this article is to present the choosing of an optimal structural variant of a basic size, which will be the basis for the construction of a size range of modules for driving automatic sliding doors.

2. Development of the set of possible structural variants

2.1. Selection of typology and requirements for the basic size

Automated sliding doors are offered in the form of different typologies. By the term "typology" is meant the arrangement and the way the wings move. In Fig. 1 are shown examples of different typologies.



(a) (b) (c)

Fig. 1. Example of different typologies of sliding doors [2]

Due to the different requirements related to installation, mass of the driven wings, frame geometry, etc. with the different typologies, it is necessary to choose a specific one for which to develop a drive. The typology for which the size range is going to be developed and the corresponding drive unit for the automatic door wings is shown in Fig. 1(a). This typology is widespread and is used both for entrance doors and for interior doors. It is characterized by the presence of two movable wings that open towards the centre of the door opening. The wings are guided by steel rollers rolling on a rail in the lower part of the frame. In its upper part, the wing is supported by the geometry of the frame, which functionally prevents the wing from overturning and assists in guiding. After market research, it was found that the dimensions of the wings for automatic sliding doors vary in length from 600 mm to 3000 mm, and in height from 1800 mm to 2800 mm. The mass of one wing can vary widely – from 20 kg to 700 kg [1], [2], [3]. The requirements for the basic size are shown in Table 1, and the specifications - in Table 2. For the requirements, a priority for implementation is indicated, with 10 indicating the highest priority ("demand" type requirement), and values between 9 and 1 varying in the degree of priority for implementation ("wish" type requirements). From the specification table it can be seen that the basic size will be developed taking into account the parameters of the wings with the largest dimensions and mass in the ranges indicated above. This decision was made on the basis of the consideration that the devices selected to fulfil the functions of the drive must be able to drive even the heaviest doors available on the market.

2.2. Development of a functional model of the basic size

In Fig. 2 is shown the overall function of the drive module. It is the positioning of the sliding door wing when control signals are given by the user. In order to be able to perform the overall function, the drive module must be provided with a certain set of inputs (Fig. 2 and Table 3): wing – this is the wing of the sliding door, suspended on a guide system; supporting structure – this is the mechanical system to which the module will be connected; • Power supply – source/sources of energy powering the motor of the module; power supply – source/sources of energy powering the motor of the module; motor control signals – signals from the control system to the motor to execute the commands given by the user.

The inputs of the system are converted by the overall function into a certain set of outputs (Fig. 2 and Table 3): positioned wing – the position of the wing changes according to the user's assignment; noise – the level of noise produced by the module must be taken into account in view of its possible application in residential areas; signals for completed movement – signals from position sensors to the control system, confirming completed positioning (reach to position).

№	**Type**	**Requirement**	**Priority**
1	D	Integration into the profiles that make up the frame structure	10
2	W	Low price	5
3	W	Low energy costs	6
4	W	Low noise	8
5	W	Easy installation	7

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Table 1. Basic size requirements

№	Requirement/Metric	Value	Dimension
1	Mass of the wing being moved	700	kg
2	Stroke	2,9	m
3	Linear speed	0,1	m/s

Table 2. Basic size specifications

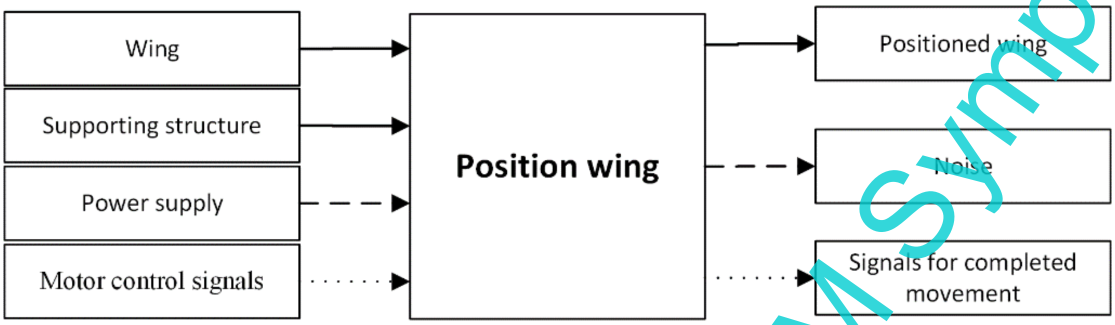

Fig. 2. General function of the basic size

Inputs			Outputs		
Material	*Energy*	*Information*	*Material*	*Energy*	*Information*
Wing	Power supply	Motor control signals	Positioned wing	Noise	Signals for completed movement
Supporting structure					

Table 3. Inputs and outputs for the drive module classified into three groups

The process of converting the inputs of the overall function into its outputs is explained by the list of functions (Table 4) and the tree of functions (Fig. 3). The function tree was obtained after analysing the components included in the structural composition of existing modules.

Designation	Function	Explanation
F1	Drive	Converting supply energy into useful mechanical motion
F2	Transmit motion	Realization of transmission - direct or with transmission ratio
F3	Connect	Connecting the elements of the system to be driven to the drive
F4	Convert motion	Converting motion from one form to another (rotation to translation)
F5	Provide position information	End position detection (wing open/closed)

Table 4. Functions list

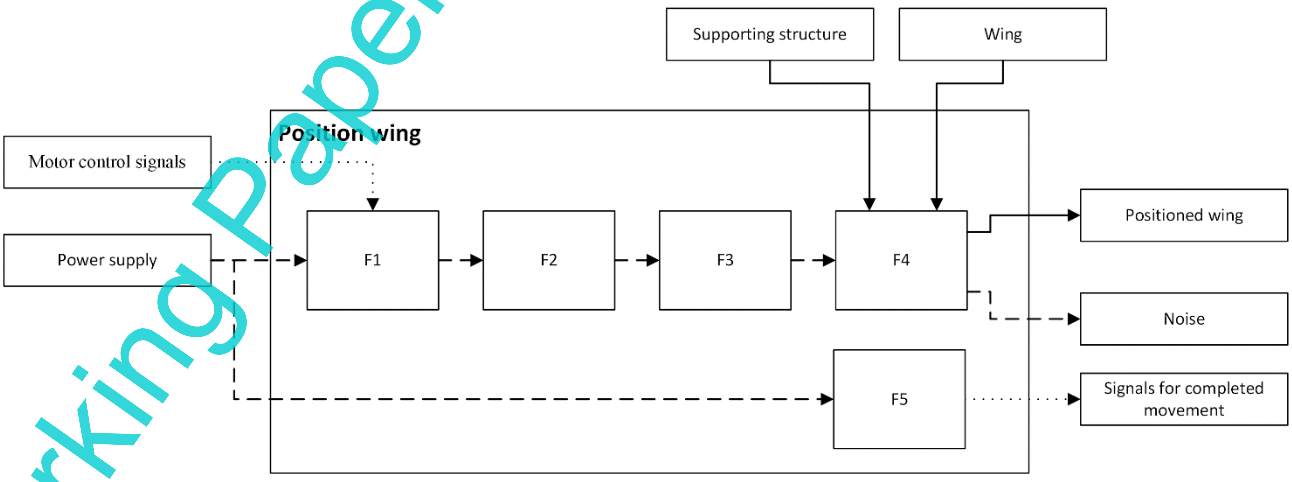

Fig. 3. Functional structure

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2.3. Development of alternative variants of devices for the implementation of functions

For each specific function of the designed module (basic size), possible implementation variants are developed. The developed variants for F1 to F5 are summarized in Table 5. The criterion for inclusion is quality of implementing the function [13]

Function	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6	Variant 7
F1	Stepper motor for direct drive	Hybrid servo motor for direct drive	AC servo motor for direct drive	Stepper motor for transmission drive	Hybrid servo motor for transmission drive	AC servo motor for transmission drive	Linear electrical motor
F2	Worm gear	Planetary gear	Bevel gear				
F3	Metal bellow coupling	Self-aligning coupling	Elastic coupling				
F4	Toothed belt drive	Chain drive	Gear rack and pinion drive				
F5	Limit switch	Proximity sensor	Reed switch	Hall effect sensor	Light proximity sensor		

Table 5. Alternative solutions

2.4. Network model of the set of possible structural variants

The set of possible structural variants X that fulfil the overall function of the module is represented in the form of a network model in Fig. 4. The vertices in the model are arranged in 5 columns according to the functions of the basic size. The possibilities of combining the devices x_n^l into structures x performing the overall function of the drive system are shown by arrows. Each path connecting the beginning (S) and the end (E) of the network model represents a possible structural variant.

The network model shown in Fig. 4 describes the possible combinations of devices and their compatibility. In the developed variants, devices x_1^1, x_1^2, x_1^3, and x_1^7 are polyfunctional (can perform more than one function). Devices x_1^1, x_1^2, and x_1^3 can perform functions F1 and F2, and device x_1^7 can perform functions from F1 to F4 inclusive.

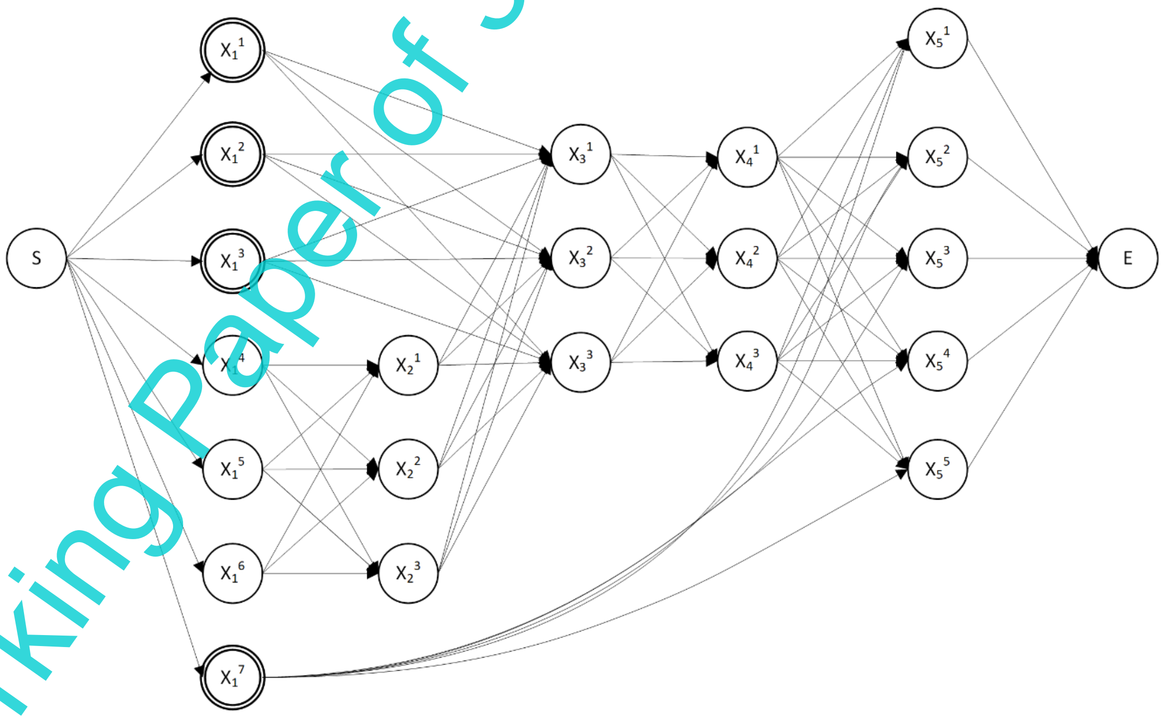

Fig. 4. Network model of the set of possible structural variants

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3. Choosing of optimization criteria and their measurement

The choosing of criteria is according to the requirements for the basic size formulated in Table 1. Four criteria are chosen for the evaluation of alternative structural variants: production costs of the developed module in euros, efficiency factor, occupied space in cubic centimetres, and service and repair time. Therefore, the considered problem is a multi-criteria optimization problem with compatibility constraints between individual devices. The compatibility constraint originates from the presence of the polyfunctional devices x_1^1, x_1^2, x_1^3, and x_1^7.

Three of the criteria require a minimum value for the developed alternative structural variants, and one (efficiency factor) - a maximum. The fourth criterion is assessed (measured) by pairwise comparisons of the developed variant. The assessment was carried out by experts according to the method of Voichinskiy and Jansson [14].

The valued criteria (transformed into objective functions) are shown in Table 6.

Function	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5	Variant 6	Variant 7
F1	320,04 -0,431 1183 0,046	343,20 -0,431 1331 0,049	1154,36 -0,186 2805 0,054	70,44 -0,431 325 0,052	315,68 -0,431 323 0,040	703,62 -0,186 800 0,044	11151,00 -0,163 1800 0,044
F2	684,46 -0,357 256 0,071	673,72 -0,020 94 0,075	1697,86 -0,041 3927 0,068				
F3	64,92 -0,020 76 0,045	225,16 -0,020 46 0,047	27,36 -0,010 25 0,050				
F4	1003,53 -0,051 2850 0,083	354,87 -0,073 3660 0,087	1468,11 -0,051 5400 0,079				
F5	12,80 -0,010 2 0,067	24,19 -0,010 20 0,054	6,84 -0,010 2 0,047	14,76 -0,010 6 0,052	23,00 -0,010 3 0,049		

Table 6. Values of the criteria for the variant solutions of the functions

4. Building the mathematical model of the problem

The solving of the following problem is assigned:

Given a set of possible structural variants of the basic size, determine the optimal structural variant so that:

$$\begin{aligned} &min\, C(x) = \sum_{n=1}^{5} C(x_n^l)\,, min\, P(x) = \sum_{n=1}^{5} P(x_n^l), \\ &min\, V(x) = \sum_{n=1}^{5} V(x_n^l)\,, min\, T(x) = \sum_{n=1}^{5} T(x_n^l) \end{aligned} \qquad (1)$$

where: $x \in X$; $n = 1 \div 5$; $|L_1| = 7$, $|L_2| = 3$, $|L_3| = 3$, $|L_4| = 3$; $|L_5| = 5$; $C(x)$ – production costs, EUR; $P(x)$ – efficiency; $V(x)$ – occupied space, cm^3; $T(x)$ – service and repair time. With the mathematical model built in this way, the value of the relevant objective function for a given possible structural variant of the system is defined as the sum of the technical and economic characteristics of the devices included in this structural variant. Mathematically, to obtain the value of the objective function for the second criterion – efficiency, it is necessary to multiply the efficiency coefficients of the devices making up the variant. Since model (1) uses summation, a logarithm is applied to the actual efficiency values [15] for the devices to obtain the values of the second objective function. The logarithmization was performed with the Napier's constant as the base (the so-called natural logarithm).

5. Solving the problem

Due to the presence of polyfunctional devices, it is necessary to first decompose the set of structural variants of the basic size into subsets where there are no constraints on compatibility. For this purpose, the PolyOptimizer [16] optimization software environment is used.

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The set of possible structural variants of the drive system is decomposed into three subsets, the elements of which are shown in Table 7.

Subset	X_1	X_2	X_3	X_4	X_5	**Number of variants**
1	$x_1^1;\ x_1^2;\ x_1^3$		$x_3^1;\ x_3^2;\ x_3^3$	$x_4^1;\ x_4^2;\ x_4^3$	$x_5^1;\ x_5^2;\ x_5^3;\ x_5^4;\ x_5^5$	135
2	$x_1^4;\ x_1^5;\ x_1^6$	$x_2^1;\ x_2^2;\ x_2^3$	$x_3^1;\ x_3^2;\ x_3^3$	$x_4^1;\ x_4^2;\ x_4^3$	$x_5^1;\ x_5^2;\ x_5^3;\ x_5^4;\ x_5^5$	405
3	x_1^7				$x_5^1;\ x_5^2;\ x_5^3;\ x_5^4;\ x_5^5$	5

Table 7. Elements of structural variant subsets

The total number of possible structural variants of the designed system is 545. To determine the upper and lower bounds of the objective functions, 24 single-criteria optimization problems are solved, and to find a solution to the multi-criteria problem, it is necessary to solve 3 multi-criteria optimization problems (one for each subset).

The considered problem is a multi-criteria optimization problem with compatibility constraints between devices. It is solved using the PolyOptimizer dialog system.

5.1. Solution under equal priority of the objective functions

The compromise solution of the problem is found for objective functions of equal importance. Table 8 shows the values of the objective functions for the variant, as well as the devices entering the structure of the module. In Fig. 4 is shown the solution from PolyOptimizer.

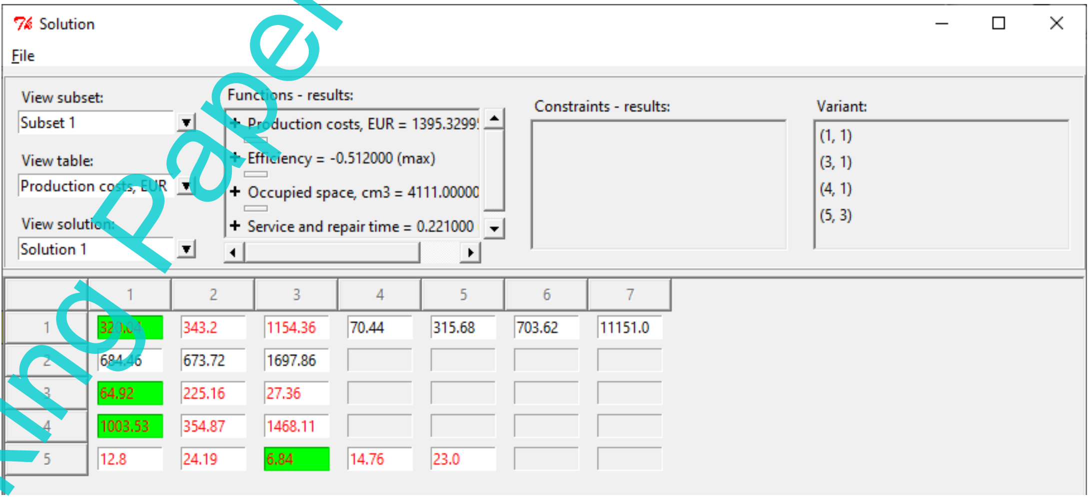
Variant x_1^* (Table 8) is a timing belt mechanism driven by a stepper motor without a transmission mechanism (direct drive). The motor is connected to the mechanism by a self-adjusting clutch, and the end positions of the wing are established by a reed contact.

When analysing the proposed solution, the following conclusions can be drawn: production costs have the smallest deviation from their optimum, and the largest - service and repair time; the compromise variant has significant deviations from the optimum of the objective functions; the optimum is found in the first subset.

In Fig. 5, the devices that make up the structural variant are marked in green, and the values of the elementary devices that make up the subset (after decomposition) are written in red.

Structural variant x_1^*				
$x_1^* = \{x_1^1; x_3^1; x_4^1; x_5^3\}$				
№	Objective function	Value	Deviation from the optimum for the objective function	Upper and lower boundary
1	$C(x)$, EUR	1395,76	$w_1 = 0{,}0656$	$709{,}11 \leq C(x) \leq 11175{,}19$
2	$P(x)$	-0,512	$w_2 = 0{,}4722$	$-0{,}891 \leq E(x) \leq -0{,}173$
3	$V(x)$, cm^3	4111	$w_3 = 0{,}2742$	$1802 \leq V(x) \leq 10\ 223$
4	$T(x)$	0,221	$w_4 = 0{,}5417$	$0{,}091 \leq T(x) \leq 0{,}331$

Table 8. Structural variant with equal priority of the objective functions



View subset: Subset 1

View table: Production costs, EUR

View solution: Solution 1

Functions - results:

+ Production costs, EUR = 1395.3299!
+ Efficiency = -0.512000 (max)
+ Occupied space, cm3 = 4111.00000
+ Service and repair time = 0.221000

Constraints - results:

Variant:
(1, 1)
(3, 1)
(4, 1)
(5, 3)

	1	2	3	4	5	6	7
1	320.04	343.2	1154.36	70.44	315.68	703.62	11151.0
2	684.46	673.72	1697.86				
3	64.92	225.16	27.36				
4	1003.53	354.87	1468.11				
5	12.8	24.19	6.84	14.76	23.0		

Fig. 5. Solution x_1^*

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5.2. Solution when setting a different priority for criteria

If the solutions obtained do not satisfy the decision maker (DM), it can continue to search for other solutions by changing the priority of the criteria. The investigation of the problem continues with the introduction of different weighting coefficients.

Due to the significant deviations of the objective functions from their optima, the problem offers good opportunities for researching alternative solutions giving priority to individual objective functions.

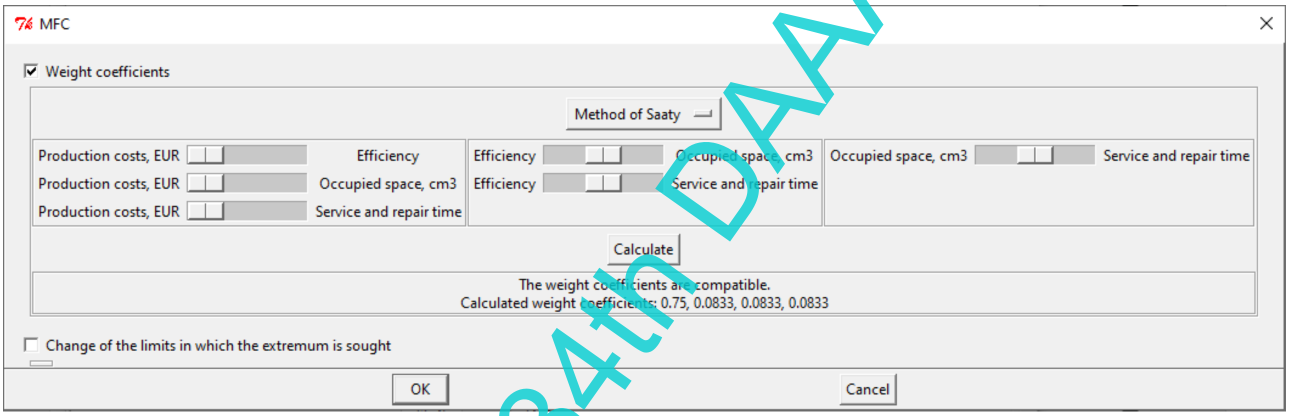
Initially, the problem is solved with a higher priority for production costs. Therefore, the following problem is set:

Determine a weight vector that assigns a higher priority to the production cost criterion $C(x)$ of the module.

Saaty's [17] method is utilized for prioritizing production costs. In Fig. 6 is shown the user interface of the method in the PolyOptimizer dialog system, through which the parameter values are entered. The binary comparisons for the particular problem are six. Production costs are prioritized over efficiency, space occupied, and service and repair time. DM has set these parameters through the sliders (Fig. 6). The figure shows that equal importance is set for the remaining criteria by placing the sliders midway between the comparison pairs. After calculating the weighting coefficients, the problem can be solved with the thus entered information about the priority of the criteria. The values obtained for this solution are shown summarized in Table 9. The calculated priority vector is $p_1 = \{0{,}7500; 0{,}0833; 0{,}0833; 0{,}0833\}$.

The differences between this structural variant and variants x_1^* are in one device – performing the function of motion conversion. Manufacturing costs improve by 6% relative to x_1^*. All other objective functions worsen – efficiency by 3%, space occupied by 10%, and service and repair time by 2%.

If the proposed variant satisfies the DM, then it is selected for the solution of the problem. Otherwise, a new priority is set. Using the PolyOptimizer dialog system, the situation where higher priority is given to efficiency was investigated.



☑ Weight coefficients

Method of Saaty

Production costs, EUR – Efficiency
Production costs, EUR – Occupied space, cm3
Production costs, EUR – Service and repair time
Efficiency – Occupied space, cm3
Efficiency – Service and repair time
Occupied space, cm3 – Service and repair time

The weight coefficients are compatible.
Calculated weight coefficients: 0.75, 0.0833, 0.0833, 0.0833

☐ Change of the limits in which the extremum is sought

Fig. 6. Prioritize production costs

Structural variant x_2^*				
$x_2^* = \{x_1^1; x_3^1; x_4^2; x_5^3\}$				
№	Objective function	Value	Deviation from the optimum for the objective function	Upper and lower boundary
1	$C(x)$, EUR	746,67	$w_1 = 0{,}0036$	$709{,}11 \le C(x) \le 11175{,}19$
2	$P(x)$	-0,534	$w_2 = 0{,}5028$	$-0{,}891 \le E(x) \le -0{,}173$
3	$V(x)$, cm3	4921	$w_3 = 0{,}3704$	$1802 \le V(x) \le 10\,223$
4	$T(x)$	0,225	$w_4 = 0{,}5583$	$0{,}091 \le T(x) \le 0{,}331$

Table 9. Structural variant with priority of production costs

When prioritizing using Saaty's method, a solution x_3^* (Table 10) is obtained, which is significantly different from x_1^*. A linear electric motor was chosen for it. It is a polyfunctional device and performs all the functions of the system without one. The choice worsens the production costs to a large extent – by 93%, but the remaining objective functions achieve their optima. The calculated priority vector is $p_2 = \{0{,}0833; 0{,}7500; 0{,}0833; 0{,}0833\}$.

It is found that when prioritizing the remaining objective functions, by Saaty's method (analogous to Fig. 6), the solutions coincide with solution x_3^*. This is because given the priority of one objective function and all else being equal, Saaty's method assigns a large weighting factor to the priority objective function. Therefore, to determine the priority of the occupied space, the method of Voichinskiy and Jansson [14] is used (Fig. 7). The solution found is shown in Table 11.

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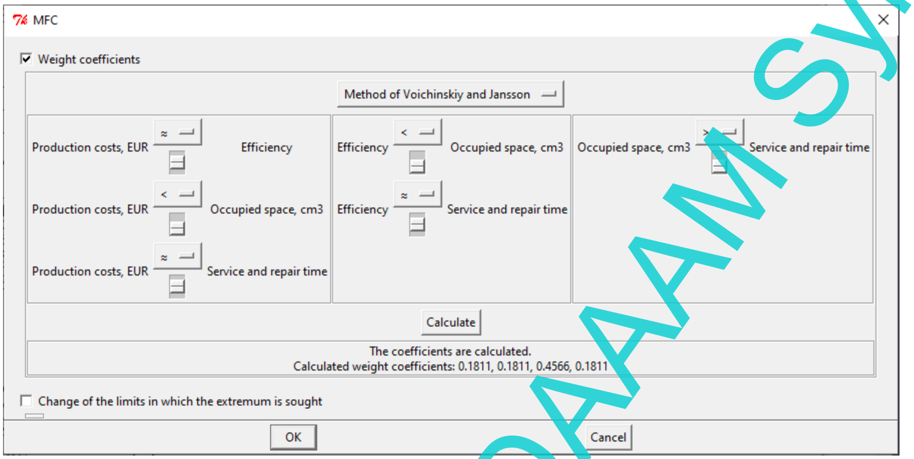
Structural variant x_3^*				
$x_3^* = \{x_1^7; x_5^3\}$				
№	Objective function	Value	Deviation from the optimum for the objective function	Upper and lower boundary
1	$C(x)$, EUR	11157,84	$w_1 = 0{,}9983$	$709{,}11 \leq C(x) \leq 11175{,}19$
2	$P(x)$	-0,173	$w_2 = 0{,}0000$	$-0{,}891 \leq E(x) \leq -0{,}173$
3	$V(x)$, cm3	1802	$w_3 = 0{,}0000$	$1802 \leq V(x) \leq 10\ 223$
4	$T(x)$	0,091	$w_4 = 0{,}0000$	$0{,}091 \leq T(x) \leq 0{,}331$

Table 10. Structural variant with priority of efficiency


MFC

☑ Weight coefficients

Method of Voichinskiy and Jansson

Production costs, EUR ≈ Efficiency
Production costs, EUR < Occupied space, cm3
Production costs, EUR ≈ Service and repair time
Efficiency < Occupied space, cm3
Efficiency ≈ Service and repair time
Occupied space, cm3 > Service and repair time

Calculate

The coefficients are calculated.
Calculated weight coefficients: 0.1811, 0.1811, 0.4566, 0.1811

☐ Change of the limits in which the extremum is sought

OK
Cancel

Fig. 7. Voichinskiy and Jansson prioritization of the occupied space objective function

Structural variant x_4^*				
$x_4^* = \{x_1^1; x_3^3; x_4^1; x_5^1\}$				
№	Objective function	Value	Deviation from the optimum for the objective function	Upper and lower boundary
1	$C(x)$, EUR	1363,73	$w_1 = 0{,}0626$	$709{,}11 \leq C(x) \leq 11175{,}19$
2	$P(x)$	-0,502	$w_2 = 0{,}4582$	$-0{,}891 \leq E(x) \leq -0{,}173$
3	$V(x)$, cm3	4060	$w_3 = 0{,}2681$	$1802 \leq V(x) \leq 10\ 223$
4	$T(x)$	0,246	$w_4 = 0{,}6458$	$0{,}091 \leq T(x) \leq 0{,}331$

Table 11. Structural variant with priority of the occupied space

With this solution, the occupied space is improved by 1%, production costs and efficiency are also improved by 0,3% and 1% respectively. Service and repair time is worsened by 10%.

In Fig. 8, the four solutions found are shown in summary. Graphical representation is made through a radar diagram, on which each axis represents an evaluation criterion. The different coloured rectangles plotted on the diagram are the four solutions. The values on the axes are the percentage deviations of the solutions found for each criterion. The ideal solution that simultaneously achieves an optimum by all criteria is the point of intersection of the axes in the centre of the diagram. The graph can be likened to a target – the more concentrated the variant's rectangle is around the zero point, the closer it is to the ideal solution. The graph shows that the compromise solution x_1^* is the most concentrated, with solutions x_2^* and x_4^* also close to it. Solution x_3^* is highly directed towards the optimum of production costs and is therefore visible on the graph as a vertical line pointing to the objective function.

On the basis of the solutions found and their graphic analysis, a decision was made by the DM, that the basic size will be based on variant x_1^* (Fig. 9).

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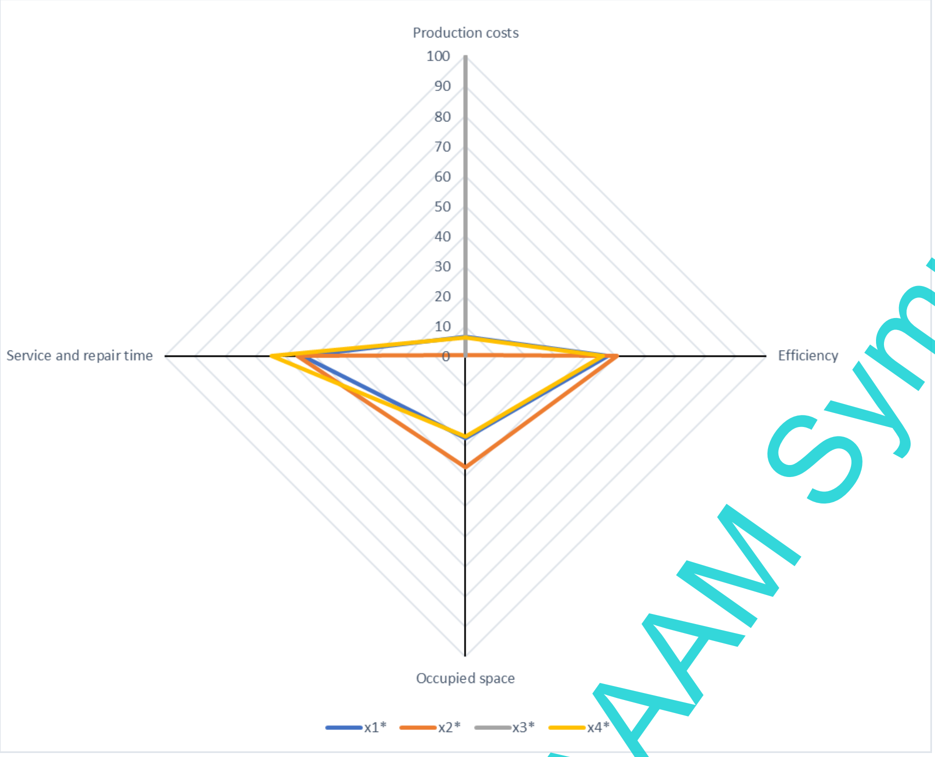

Fig. 8. Graphical interpretation of the solutions found

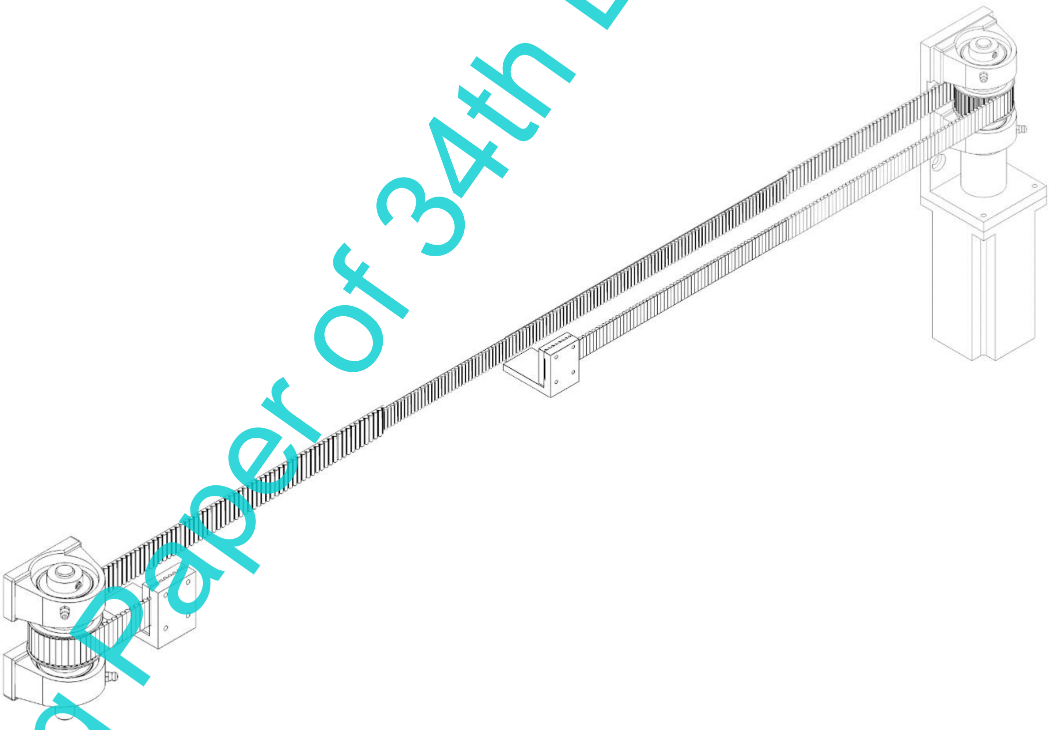

Fig. 9. Variant x_1^* drive elements

6. Conclusion

The following results have been achieved in the present development:

- A sliding door typology has been chosen for which to develop a size range of drive modules;
- After researching the market, the requirements and specifications for the developed basic size of the range are formulated;

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- The functional structure of the basic size is built, where its overall function with inputs and outputs and the function tree are formulated;
- Solution variants are developed for each function of the functional structure;
- The set of possible variants is determined by means of a directed graph and the definition of polyfunctional devices and compatibility;
- A presentation and analysis of the problem of choosing the optimal structural variant is made;
- Criteria for evaluation of the developed variants are selected;
- A significant amount of data is collected and the evaluation criteria are valued – converted into objective functions;
- A mathematical model of the problem is built;
- All problem modelling data is entered into a dialog system for multi-criteria optimization, with the help of which to facilitate analysis and finding solutions;
- The set problem of choosing an optimal structural variant of a basic size of a size range is solved under different decision-making conditions and the solutions found are analysed;
- A variant is selected to be the basis for the sizes' structure in a size range of modules for the automatic drive of sliding doors.

In addition to the achieved final goal – the choice of the optimal variant of the basic size, the present development is also an illustrative example that can be generalized to practically any type of technical system. The only requirement is the use of a systematic approach to design and functional thinking (functional representation of the structure of the product being developed).

The object of future development is the construction of a size range that integrates the solution chosen in the present work as the basic size. This will also require the development of tools that will support the process of solving the problem and will expand the capabilities of the dialog system used.

7. Acknowledgments

The results in the present research are obtained under project No. 231ПД0028-06 financed by the grant for scientific research at Technical University - Sofia.

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Working Paper of 34th DAAAM Symposium