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# A Multi-Objective Optimization model for minimizing cost, travel time and $CO_2$ emission in an AS/RS

*A multi-objective optimization of automated warehouses is discussed and evaluated in the present paper. Since most of the researchers in material handling community had performed optimization of decision variables with single objective function only (usually named with minimum travel time, maximum throughput capacity, minimum cost, maximum energy efficiency, etc.), the multi-objective optimization (cost – travel time – $CO_2$ emission/ energy efficiency) will be presented. For the optimization of decision variables in objective functions, the method with genetic algorithms was used. To find the Pareto optimal solutions, the NSGA II genetic algorithm was used. The main objective of our contribution is to determine the performance of the system according to the multi-objective optimization technique. The results of the proposed model could be useful tool for the warehouse designer in the early stage of warehouse design.*

***Keywords:*** *warehousing, automated storage and retrieval systems, multi-objective optimization, performance analyses.*

## 1. INTRODUCTION

It is evident that today, in many factories and warehouse systems, material handling (transport) demands are often observed as secondary problems. They can be resolved by improvisation, or, if they are taken more seriously, treated as an isolated problem, which will be addressed one part at a time, with an ad hoc adoption of necessary transport equipment. Thereby, a fact is neglected, that, if savings in expenses, time, labour and space are effective in every stage of production: (i) from handling raw materials and components, (ii) internal material handling in production facilities, through (iii) handling and storing finished products, than every stage cannot be considered separately, but as part of overall model of material flow and process. Transport and storage systems are integral part of production process, so for an analytical study and overall planning of process, they deserve an increased attention.

While designing warehouse systems, designers are often facing contradictory influential factors, so it is very significant to estimate which one prevails in every individual case, which is considered. If influential factors are not precisely estimated, there is a possibility that one of the uneconomical solutions is adopted [1].

### 1.1 Why an automatic warehouse and when?

The main reason for thinking about an automatic warehouse as part of distribution system are given below [2]:

OBJECTIVES OF AN AUTOMATED WARE–HOUSE:

1. To reduce or stabilize the total cost of distribution by saving in wages, land costs, stock levels and other overheads,
2. To raise customer service in a competitive market by (i) prompter delivery, and (ii) improved accuracy of order filling,
3. To attain more control over distribution operations – i.e. to achieve the most profitable use of any given level of inventory.

REASONS FOR MECHANISATION:

1. It gives more flexibility of operation, e.g. in the event of products or pallet sizes changing,
2. The second-hand value of an automated warehouse is nearly always less than that of an conventional warehouse,
3. A careful analysis may show it to be cheaper to keep to forklifts and racking (or similar equipment).

Justifications for installing an automatic warehouse are complex and far-reaching and can only be calculated after a careful assessment of the factors listed below [2]:

1. What overall contribution can be made to distribution, and cost reduction by more precise stock control related to a greater sensitivity of changes in the value of sales?
2. What improvements can be made to providing prompter service to customers by achieving greater accuracy in order filling and stock figures? How much are these improvements worth?
3. Is the most cost effective and economic cost reduction made possible by introducing

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automation going to mean a cheaper system to run, than the most efficient and economic mechanized system?
4. If it is cheaper, is there a sufficient margin to justify the high capital investment required by an automated system?

## 2. LITERATURE REVIEW

The Automated Storage and Retrieval System (AS/RS) is a major category of material handling equipment. There are primarily two types of AS/RS: unit-load AS/RS and the mini-load AS/RS. AS/RS usually consists of conveyors, Storage Racks (SR) and an automated Storage/Retrieval (S/R) machine that can travel along narrow aisles between the SR to store and retrieve loads. The S/R machine can manipulate either pallets (unit-load system) or totes (mini-load system). Over the past 50 years, many studies of AS/RS have been performed within the material handling research community. The intensive development of AS/RS began with the development of informational and computer science. Hausman et al. in 1976 [3], Graves et al. in 1977 [4] presented travel time models for AS/RS assuming that the SR was "square-in-time", which meant that times to the most distant column $t_x = L_{SR} / v_x$ and tier $t_y = H_{SR} / v_y$ were both equal ($t_x = t_y$). They analysed different storage strategies, e.g. randomised, turnover-based and class-based storage assignment rules. Gudehus in 1973 [5] presented principles for calculations of the cycle times for the Single Command Cycle (SCC) and Dual Command Cycle (DCC). In the case of the SCC the S/R machine could perform one storage or retrieval request, only. More advanced is the DCC where the storage and the retrieval request are done simultaneously by the S/R machine. With regard to other cycle time expressions, the impact of the acceleration and deceleration on travel times were considered. Bozer et al. in 1984 [6] presented an analytical travel time model for calculating the SCC and DCC for non-SIT racks. Their models were based on randomized storage and retrieval with different I/O configurations of the input queue. Their analytical travel time model was based on the assumption that the S/R machine travels all the time at constant velocity. Hwang and Lee in 1990 [7] presented travel time models by considering the operating characteristics of the S/R machines for AS/RS and non-SIT racks. Lerher et al. in 2005 [8] developed analytical travel time models for multi-aisle AS/RS by considering the operating characteristics of the S/R machine. Using the proposed analytical travel time models, average travel time can be evaluated. Gu et al. in 2007 [9] presented a comprehensive review of research on warehouse operation. Roodbergen and Vis in 2009 [10] presented a comprehensive explanation of the current state-of-the-art in AS/RS. Rouwenhorst et. al in 2010 [11] presented a comprehensive review of warehouse design and control. Lerher et al. in 2011 [12] presented simulation analysis of a mini-load multi-shuttle AS/RS. Recently Bortolini et. al in 2015a [13] proposed an extension for analytical models when computing the expected travel time for the SCCs and DCCs of AS/RS in three-class-based storage systems. Later Bortolini et. al in 2015b [14] proposed non-conventional easy-applicable configuration for unit load warehouses with diagonal cross-aisles. Accorsi et. al in 2015 [15] presented time and energy based assignment strategy for unit-load AS/RS warehouses. Janilionis et. al in 2015 [16] presented a comparison between routing algorithms for storage and retrieval mechanisms in cylindrical AS/RS.

Concerning multi-objective studies, Diao et al. in 2011 [17] studied a trade-off problem on the time-cost-quality performance of a project. A computer-based Pareto multi-objective optimisation approach applying NSGA II GA algorithm was utilized for solving trade-off problems. Based on their proposed approach, decision-making can become easy according to the sorted non-dominated solutions and project preferences. Lerher et al. in 2013a [18] studied multi-objective optimization for a CBS/RS, where the objective functions were defined as: minimisation of cost, average travel times of transactions and maximization of quality. The NSGA II GA algorithm was used for the solution procedure. The primary reason for using the evolutionary algorithm is its ability to find out the Pareto optimal solution. Recently, Lerher, 2013b [19]; Lerher et al., 2013c [12]; Lerher et al., 2015a [20]; Lerher et al., 2015b [21] studied SBS/RS by considering the energy efficient concept within the system's design. The proposed models provided several warehouse designs and their performances. Designs were considered in terms of velocity profiles of material handling devices while performances were considered as the amounts of energy (electricity) consumption, amount of $CO_2$ emissions and throughput capacity. These studies provide a significant contribution towards automated warehouse planning by taking into consideration the environmentally friendly design concept. Smew et al. in 2013 [22] presented a simulation study of trade-offs between the conflicting objectives of maximising customer service levels and minimising Work-In-Process. Bekker in 2013 [23] presented a computationally economic approach to optimize the throughput rate and allocated buffer space.

Kartnig et al. in 2012 [24] presented the outlook on the "megatrends", such as globalisation, urbanisation, demographic shifts and climate change, which are likely to determine the future functions of intralogistics and the focus of research in the field.

Hafner and Lottersberger in 2012 [25] researched energy efficiency in material flow systems, and Eder and Kartnig in 2016 [26] presented throughput analysis of S/R shuttle systems and researched ideal geometry for high performance systems.

## 3. MODEL FOR DESIGNING AUTOMATED WAREHOUSE

A multi-objective optimization of automated warehouses is discussed and evaluated in the present paper. Since most of the researchers in material handling community had performed optimization of decision variables with single objective function only (usually named with minimum travel time, maximum throughput capacity, minimum cost, maximum energy efficiency [30-33] the multi-objective optimization (cost – travel time – $CO_2$ emission/energy efficiency) will be presented. For the optimization of decision variables in objective functions, the method with genetic algorithms was used. To find the Pareto optimal solutions, the NSGA II genetic algorithm was used. The main objective of our contribution is to determine the performance of the system according to the multi-objective optimization technique. The results of the proposed model could be useful tool for the warehouse designer in the early stage of warehouse design.

The model minimizes cost, travel time, and $CO_2$ emission of a warehouse according to project restraints and conditions.

### 3.1 Minimizing cost

Cost is comparatively low relative to travel time. Application of material handling devices with efficient drive (faster movement and hoisting) will no doubt increase the cost of the warehouse and the maintenance cost of material handling devices. For relationship between cost and travel time, one can use a discrete function or continuous (linear / quadratic) function. The objective is to minimize the cost, which is described as follows:

$$\text{function:} \quad \min f_T\left(x_i\right); \; i \in [1,8] \tag{1}$$

NOTE: Variables $x_i$ are defined in chapter 7.

### 3.2 Minimizing travel time

Travel time in the most material handling facilities (in this case warehouses) relates to the movement of material handling devices like S/R machines, etc. For the calculation of the mean SCC and DCC, different approaches have been used. Some researchers are using analytical travel time models, while others are using discrete simulation. Travel time could be minimised by using efficient drives for faster movement and hoisting of material handling devices in the horizontal and vertical direction. Beside the efficient drives, the length and the height of the storage rack should be in the appropriate relationship. The travel time is inversely dependent of the throughput capacities. According to the values of the travel time and throughput capacities, the number of material handling devices MHD (S/R machine) is defined. The objective is to minimize the mean travel time which is described as follows:

$$\text{function:} \quad \min f_T\left(x_i\right); \; i \in [1,8] \tag{2}$$

NOTE: Variables $x_i$ are defined in chapter 7.

### 3.3 Minimizing $CO_2$ emission

Figure 1 [33] shows percentages of energy consumption in logistics sector on the basis of the analysis of Van Der Lande Industries. It can be seen that external transport share is 76%, which is quite a lot, but in this area can rarely be influenced.

So, what about the remaining 24% that we are using in intralogistics, which we actually can influence? Analysis of Van Der Lande Industries shows, that about 50% of intralogistics costs, in particular 35% of heating- and ventilation engineering and 15% of lighting engineering is caused by the storage area. So this is the area that contains potential with great impact.

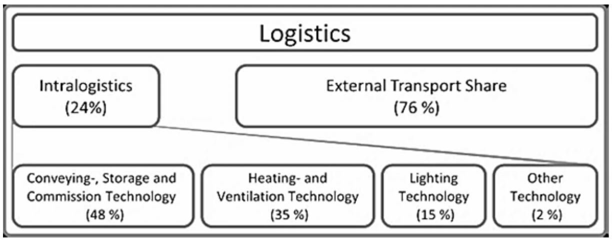


**Figure 1. Energy consumption in logistics sector [33]**

This model deals with reduction of energy consumption of AS/RS equipment. So, if we reduce number of S/R machines, we will reduce energy consumption, and the cost for buying and operating S/R machines. On the other hand we will increase the travel time, because, less S/R machines means more utilization for the existing ones. If we have, for instance, one S/R machine for every two picking aisle, we increase warehouse surface for the zone in which S/R machines change lanes, increasing the cost for land, building, and operating warehouse, etc.

The objective is to maximize energy efficiency, or, in other words, minimize the energy consumption, that is CO2 emission, which is described as follows:

$$\text{function:} \quad \min f_E\left(x_i\right); \; i \in [1,8] \tag{3}$$

NOTE: Variables $x_i$ are defined in chapter 7.

As we can see, these three objective functions effect each other and it is up to this model, to find solutions consisting of compromises between these, and giving engineers several solutions from which to choose, depending on which one of the functions is more relevant to the investor / owner of the warehouse.

## 4. DEFINITION OF THE DESIGN MODEL

The proposed model consists of decision variables, operational parameters and costs of material handling devices, land and warehouse building. When designing the model, the following assumptions and notations were applied:

1. The SR has a rectangular shape, whereby the I/O location of the SR is located on the lower left side of the SR (Figure 2) [18].

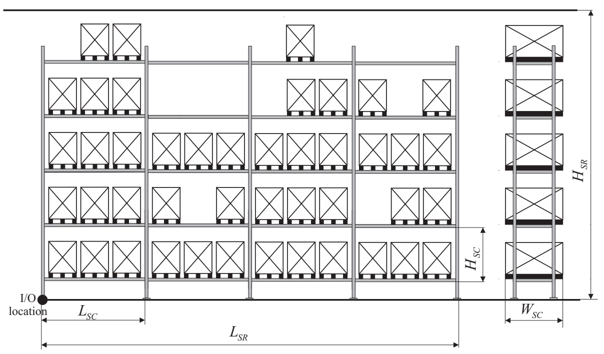


**Figure 2. The storage rack with storage compartments [18]**

2. The warehouse is divided into picking aisles with SR on both sides; 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 right side of the warehouse (Figure 3) [18].
3. The number of MHD - S/R machines is equal to the number of picking aisles ($n_{MHD} = R$).

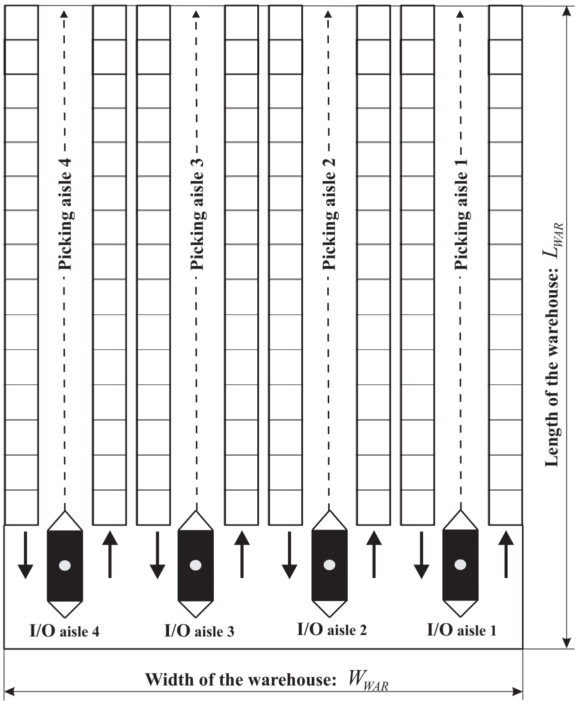


**Figure 3. Layout of the warehouse [18]**

4. The MHD enables the operation of SCC, to which a variable share of travel time for travelling in the cross aisle must be added.
5. Drive characteristics of the MHD velocity $v$, as well as the length $L_{SR}$ and height $H_{SR}$ of the SR are known.
6. The length $L_{SR}$ and height $H_{SR}$ of the SR are large enough for the MHD to reach its maximum velocity $v_{max}$ in the horizontal direction and in vertical direction.
7. 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.

The proposed model is represented with a mathematical model, which includes decision variables, all relevant operational, physical parameters, and investment costs and will be in detail discussed in the following section.

### 4.1 Cost definition

The investment in buying the land per square meter $I_1$:

$$I_1 = \left( P_{LAND} \cdot \frac{100}{P_{EFF}} \right) \cdot C_1 \qquad (4)$$

$P_{LAND}$ indicates the surface of the available land for construction [m$^2$]; $P_{EFF}$ indicates the share of surface that warehouse occupies [m$^2$]; $C_1$ [EUR/m$^2$] indicates the cost of the land per square meter.

The investment for building foundations of the warehouse $I_2$:

$$I_2 = \Big[ \Big( \big( w \cdot n + (n+1) \cdot b_1 + b_4 \big) N_x + b_5 + b_{20} \Big) + \\ + L_{TZ} \cdot \big( R \cdot W_{RD} + Y \cdot g + (R-1) b_8 \big) \Big] \cdot C_2 \qquad (5)$$

$R$, $Y$ and $N_X$ are decision variables, defined in chapter 7, $n$ refers to the number of pallets in storage compartment; $w$, $g$ and $h$ [mm] indicate the width, length and height of the pallet; $W_{RD}$ [mm] indicates the width of the SR machine; $L_{TZ}$ [mm] indicates the length of the transport zone; $b_1$, $b_4$, $b_5$, $b_8$, $b_{10}$ and $b_{20}$ [mm] stand for a safety addition to the width of the storage compartment, the width of the upright frame, the thickness of the upright frame, the safety spacing between racks that are placed close to each other, the addition to the width of the palette at the input buffer, the addition to the end of the warehouse; $C_2$ [€/m$^2$] stands for the cost of laying the foundations.

The investment in building the walls of the warehouse $I_3$:

$$I_3 = \Big[ \Big( \Big( \big( w \cdot n + (n+1) \cdot b_1 + b_4 \big) N_x + b_5 + b_{20} \Big) + \\ + L_{TZ} \cdot \big( R \cdot W_{RD} + Y \cdot g + (R-1) b_8 \big) \Big) \cdot \Big( \big( h + \\ b_2 + b_6 \big) N_y + b_7 + b_9 \Big) \Big] \cdot 2C_3 \qquad (6)$$

$N_y$ 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, the 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.

The investment in building the roof of the warehouse $I_4$:

$$I_2 = \Big[ \Big( \big( w \cdot n + (n+1) \cdot b_1 + b_4 \big) N_x + b_5 + b_{10} + b_{20} \Big) + \\ + L_{TZ} \cdot \big( R \cdot W_{RD} + Y \cdot g + (R-1) b_8 \big) \Big] \cdot C_4 \qquad (7)$$

$C_4$ [€/m²] indicates the cost of building the roof of the warehouse.

The investment for buying upright frames of SR $I_5$:

$$I_5 = \big( (N_x + 1) \cdot 2Y \big) \cdot C_5 \qquad (8)$$

$C_5$ [€/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 $I_6$:

$$I_6 = \big( N_x \cdot N_y \cdot 2Y \cdot L_v \big) \cdot C_6 \qquad (9)$$

$L_v$ [mm] is the length of the rack beam, $C_6$ [€/m] indicates the cost of buying rack beams.

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

$$I_7 = 2R \cdot C_7 \qquad (10)$$

$$I_8 = Q \cdot C_8 \qquad (11)$$

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

The investment in fire-safety $I_9$ and air conditioning $I_{10}$ equipment:

$$I_9 = \left(\left(N_x \cdot N_y\right) \cdot 3 \cdot 2\right) \cdot C_9 \tag{12}$$

$$I_{10} = \left(L_{WAR} \cdot H_{WAR} \cdot W_{WAR}\right) \cdot C_{10} \tag{13}$$

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

The investment in the single-aisle AS/RS $I_{11}$:

$$I_{11} = S_{RD} \cdot C_{11} \tag{14}$$

$S_{RD}$ indicates the number of S/R machines (and is decision variable), $C_{11}$ – cost of buying S/R machine.

The objective function Min. $f_C$ refers to all the costs of building the warehouse, and purchasing the material-handling equipment. In the objective function, the costs indicate the constant value and do not change depending on the geometry of the warehouse. The objective function Min. $f_C$ has the following form:

$$\begin{aligned} f_c &= I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + I_7 + \\ &+ I_8 + I_9 + I_{10} + I_{11} \end{aligned} \tag{15}$$

## 5. TRAVEL TIME DEFINITION (THROUGHPUT CAPACITY)

Proposed model is based on the SCC and DCC. The throughput capacity $\lambda$ is inversely dependent of the travel time. To calculate the mean travel time of the SCC and DCC, the analytical travel time model, which takes into account the real driving characteristics of the S/R machine, has been used in our analysis.

Expression for SCC by Gudehus, 1973 [5]:

$$T(SCC) = \begin{cases} t_{01} + \dfrac{L_{SR}}{v_x} + \dfrac{2v_x}{a_x} + \dfrac{Av_x}{L_{SR}^2 a_y} + \dfrac{A^2 v_x}{3L_{SR}^3 v_y^2} - \\ -\dfrac{Av_x}{L_{SR}^2 a_x v_y} & b \le 1 \\ t_{01} + \dfrac{A}{L_{SR} v_y} + \dfrac{2v_y}{a_y} + \dfrac{L_{SR}^2 v_y}{Aa_x} + \dfrac{L_{SR}^3 v_y^2}{3A^2 v_x} - \\ -\dfrac{L_{SR}^2 a_x v_y^2}{Aa_y v_x} & b > 1 \end{cases} \tag{16}$$

Expression for DCC by Gudehus, 1973 [5]:

$$T(DCC) = \begin{cases} t_{02} + \dfrac{4L_{SR}}{3v_x} + \dfrac{3v_x}{a_x} + \dfrac{3Av_x}{2L_{SR}^2 a_y} + \dfrac{A^3 v_x}{30L_{SR}^5 v_y^3} + \\ +\dfrac{A^2 v_x}{2L_{SR}^3 v_y^2} - \dfrac{3Av_x^2}{2L_{SR}^2 a_x v_y} & b \le 1 \\ t_{02} + \dfrac{4A}{3L_{SR} v_y} + \dfrac{3v_y}{a_y} + \dfrac{3L_{SR}^2 v_y}{2Aa_x} + \dfrac{L_{SR}^5 v_y^2}{30A^2 v_x^3} + \\ +\dfrac{L_{SR}^3 v_y}{2Av_x^2} - \dfrac{3L_{SR}^2 v_y^2}{2Aa_y v_x} & b > 1 \end{cases} \tag{17}$$

$$b = \frac{H_{SR}}{L_{SR}} \cdot \frac{v_x}{v_y} \tag{18}$$

For a more detailed insight into analytical travel time model considering the real operating characteristics of the S/R machine, see papers of Hwang and Lee [7], Vössner 1994 [34] and Vidovics 1994 [35].

The throughput capacity in case of SCC and DCC equals the next expression:

$$\lambda(p) = \frac{2 \cdot T_{shift}}{p \cdot T(SCC) + 2(1-p) \cdot T(DCC)} \cdot \eta_{MHD} \tag{19}$$

### 5.1 $CO_2$ emission definition

Mechanical model of the S/R machine with the hoisted carriage is discussed in the paper by Lerher et al. [12].

In continuation of the paper, the condition of hoisting of the hoisted carriage with constant velocity only, will be considered.

Total engine power P for travelling of the S/R machine in the horizontal direction and hoisting of the hoisted carriage in the vertical direction, equals the next expression:

$$P = P_x + P_y \left(kW\right) \tag{20}$$

Energy consumption $W$ counted on a yearly basis depends of the total engine power $P$, number of working hours in a shift $T_{shift}$, number of working days in a week $n_{wd}$, number of weeks $n_{weeks}$, the efficiency of the warehouse (distribution centre) $\varepsilon$ and equals the following expression:

$$W = P \cdot T_{shift} \cdot \eta_{WD} \cdot \eta_{weeks} \cdot \varepsilon\left(kWh / year\right) \tag{21}$$

According to the energy consumption $W$, is the amount of the $CO_2$ emission which goes in the atmosphere, equivalent to the next expression:

$$E_{CO_2} = W \cdot \rho\left(kgCO_2 / year\right) \tag{22}$$

The letter $\rho$ stands for the factor which is obtain based on measurements. In our case, we refer the factor $\rho$ of the Umweltbundesamt from Germany [36].

In nature, 100 m$^2$ of the forest consume for the operation of photosynthesis from the atmosphere, approximately 1 tonne of $CO_2$ within 10 years. This relationship can be applied when we want to express $CO_2$ emission into the atmosphere with the required amount of forest, with the objective to neutralise $CO_2$ emission in 10 years.

If the amount of the $CO_2$ emission is measured in $tCO_2$/10 years, then the next expression is valid:

$$S_{Forest} = E_{CO_2} \cdot 100m^2 \left(m^2\ of\ forest / year\right) \tag{23}$$

Generally the efficiency of the AS/RS depends mainly from the geometry of the SR ($L$ and $H$), velocity profile $v_{pi}$ of the S/R machine and the hoisted carriage and the control policy.

Like different types of AS/RS and the velocity profile of the S/R machine and the hoisted carriage, the control policy also has a significant share on the average travel time.

## 6. OPTIMIZATION

Tendency towards increase of efficiency of transport and warehouse systems, dictates necessity of use of simulation methods for analysis of material flow. Simulation of processes enables that separate elements and the whole material flow is analyzed in detail. Vantage of simulation over analytical methods is in the fact that it gives more accurate results, and it does not require expensive and long verification or results obtained in exploiting conditions. Wide possibilities which using simulation gives, are in the fact that simulation enables study of processes, which exist in real cases, and also processes which could occur in hypothetical conditions [1].

Optimization problems seek a point in which given function is maximum or minimal. Often, this point also has to fulfill some limitations.

Adding more than one objective to an optimization problem adds complexity. For example, to optimize a structural design, one would desire a design that is both light and rigid. When two objectives conflict, a trade-off must be created. There may be one lightest design, one stiffest design, and an infinite number of designs that are some compromise of weight and rigidity. The set of trade-off designs that cannot be improved upon according to one criterion without hurting another criterion is known as the Pareto set. The curve created plotting weight against stiffness of the best designs is known as the Pareto frontier.

A design is judged to be "Pareto optimal" (equivalently, "Pareto efficient" or in the Pareto set) if it is not dominated by any other design: If it is worse than another design in some respects and no better in any respect, then it is dominated and is not Pareto optimal.

The choice among "Pareto optimal" solutions to determine the "favorite solution" is delegated to the decision maker. In other words, defining the problem as multi-objective optimization signals that some information is missing: desirable objectives are given but not their detailed combination. In some cases, the missing information can be derived by interactive sessions with the decision maker.

Multi-objective optimization problems have been generalized further into vector optimization problems where the (partial) ordering is no longer given by the Pareto ordering.

## 7. PARETO OPTIMIZATION DESIGN

Although single objective optimization problems may have a unique optimal solution, multi objective problems offer a possibly uncountable set of solutions, which when evaluated produce vectors whose components represent trade-offs in decision space (Figure 4) [18]. A decision maker then implicitly chooses an acceptable solution by selecting one of these vectors.

The objective used in our contribution is to optimize *cost – travel time – $CO_2$ emission* which is formulated

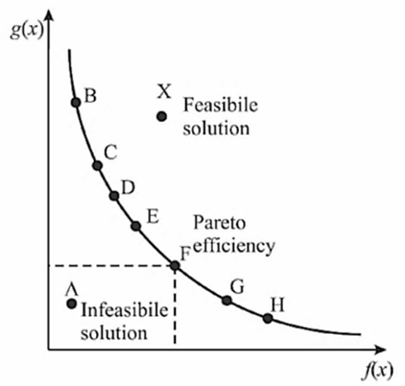


**Figure 4. Multi criterion optimization problem [18]**

as a multi objective problem. When optimizing decision variables $x_i$, $i \in [1,8]$ 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 throughput capacity has to be higher than or equal to the required throughput capacity, (4) the number of MHD has to be equal to the number of picking aisles ($n_{MHD} = R$).

To search for an optimal trade of among *cost – travel time – $CO_2$ emission*, the NSGA II genetic algorithm was used. The algorithm is designed for solving multi-objective problems. The output of the algorithm is a large number of solutions lying on or near the Pareto optimal frontier.

To find the Pareto optimal solutions, the design procedure used in present model is explained as follows [18]:

1. **Initialization**: Parameters initialization on optimization model: set the number of objectives; set the number of constraints; set the number of independent and dependant variables. Parameters initialization on genetics algorithm: set the size of population; set the number of generations; set the probability of crossover operation; set the probability of mutation.
2. **Forming Pareto front**: Cost, travel time, and $CO_2$ emission for every solution are computed in P($t$) according to equations (1), (2) and (3). Next, the population P($t$) is sorted based on the non-domination algorithm into each front F($t$) in criterion space. Individuals in first front are given a fitness value of 1 and individuals in the second front are given a fitness value 2 and so on. The first front is also called Pareto front which will include the best solutions.
3. **Genetic Operation**: *Genetic algorithm* (GA) is a procedure for searching optimized objective functions by the principles of natural genetics and natural selections. The main operation is related to *selection*, *crossover* and *mutation*.

## 8. ANALYSIS: AN EXAMPLE OF DESIGNING ASRS

With the optimization of the decision variables $x_i$ ($N_x$, $N_y$, $S$, $R$, $V_x$, $a_x$, $V_y$, $a_y$,) in the *Min TC*, where variables are:

$N_x$ – number of storage compartments in the horizontal direction

| | | |
|---|---|---|
| $N_y$ | – | number of storage compartments in the vertical direction |
| $S$ | – | number of S/R machines, |
| $R$ | – | number of picking aisles in a warehouse, |
| $V_x$ | – | velocity of S/R machine in horizontal direction, |
| $a_x$ | – | acceleration of S/R machine in horizontal direction, |
| $V_y$ | – | velocity of S/R machine in vertical direction, |
| $a_y$ | – | acceleration of S/R machine in vertical direction. |

The optimum design of the ASRS was searched for. The optimum design of the ASRS should suit the following project constraints:

$L_{WAR}$ – (20 m – 80 m) – the length of the warehouse

$W_{WAR}$ – (20 m – 60 m) – the width of the warehouse

$H_{WAR}$ – (10 m – 20 m) – the height of the warehouse

In addition, two constraints are added into model:

| | | |
|---|---|---|
| $g_1$ | – | constraint which limits capacity, so that the resulting $Q$, cannot be smaller than the *minQ*, that is required by project, |
| $g_2$ | – | constraint that limits throughput capacity so that it cannot be smaller than the project required throughput capacity. |

The input data for this example is based on information from practice. The analysis refers to the chosen model of the ASRS, which is determined by the following parameters: (*i*) ***entry-level parameters***: the storage volume of the warehouse $Q$ = 6000 TUL, throughput capacity of the warehouse $P_f$ = 160 TUL/h, (*ii*) ***operational parameters of the warehouse***: $w$ = 800 mm, $g$ = 1200 mm, $h$ = 1200 mm, $m$ = 800 kg, $b_1$ = 75 mm, $b_2$ = 300 mm, $n$ = 3, $b_3$ = 1100 mm, $b_4$ = 120 mm, $b_5$ = 65 mm, $b_6$ = 112 mm, $b_7$ = 300 mm, $b_8$ = 200 mm, $b_9$ = 1000 mm, $b_{10}$ = 1000 mm, $t_{01}$ = 6 sec., $t_{02}$ = 10 sec., $n$(SCC) = 40, $n$(DCC) = 60, $L_{TZ}$ = 10000 mm, $W_{RD}$ = 1500 mm, $L_{RD}$ = 2000 mm, (*iii*) ***material handling equipment***: the single-aisle ASRS - Stöklin AT RBG 0-Q: $G_{RD}$ = 1250 kg, $H_{RD}$ = 22000 mm, $W_{RD}$ = 1400 mm, $v_x = 0 – 3$ m/s, $v_y = 0 – 1$ m/s, $a_x = 0 – 1$ m/s$^2$, $a_y = 0 –$ 0,8 m/s$^2$, (*iv*) ***costs***: $C_1$ = 500 €/m$^2$, $C_2$ = 168 €/m$^2$, $C_3$ = 23 €/m$^2$, $C_4$ = 25 €/m$^2$, $C_5$ = 30 €/m$^2$, $C_6$ = 23 €/m$^2$, $C_7$ = 200 €/piece, $C_8$ = 10 €/RO, $C_9$ = 5 €/PM, $C_{10}$ = 10 €/m3, $C_{11}$ = 431.000 €/piece. Based on the performed analysis of the optimization of the decision variables in the min. *cost – travel time – $CO_2$ emission* with the method of GA, the main conclusions, which are shown in the Table 1, can be presented. The following Table 1 shows the results of the optimization of the decision variables $N_x$, $N_y$, $R$, $v_x$, $a_x$, $v_y$, $a_y$ with the number of generations $n(pop)$ = 10 and $n(pop)$ = 100 in the GA.

As can be seen from the results (Table 1), choosing the solutions with lowest cycle times (which means fastest SR machines) results in the highest cost and energy consumption (which means consequently high $CO_2$ emission).

Selecting lowest $CO_2$ emission solutions means that we will have slower SR machines.

Lastly, we can see that if we choose the most cost effective solutions, we will get lowest SR machine.

## 9. CONCLUSION

Unlike the single objective optimization problem, the multi objective optimization problem has not been used a lot in warehousing design process. As can be seen in literature review, this model is unlike others, and not many authors are researching multi objective and multi aisle AS/RS. In this paper, improved multi objective optimization approach of designing automated warehouses is presented. Due to the high complexity in designing and optimizing modern warehouses, the conventional design process rises at higher and more demanding levels, in the form of the computer aided design and optimization.

The proposed improved design model is based on the structured approach and refers to pallet storage system with several picking aisles. The essential part in the proposed model is the application of three objective functions named *cost – travel time – $CO_2$ emission*. The objective functions are represented with a mathematical model, which includes decision variables $x_i$, $i \in$ [1,8], all relevant operational and physical parameters, investment and operating costs.

In the chapter 7, we can see the contribution in the discussion part, as we are provided with several optimal solutions, and can choose from them.

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**NOMENCLATURE**

| | |
|---|---|
| AS/RS | automated storage and retrieval systems |
| SR | storage rack |
| S/R | storage and retrieval |
| SC | storage compartment |
| SCC | single command cycle |
| DCC | dual command cycle |
| $T$(SC) | mean single command travel time |
| $T$(DC) | mean dual command travel time |
| NSGA II | non-dominated sorting genetic algorit. II |
| CBS/RS | class based storage and retrieval systems |
| SBS/RS | shuttle based storage and retrieval systems |
| MHD | material handling device |
| I/O | input/output location |
| $CO_2$ | carbon dioxide |
| SIT | square in time |
| GA | genetics algorithm |
| TUL | transport unit load |
| $x_i$ | variable |
| $g_i$ | constraint |
| $b$ | shape factor |
| $Q$ | warehouse volume (capacity) |
| $minQ$ | minimal required warehouse volume |
| $f(x_i)$ | objective function |
| $m$ | mass |
| $P_{LAND}$ | surface of the available land |
| $P_{EFF}$ | share of surface that warehouse occupies |
| $L_{WAR}$ | length of the warehouse |
| $L_{SR}$ | length of the storage rack |
| $L_{SC}$ | length of the storage compartment |
| $H_{WAR}$ | height of the warehouse |
| $H_{SR}$ | height of the storage rack |
| $H_{SC}$ | height of the storage compartment |
| $W_{WAR}$ | width of the warehouse |
| $W_{SR}$ | width of the storage rack |
| $W_{SC}$ | width of the storage compartment |
| $P$ | total engine power for travelling of S/R machine |
| $W$ | energy consumption based on the $P$ |
| $T_{shift}$ | working hours in one shift |
| $n_{wd}$ | number of working days in a week |
| $n_{weeks}$ | number of weeks in a year |
| $\varepsilon$ | efficiency of the warehouse |
| $E_{CO2}$ | amount of $CO_2$ which is emitted |
| $\rho$ | factor based on measurements of Umweltbundesamt |
| $n_{MHD}$ | number of S/R machine |
| $S_{RD}$ | number of S/R machine |
| $R$ | number of picking aisles |
| $Y$ | number of single deep racks |
| $N_x$ | number of SC in the horizontal direction |
| $N_y$ | number of SC in the vertical direction |
| $P_f = \lambda$ | throughput capacity of the warehouse |

| | |
|---|---|
| $n$(pop) | number of generations in NSGA II population |
| $P(t)$ | solutions population |
| $F(t)$ | Solution front |
| $v$ | velocity |
| $v_{pi}$ | velocity profile |
| $v_{max}$ | maximum velocity |
| $v_x$ | velocity in the horizontal direction |
| $v_y$ | velocity in the vertical direction |
| $a_x$ | horizontal acceleration of the MHD |
| $a_y$ | vertical acceleration of the MHD |
| $t_x$ | travel time in the horizontal direction |
| $t_y$ | travel time in the vertical direction |
| $I_1$ | investment for buying the land |
| $I_2$ | investment for building foundations |
| $I_3$ | investment for building walls |
| $I_4$ | investment for building roof |
| $I_5$ | invest. for buying upright frames of SR |
| $I_6$ | investment for buying beams of SR |
| $I_7$ | investment for buying buffers |
| $I_8$ | price of montage of SR |
| $I_9$ | investment for buying fire safety equipment |
| $I_{10}$ | investment for buying heating and ventilation equipment |
| $I_{11}$ | investment for buying S/R machines |
| $w$ | width of the pallet |
| $g$ | length of the pallet |
| $h$ | height of the pallet |
| $m$ | mass (weight) of the pallet |
| $b_1$ | the safety addition to the width of the storage compartment |
| $b_2$ | the safety addition to the height of the storage compartment |
| $b_3$ | width of the upright frames of SR |
| $b_4$ | the width of the upright frame |
| $b_5$ | the thickness of the upright frame |
| $b_6$ | the height of rack beams |
| $b_7$ | the deviation of the storage comp. from the floor |
| $b_8$ | the safety spacing between racks that are placed close to each other |
| $b_9$ | the safety addition to the height of the warehouse |
| $b_{10}$ | the addition to the width of the palette at input buffer |
| $b_{20}$ | the addition to the end of the warehouse |
| $n$ | number of pallets in storage compartment |
| $t_{01}$ | additional time for SCC |
| $t_{02}$ | additional time for DCC |
| $n$(SC) | number of SCC |
| $N$(DC) | number of DCC |
| $W_{RD}$ | width of the S/R machine |
| $L_{RD}$ | length of the S/R machine |
| $G_{RD}$ | maximum weight capacity of the S/R machine |
| $H_{RD}$ | maximum lifting height of the S/R machine |
| $C_1$ | cost of buying the land |
| $C_2$ | cost of laying the foundations |
| $C_3$ | cost of building the walls of the |

| | |
|---|---|
| | warehouse |
| $C_4$ | cost of building the roof of the warehouse |
| $C_5$ | cost of buying upright frames |
| $C_6$ | cost of buying rack beams |
| $C_7$ | cost of buying buffers |
| $C_8$ | cost of the assembly |
| $C_9$ | cost of fire safety equipment |
| $C_{10}$ | cost of air ventilation system |
| $C_{11}$ | cost of buying S/R machine |

## ВИШЕЦИЉНИ ОПТИМИЗАЦИОНИ МОДЕЛ ЗА МИНИМИЗИРАЊЕ ТРОШКОВА, ВРЕМЕНА ЦИКЛУСА И ЕМИСИЈЕ $CO_2$ У АУТОМАТСКОМ СКЛАДИШНОМ СИСТЕМУ

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У представљеном раду, дискутовано је и вршена је евалуација вишециљне оптимизације аутоматских складишних система. С обзиром да је већина истраживача у области манипулације материјалом и логистици, вршила оптимизацију променљивих само са једном функцијом циља (најчешће је то функција минимално време циклуса, максимални интензитет опслуживања, минимална цена, тј. трошкови, максимална енергетска ефикасност, итд.), предложен је модел вишециљне оптимизације (са трима функцијама циља: минимални трошкови – минимално време циклуса – минимална емисија $CO_2$, односно максимална енергетска ефикасност). За оптимизацију променљивих у функцијама циља, коришћени су генетски алгоритми. Да бисмо пронашли оптимална Парето решења, употребили смо NSGA II генетске алгоритме. Главни задатак нашег доприноса јесте да се утврде перформансе аутоматског складишног система, у складу са процедуром вишециљне оптимизације. Резултати предложеног модела, могу бити од користи пројектантима у раним фазама пројектовања аутоматског складишног система.

**Table 1. Best 5 solutions for each objective function, after optimization of 10 generations and population of n(pop)=100.**

| ID | $Nx$ | $Ny$ | $R$ | $v_x$ [m/s] | $a_x$ [m/s$^2$] | $v_y$ [m/s] | $a_y$ [m/s$^2$] | $T$ (cycle) [s] | $TC$ (cost) [EUR] | $CO_2$ (emmis.) [kg/year] |
|---|---|---|---|---|---|---|---|---|---|---|
| **Travel time *T*** (best five solutions sorted by throughput time) | | | | | | | | | | |
| 938 | 8 | 7 | 10 | 2,25 | 0,93 | 0,98 | 0,64 | 31,94 | 9.440.968,22 | 44.759,16 |
| 960 | 10 | 7 | 8 | 2,89 | 0,89 | 0,98 | 0,69 | 32,58 | 8.570.861,03 | 43.113,89 |
| 945 | 9 | 8 | 9 | 2,97 | 0,88 | 0,99 | 0,74 | 32,72 | 8.590.277,73 | 43.502,44 |
| 676 | 12 | 5 | 11 | 2,70 | 0,62 | 0,99 | 0,69 | 32,88 | 9.916.969,39 | 43.579,19 |
| 752 | 9 | 7 | 9 | 2,25 | 0,93 | 0,98 | 0,65 | 33,12 | 9.010.077,53 | 43.894,89 |
| **$CO_2$ emmisions** (best five solutions sorted by minimum $CO_2$ emmisions) | | | | | | | | | | |
| 916 | 21 | 17 | 9 | 2,34 | 0,81 | 0,99 | 0,67 | 58,63 | 8.671.386,47 | 35.354,23 |
| 832 | 21 | 17 | 9 | 2,37 | 0,25 | 0,58 | 0,29 | 65,51 | 8.671.386,47 | 35.354,23 |
| 919 | 21 | 17 | 9 | 2,37 | 0,25 | 0,58 | 0,29 | 65,51 | 8.671.386,47 | 35.354,23 |
| 990 | 21 | 17 | 9 | 2,37 | 0,23 | 0,58 | 0,29 | 65,55 | 8.671.386,47 | 35.354,23 |
| 848 | 21 | 16 | 9 | 2,34 | 0,82 | 0,99 | 0,69 | 57,49 | 8.560.509,54 | 35.447,74 |
| **Total cost *TC*** (best five solutions sorted by minimum total cost) | | | | | | | | | | |
| 951 | 24 | 6 | 6 | 2,92 | 0,90 | 0,74 | 0,39 | 45,68 | 5.873.859,19 | 37.519,29 |
| 749 | 13 | 10 | 4 | 2,33 | 0,80 | 0,98 | 0,50 | 42,59 | 5.882.942,93 | 40.391,96 |
| 913 | 12 | 11 | 4 | 2,33 | 0,80 | 0,97 | 0,49 | 42,70 | 5.882.942,93 | 40.391,96 |
| 952 | 13 | 12 | 4 | 2,66 | 0,83 | 0,98 | 0,75 | 42,17 | 5.925.176,63 | 39.794,76 |
| 865 | 13 | 12 | 4 | 2,66 | 0,83 | 0,98 | 0,67 | 42,25 | 5.925.176,63 | 39.794,76 |