Evaluation of the Logistic Process Robotisation Using the Multiple-Criteria Decision-Making

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***Abstract* - In the recent past, a rather fast growth of automated and robotised technological workplaces has been observed in various industries, including the logistics processes which have been, until now, avoided by the automation and robotisation. One of the reasons of a currently low degree of automation in this segment is the complexity of logistics activities that relates to the manipulation with various types of objects in a rather large number of various combinations of their shapes and sizes, in most cases in a very constrained manipulation space. The output of the present article is comparative analysis of 3 different types of robots suitable for manipulation in automated warehouses using the methods of decision-making analysis. The purpose of the multiple-criteria analysis of alternative robots is to describe the objective reality in the selection carried out while applying standard procedures and formalise thus the given decision-making problem, i.e. transform it into a mathematical model of a multiple-criteria decision-making situation.**

***Keywords* – Robotisation, logistic process, multiple-criteria decision-making**

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1. Introduction

To ensure the accuracy and quality of a production process, it is necessary to properly arrange production machines, interoperable storages and supply routes for the removal of material, products, and semifinished product [1, 2]. Innovations which allow a reduction in the costs and an increase in the efficiency of planned and performed processes are beneficial for every organization [3]. Robots can be applied, for example, in the automation of loading and unloading of semi-trailers and containers. An integrated computer analyses various consignment dimensions and, on the basis of such analysis, determines an optimal order of loading or unloading operations. Another potential application is the retrieval of goods from warehouses, instead of the conventional warehouse staff, using stationary or mobile robots. A good opportunity to use robots can also be the field of work-intensive individualisation of consumer goods packing according to the requirements of individual chain stores. Also, the intensity of work in e-shops is a stimulus for the development of robots specialised in the automated package delivery to end recipients.

2. Relationships between humans, automation, and robotics

The graphical representation of the relationships between humans, simple mechanisation, and robotics presented in Figure 1. clearly indicates that humans surpass the simple mechanisation and the controlling information technologies (control systems) with their functional mobility - with plenty of degrees of freedom, and with their intelligence [4].

The automated and robotised warehouses and the storage equipment comprising the automation features belong to the category of industrial manipulators and industrial robots. The automated warehouses are usually used for the storage of pallets, boxes or containers. The warehouses working in the automatic mode are designed to minimise the need for the human work when racking the pallets, boxes and containers. The concept of warehouses, management thereof, data management, good arrangement and order in warehouses and storage premises are designed to eliminate the storage errors and, above all, the retrieval errors which are often caused particularly by human error. The technical execution related to the automation of logistics processes in the warehouse management is targeted and assumes the minimum need for the physical presence of staff. The minimisation of the occurrence of potential errors means also minimisation of the necessary facility lighting, heating, etc. The implementation of automation and robotisation of logistics processes within the warehouse management requires respecting the subordination of all the processes, including the inspection and control operations, to the administration by the control system. An advantage of such control system is the reduction of the time required for racking or retrieval of the demanded goods/pallets. It is assumed that the duration of storage activities is as much as by one third shorter in an automated warehouse than in a conventional warehouse.

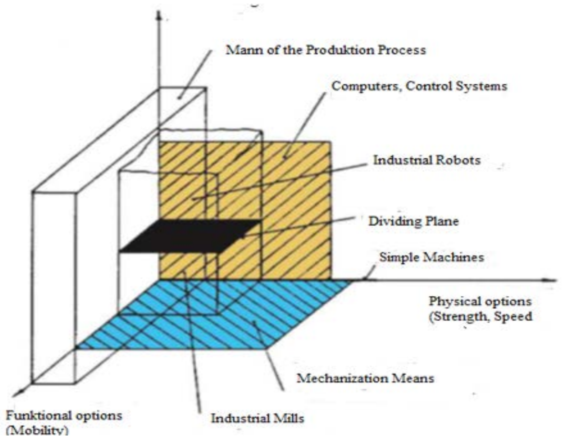

Figure 1. Interactions between a human and machine [4].

3. Basic structure of a robotised workplace

In terms of the basic characteristic structures of robotised workplaces (hereinafter referred to as RW), these may be characterised as a specialised group of industrial robots and manipulators (hereinafter referred to as IRaM) and peripheral equipment that perform the manipulation or technological operations in the automatic cycle within a respective manufacturing process or a part thereof.

The foundations of the construction of robots and manipulators are the mechanisms, i.e. the mechanical equipment used for the motion transformation and the force transmission and performing relocation of items (objects, tools, etc.) in a particular manner, depending on the required system function [5].

Mechanisms of robots and manipulators consist of the system of movably joined links, whereas one of them does not move and serves as the frame. These mechanisms are derived from the open spatial kinematic chains. They contain binary links interlinked by spatial kinematic couples [6]. Mutual mobility of the links forming a kinematic couple is characterised with the number of degrees of freedom and equals the number of independent simple movements (shifts and rotations) that both the links can make towards each other.

A screw-nut kinematic couple has 1° of freedom, as in this case the rotation and shift movements are mutually dependent. A couple that removes *j* degrees of freedom from a relative motion of two free objects in the space is referred to as the couple of j^{th} class. As a free object in the space has 6° of freedom, probably for every spatial kinematic couple $j = 6 - i$.

The total number of degrees of freedom (mobility) of a mechanism (a kinematic chain) is determined by the generally applicable formula [5]:

$$i' = 6(n-1) - \sum_{j=1}^{5} j d_j$$

where

n – is the total number of links, including the frame,

d_j – is the number of kinematic couples of the j^{th} class.

By the architecture of the motion flow we distinguish:

- cartesian kinematic architecture,
- cylindrical kinematic architecture,
- spherical kinematic architecture,
- angular kinematic architecture.

Human arm:

- between the shoulder joint and the end of one of the fingers there is 11^0 of freedom,
- if we consider all the fingers, we will get 27^0 of freedom.

The structure of an anthropomorphic manipulator is similar to a human arm. It consists of at least three rotating joints that form a spherical coordinate system. The manipulator has six degrees of freedom and achieves thus high flexibility. It is also capable of performing the required activity despite any obstacles. This may be achieved in any position and orientation of the end effector in the robot's working space. Typical anthropomorphic manipulators have 5 or 6 freely programmable arms of axes. As mentioned above, thanks to the robot's flexibility, it is suitable for a wide range of industrial applications.

The main body of the manipulator is formed by joining the links, joints, and other structural elements. A manipulator becomes a robot upon connecting the wrist and the gripper (effector) and implementing the control system. Most industrial robots have the anthropomorphic construction (6 degrees of freedom - 3 rotation degrees and 3 translation degrees) [5].

Universal types of manipulators and robots have thus 6 and more degrees of freedom. By increasing their mobility their design becomes more complicated, production costs increase, and, as a result, the price increases as well. On the other hand, their accuracy and carrying capacity decrease. In practice, therefore, the number of degrees of freedom is limited, depending on the required function and design.

The total number of degrees of freedom in the given manipulator design is determined by the sum of degrees of freedom of all used joints, including the metal end effector (Fig. 2.).

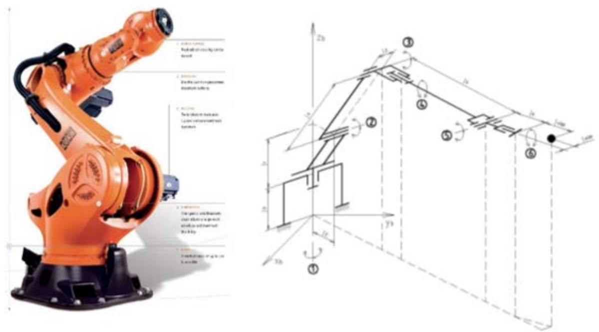

Figure 2. Anthropomorphic manipulator and a functional model of the action subsystem of the robot [8]

The end effector is the last link of the kinematic chain used for the execution of the required robot's activity (gripping, technological activities, combined activities). The simplest example of an effector is a gripper used for the relocation and the positioning of various objects [7].

4. Robotisation of logistics processes

The strongest motivation to implement the automation and the robotisation is currently the lack of labour force. Not long ago, a decisive criterion for the implementation of automation and robotisation was the investment return that was ranging between 1 and 2 years. Thanks to flexible and collaborative robotic solutions, the return time of the investment in the automation of mainly logistics processes is being reduced to less than three years. The performed studies report that the hourly costs of one robot range between € 18 and 20/hour, whereas the average costs of labour force are € 14 to 15/hour.

Robots have been most intensively used in the warehouse management where the number of operators able to work with heavy loads is decreasing and the physically demanding work is taken over by robots. Such works include logistic activities, beginning with the unloading the goods and ending with compiling the customer pallets.

Automated workplaces are applied mainly within the processes comprising the relocation of large and heavy goods.

The ever-increasing flexibility of robotised workplaces, together with the decreasing purchase costs, creates the preconditions for a wider range of applications thereof in the goods retrieval and completion, packing and necessary identification, in the field of manipulation within the goods loading and unloading, in the transportation, etc. In a combination with autonomous means, more options are being offered, heading towards the fully automated logistics processes.

5. Comparative analysis of robots using the multiple-criterial decision-making

The decision-making process is a nonrandom choice of one of the set of possible solutions on the basis of certain well-thought reason, in terms of fulfilment of the determined objective. Depending on the application of particular scientific procedures when formulating a decision, these methods are divided into empiric, exact and Heuristic decision-making methods [8].

The purpose of the comparative analysis is to choose the most appropriate robot type from the same series of 3 robots. The selection is carried out on the basis of seven evaluation criteria using 2 multiple-criteria methods. The multiple-criteria analysis belongs to the comprehensive analysis methods, used to minimise the subjectivity rate in the selection of an appropriate alternative. Multiple-criteria methods have the same objective - to assess several alternatives of the solution to the assigned problem on the basis of the selected criteria and to identify the order of their importance [9]. In the event of decision-making problems, it is necessary to consider all the factors affecting the analysis results, the relationships between them, and the intensity of their mutual effects [10].

6. Criteria for the selection of the kinematic architecture of manipulators and robots

The important factors affecting the selection of a particular robot include the weight to be manipulated with by the robot, the grasp distance necessary for the manipulation, the number of degrees of freedom the robot needs to manage the given application, the required product positioning accuracy, the required motion speed, as well as other requirements.

The robot selection is usually conditioned by the requirement related to the servicing, assuming thus existence of the servicing department so that the warranty and post-warranty services meet the requirement for the maximum reaction time of 12 hours.

The decisive criteria in the robot selection usually include the purchase price, the motion speed, and the motion range in individual axes.

When selecting and designing new robots of well-proven types (according to the characteristic kinematic architecture), the solution must be competitive. This requires the comparison thereof with the best competitive products of the same class, carried out already

we can create their database (gradually supplemented). Apparently, the know-how

created as described above may be used in the robot selection as well as in the selected robot evaluation (i.e. ex post as well as ex ante).

The main criteria for the selection of kinematic architectures of manipulators and robots are as follows:

- required route of the centre of gravity of object manipulators,
- positioning accuracy when relocating the object's centre of gravity,
- object's orientation with regard to the carried coordinate system,
- connection between manipulators and robots and other manipulation and auxiliary mechanisms.

7. Application of the decision-making analysis methods

Within the decision-making process, 3 types of robots: **ABB IRB 120, Stäubli TX80, and KUKA KR 6 types,** will be assessed from the technical, economical, and logistics points of view. The three types of robots were chosen as representative specimens out of many types of robots of the same class. The selection of an appropriate type was carried out on the basis of the input parameters listed in Table 1.

Two different methods were applied within the decision-making. The first one is the weighted-sum method and the second one is the decision-matrix method (DMM).

The weighted-sum method belongs to the direct multiple-criteria decision-making methods in which the input parameters and the relationships between them are decided exclusively by the decision-making subject.

In the weighted-sum method (the ratio index-based method), the following general requirement applies:

$$U_m(x) = \sum_{i=1}^{n} \alpha_i u_i(x_i)$$

where:

α_i - the weight of the i^{th} criterion, determined by the decision-making person, $\sum_{i=1}^{n} \alpha_i = 1$,

$u_i(x_i)$ - the utility of the i^{th} evaluation criterion,

x_i - the result value according to the i^{th} criterion,

$U_m(x)$ - the total utility of the evaluated robot, the stability index, m = 1,2,3,...

The maximum or the minimum value $U_m(x)$ best meets the defined criteria and represents the searched position.

Table 1. Table of the input data for the multiple-criteria evaluation of robots of the same class

Evaluation criterion	**A1: ABB IRB 120**	**A2: Stäubli TX80**	**A3:KUKA KR 6**
K1- number of degrees of freedom	6	6	6
K2- useful load [kg]	6	15	120
K3- arm's reach [mm]	810	1,450	3,195
K4- repeatability [mm]	0.03	0.03	0.06
K5- control system	IR C5	CS8C	KR C4
K6- motion speed [m/s]	2.5	5.2	4.8
K7- price [€]	24 500	24 000	25 000

Solution procedure: Each selected factor must be assigned certain weight α_i while respecting the requirement that the sum of the weights equals 1. The higher weight is assigned to the criterion, the higher is the criterion significance within the selection of an optimal robot type. This requirement applies when the task is calculated as maximising. Individual selected robots are also assigned a point value u_i within the range of the so-called cardinal utility in the interval $CU \in \langle 0,10 \rangle$. The points must be multiplied by the weights and the sum of the points multiplied by the weights determines the searched optimal robot type. The selection of an appropriate robot type by the weighted-sum method is presented in the decision-making Table 2. The table indicates that the most appropriate robot type is the KUKA KR 6.

Table 2. Decision-making table according to the weighted-sum method

Evaluation criterion	**Criterion weight** u_i	**A1**		**A2**		**A3**	
		a_i	$u_i.a_i$	a_i	$u_i.a_i$	a_i	$u_i.a_i$
K1	0.04	2	0.08	2	0.08	2	0.08
K2	0.21	1	0.21	2	0.42	8	1.68
K3	0.09	2	0.18	4	0.36	8	0.72
K4	0.05	2	0.10	2	0.10	5	0.25
K5	0.15	3	0.45	5	0.75	6	0.90
K6	0.27	3	0.81	6	1.62	5	1.35
K7	0.19	2	0.38	8	1.52	7	1.33
Sum	∑1		∑2.21		∑4.85		∑6.31
Order			**3rd**		**2nd**		**1st**

Decision Matrix Method (DMM).

The DMM is regarded as the basic method (it can have more solution alternatives). One of the alternatives represents the evaluation of the weight (importance) of individual criteria on the **point scale from 1 to 10** whereas degree **1** is assigned to the lowest weight and degree **10** to the highest weight. The same scale is applied when evaluating how individual solution alternatives meet the selected criteria, i.e. degree "1" does not meet the criterion; degree "10" ideally meets the criterion.

To verify the results of the selection of an optimal robot type by the weighted-sum method listed in Table 2., the second method, DMM, was applied; the results are listed in Table 3.

Table 3. Decision-making table of the selection of the most appropriate robot according to the DMM method

Evaluation criterion	**Criterion weight** u_i	**A1**		**A2**		**A3**	
		a_i	$u_i.a_i$	a_i	$u_i.a_i$	a_i	$u_i.a_i$
K1	3	2	6	2	6	2	6
K2	8	1	8	2	16	8	64
K3	5	2	10	4	20	8	40
K4	4	2	8	2	8	5	20
K5	6	3	18	5	30	6	36
K6	9	3	27	6	54	5	45
K7	7	2	14	8	14	7	49
Sum			∑ 91		∑148		∑ 254
Order			**3rd**		**2nd**		**1st**

Upon an expert evaluation, certain weights were assigned to individual criteria and on the basis of the input parameters of the robots listed in Table 1., the weights were assigned also to individual robot types while applying the same expert method. The results of the robot evaluation are listed in Table 3. When the second method, DMM, was applied, the most appropriate robot type was again KUKA KR 6.

8. Conclusion

The use of robots in warehouse operations, sorting centres, or in goods delivery to end customers promises faster services and higher quality. Thanks to robots, logistics supply chains may be even faster, safer, and more productive.

Robots' task is usually repeating the same actions with high accuracy; such skills, however, are only sufficient in number of simple manufacturing processes, not in the logistics where the requirements are much higher. Robots in logistics will have to deal with various parts in an endless number of combinations; they will thus need to perceive their surroundings, move, interact with their surroundings, and cooperate with people. The development of a new generation of smart robots is also accelerated by the progress in the field of scanning technology, faster computer technology, big data analysis, accumulators, the use of clouds, and mobility. One of the key objectives of the development of new robots is the imitation of five human senses without which the above described application in the logistics is hardly conceivable.

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