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Abstract

The successful performance of the automated storage and retrieval systems is dependent upon the appropriate design and optimization process. In the present work a comprehensive model of designing automated storage and retrieval system for the single- and multi-aisle systems is presented. Because of the required conditions that the automated storage and retrieval systems should be technically highly efficient and that it should be designed on reasonable expenses, the objective function represents minimum total cost. The objective function combines elements of layout, time-dependant part, the initial investment and the operational costs. Due to the non-linear, multi-variable and discrete shape of the objective function, the method of genetic algorithms has been used for the optimization process of decision variables. The presented model prove to be very useful and flexible tool for choosing a particular type of the single- or multi-aisle system in designing automated storage and retrieval systems. Computational analysis of the design model indicates the model suitability for addressing industry size problems.

1 Introduction

Warehouses with their basic purpose are an absolute necessity for a continuous and optimum operation of the production and distribution processes [1]. Unfortunately, in the past warehousing, transport systems and transferring processes were neglected in some area of industry and this nowadays shows in a relatively low degree of automation in comparison with the production process. Warehouses present a technical part of dealing with goods. Since they were neglected in the past, they present an option for the reduction of total costs concerning the design, re-design and operation processes.

In this study automated warehouses, unit-load automated storage and retrieval systems (unit-load AS/RS) are presented. In the last few decades, the share of unit-load AS/RS on the world scale, which in comparison with conventional warehouses enables a higher level of technological efficiency, has increased. The use of the unit-load AS/RS received consideration already decades ago, when in 1962 the company Demag created the first unit-load AS/AR [2]. The aforementioned unit-load AS/RS was a high-bay warehouse measuring 20 meters in height, which marked the beginning of a new era in the development of material handling equipment in Europe. The unit-load AS/RS consists of storage racks (SR), storage and retrieval machine (S/R machine), accumulating conveyors, input and output location (I/O location) and a computer system for managing and organizing activities in the warehouse. In comparison with conventional warehousing systems, the key advantages of the AS/RS are: (*i*) high throughput capacity and warehouse volume (rack capacity), (*ii*) high reliability and better control of the warehousing process, (*iii*) improved safety conditions and (*iv*) decrease in damage and the loss of goods. Due to advanced technology and the complete automation of the system, the unit-load AS/RS demands extensive investment. Additionally, those unit-load AS/RS where the S/R machine operates only in the single picking aisle (single-aisle system) are rather inflexible as far as a possible change of the throughput capacity of the warehouse is concerned.

Due to the well known benefits of the unit-load AS/RS a high initial investment is necessary for the success of such systems. In the total initial investment for automated warehouse, storage and retrieval (S/R) machines alone represent approximately 40 % or more of the costs [3]. A measure to reduce the initial investment cost is application of the multi-aisle unit-load AS/RS. In the abovementioned system, the S/R machine serves several picking aisles with the help of the aisle transferring vehicle, which ensures driving in the cross aisle. Many of the warehouse equipment producers like Siemens Dematic [4], Stoecklin [5] and Dambach [6] have begun to offer such systems served by automatic curve-going or automatic aisle-transferring S/R machines. Additional benefits of using those systems are: subsequent expansion of S/R machines is possible at any time, optimum use is made of space due to minimal overrun dimensions and high throughputs resulting from pallet buffer positions on the transfer car (automatic aisle-transferring S/R machines). In order to evaluate the optimal number of S/R machines in multi-aisle AS/RS the average travel time for a storage and retrieval operation has to be determined [7], [8], [9].

In the design of the unit-load AS/RS, the major objective is to satisfy the required warehousing needs, which are subject to operational and physical constraints, at minimal total costs. The total cost of the system is composed of the initial investment and of annual operating costs. The design of warehouses (not necessarily unit-load AS/RS) has been studied by several authors. One of the first publications in the subject of optimizing the warehouses is represented by the work of Basan et al. [10], who have analyzed optimum dimensions of the warehouse, considering the chosen warehouse volume of the warehouse in dependence on various storage strategies. Karasawa et al. [11] have presented a design model of the AS/RS. In their work, the objective function is defined as non-linear and multi-variable, consisting of three main variables: (*i*) the number of S/R machines, (*ii*) the length of the SR and (*iii*) the height of the SR; and also of constant values: cost of buying the land, cost of building the warehouse, cost of buying the SR construction and cost of buying S/R machines. The main disadvantage of this model [11] is that it refers only to the single-aisle AS/RS and the warehousing operation of only the single command cycle. Ashayeri et al. [12] have presented a design model of the AS/RS that enables the determination of the main influential parameters when designing warehouses. Unlike Karasawa et al. [11], they have considered the warehousing operation of the dual command cycle. Bafna et al. [13] and Perry et al. [14] have used a combination of the analytical model and the system of discrete event simulations when designing the warehouse. Perry et al. [14] have used a special search method to determine optimum solutions for the AS/RS, which they have included in the simulation model of the AS/RS. As a measure of the efficiency of the system, they have used the throughput capacity of the warehouse, in dependence on the number of S/R machines and the number of workplaces. The design of warehouses with regard to the influence of the storage policy has been presented by Rosenblatt and Roll [15]. When describing total costs, the authors have taken into account: (*i*) cost of building the warehouse, (*ii*) cost of buying storage equipment, (*iii*) costs arising from overloading the warehousing system (temporary shortage of the storage space) and (*iv*) costs that depend on a particular storage policy. An in-depth overview of the area of designing and controlling warehouses has been presented by Rouwenhorst et al. [16] in the form of the methodology of designing warehousing systems. The design process is presented with a structured approach, which takes into account the strategic, tactical and operational level of decision making. Gu at al. [17] have presented a comprehensive review of research on warehouse operation. Roodbergen and Vis [18] have presented a comprehensive explanation of the current state of the art in AS/RS.

The majority of described models refer only to the single-aisle AS/AR [11], [12], [13], [14]. The difference between approaches and models lies in the cost of elements included in the objective function, the decision on considered variables and the use of optimization techniques. Less has been done for other types of warehouses, especially for systems where the number of S/R machines (S) is less than or equal to the number of picking aisles (R) (the condition $S \leq R$) [3], [19], [20].

The purpose of our paper is to present the design and optimization of the unit-load AS/RS, with which an optimal solution to the minimization of the initial investment and annual operating cost of the system is developed. The adopted approach is to use optimization in order to create the most economical design of automated warehouses. Due to non-linear, discrete and multi-variable objective function Minimal total cost [2], the heuristics method with genetic algorithms [21], [22] was used. The significant part of our research lies in the creation of a tool for designing and optimizing AS/RS [2] supported by the computer.

2 Model for designing of AS/RS

The model for designing the AS/RS is based on the structured approach [16], where all parameters influencing the warehouse volume (Q), load activity (Pf), investment and maintenance costs are taken into account. When developing and creating the model, propositions and references from other authors were considered [3], [11], [15], [20].

Figure 1 shows the algorithm of the design model of the AS/RS, including the following main modules.

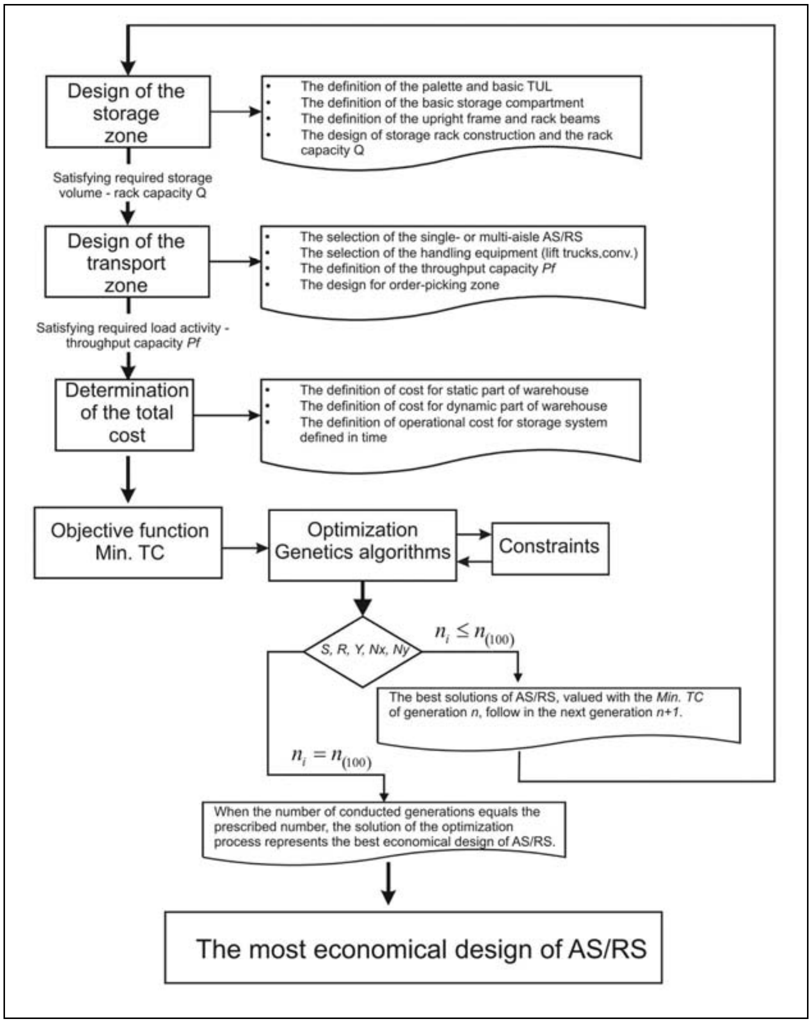

Figure 1: The algorithm of the design model of the AS/RS

- ***Design of the storage zone:*** includes the choice of the palette and the building of the basic transport unit load (TUL). The definition of the storage compartment, which represents a foundation for the storage system, is to come after. Next, the design of SR structure (upright frames and rack beams) depends on the weight of TUL and arrangement of TUL in the horizontal and vertical direction. Finally, with regard to the *Q*, geometry and type of SR, the configuration of the storage zone can be determined.
- ***Design of the transport zone and determination of the efficiency of the warehouse:*** considers selection of the material handling equipment, which depends, mainly, on the SR geometry, *Pf* and *Q*. Due to the *Pf*, two systems of handling equipment are possible: (*i*) single-aisle system

and (*ii*) multi-aisle system. Lift trucks and conveyors are used for manipulating TUL to the storage rack zone. Depending on the combination of the material handling equipment *Pf* and *Q*, the dimensions of the transport zone can be determined.

- ***Determination of the total cost:*** is divided into: (*i*) costs of the static part of the warehouse, (*ii*) costs of the dynamic part of the warehouse and (*iii*) operational costs of the warehouse defined with time.
- ***Design of the objective function and optimization of parameters of the objective function Min. TC:*** present a combination of decision variables, operational parameters and total costs of the AS/RS. The optimization of the objective function is based on the optimization *method of genetic algorithms* [21], [22]. The aim of the optimization of decision variables in *Min. TC* is to define the cost of the optimal solution for the AS/RS, considering the conditions of technically highly efficient and economically optimal solution for the AS/RS.

A novelty in the design model is the application of the condition that the number of S/R machines (*S*) is lower than or equal to the number of picking aisles (*R*). *Karasawa et al.* [11], *Ashayeri et al.* [12] have applied the condition ($S = R$) to their models. Given that the S/R machine is the most expensive element in the AS/RS (taking up approximately 40 % of the entire investment [3]), the utilization of aisle transferring storage and retrieval machine, which refers to the condition $S \leq R$, has been included in the design model [2]. The essential element of the abovementioned system reflects in a high degree of flexibility regarding a possible increase of *Q* and *Pf* of the warehouse and in smaller investment costs in comparison with the single-aisle AS/RS. The same condition $S \leq R$ was set out by *Rosenblatt and Roll* [3] in their combined analytical and simulation approach to designing the AS/RS. In their model, the *Pf* of the warehouse is determined under the condition $S \leq R$ with a simulation of the AS/RS, which then ensures the input of basic relevant information into the analytical optimization design model. The design model [3] is based on the interaction between simulations of the AS/RS (discrete system) and analytical model (the utilization of the continuous optimization).

The essential difference between the design model [3] and the design model presented in this paper lies in the introduction of newly improved analytical travel time models under the condition that $S \leq R$ [7], [8], [9].

In comparison with the design model [3], the presented model enables the creation of a faster, entirely documented, technical highly efficient and also the most economical design of the AS/RS. Along with the enumerated advantages, the essential element in the design model is presented by the introduction of the objective function *Min. TC* and optimization of decision variables within the *Min. TC*.

The objective function *Min. CS* consists of decision variables, operational parameters and costs of building and operating the warehouse. When designing the objective function, the following assumptions, notations and constraints have been applied to the design model of the AS/RS:

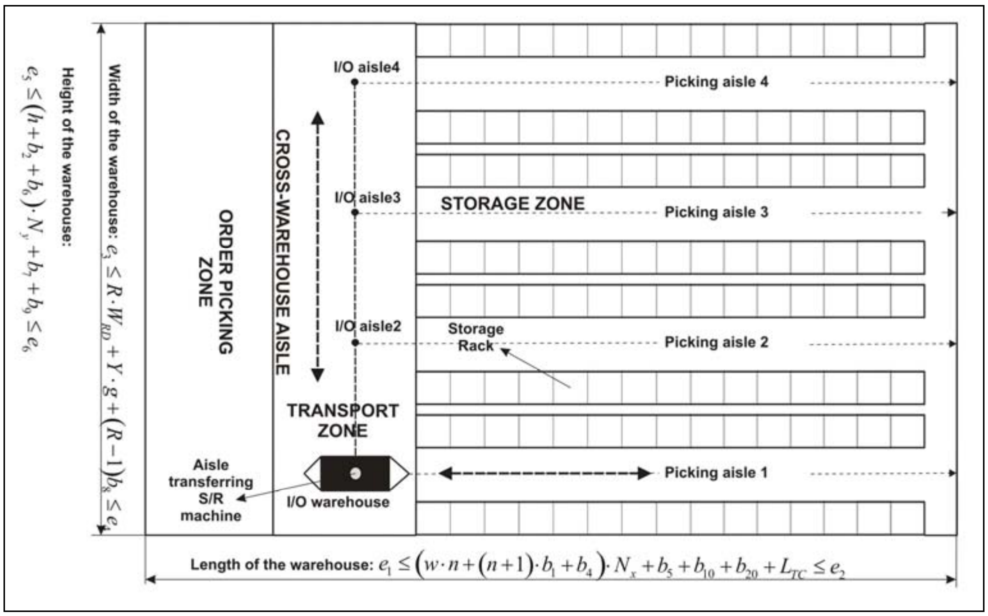

Figure 2: The layout of the automated warehouse

- The warehouse is divided into picking aisles with SR on both sizes; therefore there are double SR between the picking aisle and single SR along the warehouse walls. The I/O location of the warehouse is located on the lower, extreme left side of the warehouse (Figure 2).
- The number of the S/R machines is less than or equal to the number of picking aisles ($S \le R$).
- The multi-aisle AS/RS travels in the cross aisle on the transferring vehicle, which enables access to adjacent picking aisle.
- The SR has a rectangular shape, whereby the I/O location of the SR is located on the lower left side of the SR.
- The S/R machine enables the operation of SC and DC, to which a variable share of travel time for travelling in the cross aisle ($S \le R$) must be added.
- When performing the operation of the DC ($S \le R$), two different cases have been used: (*i*) the storage and retrieval operation is performed in

the same picking aisle *i* and (*ii*) the storage and retrieval operation is performed in two randomly chosen picking aisles *i* and *j*.

- Real drive characteristics of the S/R machine (velocity *v*, acceleration and deceleration *a*) as well as the length *L* and height *H* of the SR are known.
- The aisle transferring S/R machine travels in the picking aisle simultaneously in the horizontal direction and vertical direction.
- The length (*L*) and height (*H*) of the SR are large enough for the S/R machine to reach its maximum velocity v_{max} in the horizontal direction and vertical direction.
- The length of the cross aisle (*W*) is large enough for the transferring vehicle with the S/R machine to reach its maximum velocity v_{max} in the cross direction.
- Randomized storage is used, which means that any rack opening in the storage compartment is equally likely to be selected for the storage or retrieval assignment.

Decision variables that are used in our design model correspond to the number of S/R machines *S,* the number of picking aisles *R*, the number of storage racks *Y*, the number of storage compartments in the horizontal direction N_x and the number of storage compartments in the vertical direction N_y. The operational and physical parameters correspond to the warehouse efficiency and the warehouse design. Meanwhile, costs consist of the cost of building the warehouse, cost of buying the warehouse equipment and the cost of operating the warehouse. The *Min. TC* is represented with a mathematical model, which includes decision variables, all relevant operational and physical parameters, investment and operating costs:

1) The warehouse building

- ***The investment in buying the land I_1:***

$$I_1 = \left(P_z \cdot \frac{100}{D_z} \right) \cdot C_1 \tag{1}$$

P_z [m²] indicates the surface of the land; D_z stands for the share of the built warehouse and C_1 [€/m²] refers to the cost of buying the land.

- ***The investment in laying the foundations per square meter I_2:***

$$I_2 = \begin{bmatrix} \left(\left(w \cdot n + (n+1) \cdot b_1 + b_4 \right) \cdot N_x + b_5 + b_{10} + b_{20} \right) + L_{TZ} \cdot \\ \left(R \cdot W_{RD} + Y \cdot g + (R-1) b_8 \right) \end{bmatrix} \cdot C_2 \tag{2}$$

R, Y and N_x are decision variables; n refers to the number of TUL´s in the storage compartment; w, g and h [mm] indicate the width, length and height of the palette/TUL; W_{RD} [mm] indicates the width of the S/R machine; L_{TZ} [mm] indicates the length of the transport zone; b_1, b_4, b_5, b_8, b_{10}, b_{20} [mm] stand for a safety addition to the width of the storage compartment, width of the upright frame, thickness of the upright frame, safety spacing between racks that are placed close to each other, addition to the width of the palette at input buffer, addition to the end of the warehouse; C_2 [€/m²] stands for the cost of laying the foundations (Figures 2 and 3).

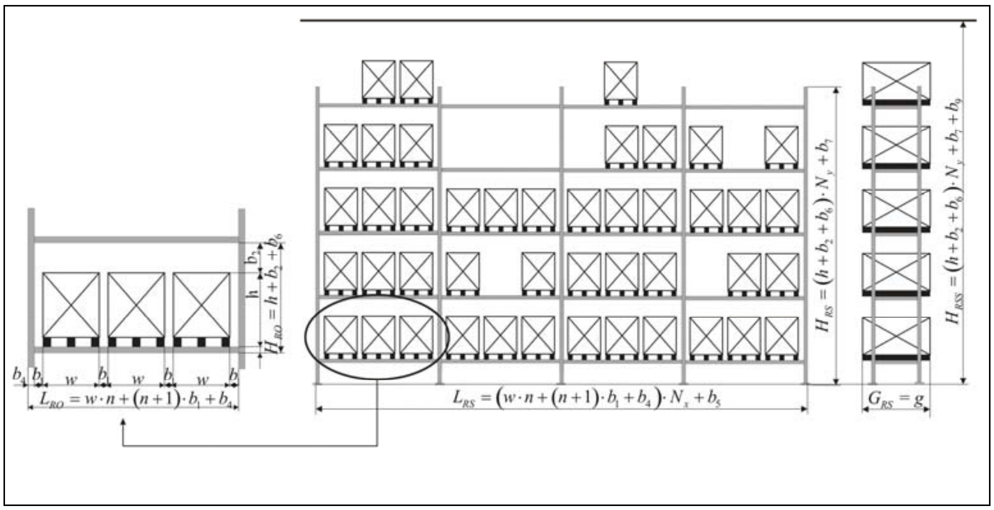

Figure 3: The layout of the storage compartment and storage rack

- ***The investment in building the walls of the warehouse per square meter I_3:***

$$I_3 = \left[\begin{array}{l} \left(\begin{array}{l} \left(\left(w \cdot n + (n+1) \cdot b_1 + b_4 \right) \cdot N_x + b_5 + b_{10} + b_{20} \right) + L_{TZ} + \\ \left(R \cdot W_{RD} + Y \cdot g + (R-1) b_8 \right) \end{array} \right) \cdot \\ \left(\left(h + b_2 + b_6 \right) \cdot N_y + b_7 + b_9 \right) \end{array} \right] \cdot 2C_3 \qquad (3)$$

N_y is the decision variable; b_2, b_6, b_7, b_9 [mm] indicate the safety addition to the height of the storage compartment, the height of rack beams, deviation of the storage compartment from the floor and a safety addition to the height of the warehouse; C_3 [€/m²] is the cost of building the walls of the warehouse (Figures 2 and 3).

- ***The investment in building the roof of the warehouse per square meter I_4:***

$$I_4 = \left[\begin{array}{l} \left(\left(w \cdot n + (n+1) \cdot b_1 + b_4 \right) \cdot N_x + b_5 + b_{10} + b_{20} \right) + L_{TZ} \cdot \\ \left(R \cdot W_{RD} + Y \cdot g + (R-1) b_8 \right) \end{array} \right] \cdot C_4 \qquad (4)$$

C_4 [€/m²] indicates the cost of building the roof of the warehouse (Figures 2 and 3).

2) Storage and material handling equipment

- ***The investment in buying upright frames I_5:***

$$I_5 = \left(\left(N_x + 1\right) \cdot 2Y\right) \cdot C_5 \tag{5}$$

C_5 [€/m] indicates the cost of buying upright frames.

- ***The investment in buying rack beams and an addition to the reinforcement of the storage rack structure I_6:***

$$I_6 = \left(\left(\left(\left(N_x + 1\right) \cdot 2Y\right) \cdot C_5\right) + \left(N_x \cdot N_y \cdot 2Y \cdot L_v\right) \cdot C_6\right) \cdot \left(1 + \frac{PD}{100}\right) \tag{6}$$

L_v [mm] is the length of the rack beam; *PD* indicates an addition to the reinforcement of storage racks, C_6 [€/m] indicates the cost of buying rack beams.

- ***The investment in buying buffers I_7 and the assembly of the storage rack structure I_8:***

$$\begin{aligned} I_7 &= 2R \cdot C_7 \\ I_8 &= Q \cdot C_8 \end{aligned} \tag{7}$$

C_7 [€] indicates the cost of buying buffers and C_8 [€] the cost of assembly.

- ***The investment in fire safety I_8 and air conditioning I_9:***

$$\begin{aligned} I_9 &= \left(\left(N_x \cdot N_y\right) \cdot 3 \cdot 2\right) \cdot C_9 \\ I_{10} &= \left(L_{WAR} \cdot H_{WAR} \cdot W_{WAR}\right) \cdot C_{10} \end{aligned} \tag{8}$$

C_9 [€/PM] indicates the cost of fire safety and C_{10} [€/m³] the cost of air conditioning.

- ***The investment in lift truck I_{11} and reach trucks I_{12}:***

$$\begin{aligned} I_{11} &= S_{TV} \cdot C_{11} \\ I_{12} &= S_{RV} \cdot C_{12} \end{aligned} \tag{9}$$

S_{TV} indicates the number of lift trucks (variable), S_{RV} indicates the number of reach trucks (variable); C_{11} [€] indicates the cost of buying a lift truck; C_{12} [€] indicates the cost of buying a reach truck.

- ***The investment in the single-aisle AS/RS I_{13}:***

$$I_{13} = S_{RD} \cdot C_{13} + L_{TZ} \cdot C_{14} \tag{10}$$

- ***The investment in the multi-aisle AS/RS I_{14}:***

$$I_{14} = C_{13} \cdot S_{RD} + \left(L_{TZ} \cdot C_{14}\right) \cdot R - \left(W_{WAR} - \left(\frac{2g + S_{RD}}{2}\right)\right) \cdot C_{15} \tag{11}$$

S_{RD} indicates the number of S/R machines (decision variable); L_{TZ} [mm] is the length of the transport zone; W_{WAR} [mm] is the width of the warehouse; C_{13} [€] indicates the cost of buying S/R machines; C_{14} [€] indicates the cost of the picking aisle; C_{15} [€] indicates the cost of the cross aisle.

The material handling equipment that can be used in the picking aisles is represented only with reach trucks and S/R machines only. Lift trucks are used in the order picking and transport area.

- ***The investment in the accumulating conveyor I_{15}:***

$$I_{15} = C_{16} + 2 \cdot R \cdot C_{17} \tag{12}$$

C_{16} [€] indicates the cost of the accumulating conveyor (the controls, the control system); C_{17} [€] indicates the cost of the diverted element.

3) Operating the AS/RS

- ***Costs of maintaining the automated storage and retrieval system C_{VZD}:***

$$C_{VZD} = P(\%) \cdot C_{13} \cdot S \tag{13}$$

- ***The method of net present value NPV –*** discount operational costs which assume a certain life expectancy of the AS/RS *i* and the discount rate *r*

$$NPV = \sum_{i=1}^{T} \frac{\left(\left(P(\%) \cdot C_{13} \cdot S\right) + C_{OD}\right)}{\left(1+r\right)^{i}} \tag{14}$$

P (%) indicates the share of the value of the material handling equipment for maintenance; *S* indicates the number of pieces of material handling equipment; C_{OD} is the cost of personal income for people working with lift trucks and reach trucks; *r* is the discount rate; T_i is the anticipated life expectancy of the operation of the AS/RS.

The objective function *Min. TC* refers to all costs of building the warehouse, purchasing the material handling equipment and costs of operating the warehouse within the expected operational time period. In the objective function, costs indicate the constant value and do not change in dependence on the geometry of the warehouse. The objective function *Min. TC* has the following form:

$$\begin{aligned} Min.TC = {} & I_{\text{Land}} + I_{\text{Floor}} + I_{\text{Walls}} + I_{\text{Ceiling}} + I_{\text{Upright frames}} + I_{\text{Beams}} + I_{\text{Reinforcement}} + I_{\text{Buffers}} + \\ & I_{\text{Assembly}} + I_{\text{Fire safety}} + I_{\text{Air conditioning}} + I_{\text{Forklift trucks}} + I_{\text{S/R machine}} + NPV \end{aligned} \tag{15}$$

When optimizing decision variables *S, R, Y*, N_x, N_y in the objective function *Min. TC,* one must take into account certain constraints referring to: (1) geometrical constraints of the warehouse, (2) the minimum required *Q* of the warehouse and (3) the number of S/R machines has to be lower than or equal to the number of picking aisles ($S \leq R$).

Therefore *Min.TC* corresponds to the following restrictions:

1) **Satisfying the required constructional restriction** – constructional restrictions are imposed on the length L_{WAR}, width W_{WAR} and height H_{WAR} of the warehouse which will be constructed:

- The length of the warehouse L_{WAR}:

$$e_1 \leq \left(w \cdot n + (n+1) \cdot b_1 + b_4\right) \cdot N_x + b_5 + b_{10} + b_{20} + L_{TZ} \leq e_2 \tag{16}$$

- The width of the warehouse W_{WAR}:

$$e_3 \leq R \cdot W_{RD} + Y \cdot g + (R-1) b_8 \leq e_4 \tag{17}$$

- The height of the warehouse H_{WAR}:

$$e_5 \leq \left(h + b_2 + b_6\right) \cdot N_y + b_7 + b_9 \leq e_6 \tag{18}$$

2) **Satisfying the required warehouse volume** – the total number of rack openings has to be higher than or equal to the prescribed warehouse volume.

$$2 \cdot 3 \cdot N_x \cdot N_y \cdot R \geq Q \tag{19}$$

3) **Satisfying the required load activity** – the automated warehouse dependent upon the number of the S/R machines S should be able to manage the load activity.

$$S_{pot} = \frac{n_{SC} \cdot T(SC) + n_{DC} \cdot T(DC)}{T \cdot \eta}. \tag{20}$$

Considering the discrete form of the objective function *Min. TC*, non-linearity and proposed decision variables, *the method of genetic algorithms* to optimize decision variables in the *Min TC* has been applied. Genetic algorithms are heuristic search algorithms which are used to perform demanding analyses and to solve problems of optimization. The method of GA simulates evolutionary processes "the survival of the most flexible organism" [22].

3 Case study: an example of designing AS/RS

In this chapter a case study will be presented. With the optimization of decision variables in the *Min. TC*, the optimal design of AS/RS has to be defined. The input data for this example are based mainly on information from practice and sales representatives of companies supplying the AS/RS equipment. With regard to the following project constraints: the length of the warehouse L_{WAR} ($e_1 = 0 – e_2 = 100$) m, the width of the warehouse W_{WAR} ($e_3 = 0 – e_4 = 200$) m and the height of the warehouse H_{WAR} ($e_5 = 0 – e_6 = 20$) m. Operational parameters, material handling equipment and costs are presented in detail in Table 1.

Table 1: The input data for the analysis

Q	15.000 TUL	b_7	200 mm
λ	100 TUL/h	b_8	200 mm
n	3	b_9	1000 mm
w	800 mm	C_1	200 €/m^2
g	1200 mm	C_2	150 €/m^2
h	800 mm	C_3	50 €/m^2
n_{DC}	50 TUL/h	C_4	50 €/m^2
m	500 kg	C_5	30 €/m
T	1 hour	C_6	35 €/m
η	0,9	C_7	300 €
L_v	2800 mm	C_8	5 €/TUL
D_Z	70 %	C_9	5 €/TUL
b_1	100 mm	C_{10}	10 €/m^3
b_2	200 mm	C_{11}	17.000 €
b_4	1100 mm	C_{12}	240.000 € (multi-aisle S/R machine), 185.000 € (single-aisle S/R machine)
b_5	120 mm	C_{13}	50 €/m
b_6	120 mm	C_{14}	40 €/m

For the single and multi-aisle S/R machine, Stöcklin automatic transferring AT RBG 0-Q and Single MAN were used, meanwhile for the transport zone the Jungheinrich ERC 214 forklift truck was used. In addition, the following data for the efficiency of the S/R machine were used: horizontal, vertical and transfer speed (acceleration): $v_x = 3$ m/s (2 m/s^2), $v_y = 2$ m/s (2 m/s^2) and $v_i = 0.6$ m/s (0.4 m/s^2) respectively. The shuttle time was estimated to 5 second for a transaction.

From the presented input data, the optimal design of AS/RS to satisfy required constructional restriction, the required warehouse volume and required load activity has to be found. With the developed computer aided design tool (DeSklad [2]), the optimal design of automated warehouse was determined. The results for the presented example are summarized in Tables 2 and 3.

Table 2: Results – alternative proposals for the automated warehouse

	WAREHOUSE I. Multi-aisle S/R machine	WAREHOUSE II. Single-aisle S/R machine
L_{RO}	2920 mm	2920 mm
H_{RO}	1120 mm	1120 mm
G_{RS}	1200 mm	1200 mm
L_{RS}	70.2 m	71 m
W_{WAR}	16.2 m	16.2 m
W_R	1.5 m	1.5 m
H_{WAR}	21.16 m	21.16 m
Y	8	8
R	4	4
S	2	4
Q	10.368	10.368

Table 3: Investment – alternative proposals for the AS/RS

	WAREHOUSE I. Multi-aisle S/R machine	WAREHOUSE II. Single-aisle S/R machine
Land	499.867 €	481.992 €
Warehouse building	449.388 €	434.525 €
Storage construction	901.090 €	903.490 €
Fire safety	51.840 €	51.840 €
Air ventilation	264.429 €	254.974 €
Forklift truck	17.000 €	17.000 €
S/R machine	487.582 €	754.040 €
Operation (P = 5 %, T_i = 10, r = 8 %)	161.042 €	248.273 €
TOTAL COST	2.832.238 €	3.146.134 €

Tables 2 and 3 show the results of design and optimization of decision variables with the number of generation n = 100. The response to the optimization of decision variables S, R, Y, N_x, N_y in the *Min. TC* indicates the optimal warehouse layout with material handling equipment for the chosen single- or multi-aisle S/R machine. The optimization of project variables was carried out according to the following evolutionary and genetics operators: *the degree of crossover was set to* 0.8; *the degree of mutation was* *set to* 0.05; *the degree of elitism was set to* 0.05; *the size of population was set to* 100; *the number of generations was set to* 100. Values of *crossover, mutation* and *elitism degrees* are chosen in accordance with our extensive analyses and experience of researchers who have been engaged in the development and application of the GA method. The size of population depends greatly on the number of decision variables in the *Min. TC*, which indirectly influences the necessary number of generations. Due to the proposed decision variables S, R, Y, N_x, N_y in the *Min. TC*, the comprehensive analyses has indicated that in most cases the GA finds the most economical solution already with 100 generations.

According to the results presented in Tables 2 and 3, the best economical design (optimal cost) of AS/RS lies within large numbers of storage compartments in the horizontal and vertical direction, which indicate to large storage racks. For large storage racks (large N_x and large N_y), there is no need for a large number of picking aisles R and consequently large number of the S/R machines S. Since the S/R machines are very expensive equipment and may be dominant investment in the total investment, their number influences greatly on the total investment of automated warehouse. The solution of the presented example (Tables 2 and 3) suggests the cost optimal design with 8 picking aisles and 2 multi-aisle S/R machines – a mechanism for traversing S/R machines across aisle is required (Warehouse I.) and 4 single-aisle S/R machines (Warehouse II.).

5 Conclusion

Automated warehouses are very expensive and should therefore be carefully designed. The conventional design process is a time-consuming manual process, which depends mostly on the experiences of designers. Therefore the computer aided model for design and optimization of automated warehouses (DeSklad [2]) was presented. The main module in the design model, the objective function *Min.TC*, which minimise total investment and operating costs over the warehouse lifetime, was presented. The usefulness of the design model was presented by a case study involving the design of AS/RS. Applying the optimization with genetic algorithms, it was found that the optimal (best economical) solution of AS/RS was obtained in the 100 generation. Generally the most cost optimal solution of AS/RS lies within the large number of storage compartments in horizontal N_x and in vertical N_y directions for any type of AS/RS with single- or multi-aisle S/R machine.

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