TRANSPORT
ISSN 1648-4142 / eISSN 1648-3480
2019 Volume 34 Issue 2: 275–286
https://doi.org/10.3846/transport.2019.9686

A MULTI-OBJECTIVE OPTIMIZATION MODEL FOR MINIMIZING INVESTMENT EXPENSES, CYCLE TIMES AND CO_2 FOOTPRINT OF AN AUTOMATED STORAGE AND RETRIEVAL SYSTEMS

Miloš RAJKOVIĆ[1], Nenad ZRNIĆ[2], Nenad KOSANIĆ[3],
Matej BOROVINŠEK[4], Tone LERHER[5*]

[1, 2, 3]*Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia*
[4, 5]*Faculty of Mechanical Engineering, University of Maribor, Maribor, Slovenia*

Received 16 February 2017; revised 2 June 2017, 14 July 2017; accepted 7 October 2017

Abstract. A new optimization model of Automated Storage and Retrieval Systems (AS/RS) containing three objective and four constraint functions is presented in this paper. Majority of the researchers and publications in material handling field had performed optimization of different decision variables, but with single objective function only. Most common functions are: minimum travel time, maximum throughput capacity, minimum cost, maximum energy efficiency, etc. To perform the simultaneous optimization of objective functions (minimum: "investment expenses", "cycle times", "CO_2 footprint") the Non-dominated Sorting Genetic Algorithm II (NSGA II) was used. The NSGA II is a tool for finding the Pareto optimal solutions on the Pareto line. Determining the performance of the system is the main goal of our model. Since AS/RS are not flexible in terms of layout and organizational changes once the system is up and running, the proposed model could be a very helpful tool for the warehouse planners in the early stages of warehouse design.

Keywords: warehouses, automated storage and retrieval system, multi-objective optimization, performance analysis, mathematical modelling.

Introduction

In recent times, the trend of globalisation and ever-increasing competitiveness in world market, means that companies are forced to find optimal balance between quality and availability of their products or services, and lowest possible expenses, as a way of reducing the price of the final product. Modern means of transport allow companies to have production facilities on different continents, and it is not uncommon for materials to "travel" for thousands of kilometres and go through several production phases from raw materials to finished products. In this process, warehouses are an absolute necessity.

Warehouses. Although the best solution for storage expenses would be, not to have warehouses at all, there are only a handful of examples in the world where production chain is organized in such manner, that all raw materials, parts and components are brought to processing location at the exact time when they are needed. Since these supply chains are extremely difficult to organize efficiently, and are very susceptible to external disruptions, in most cases, warehouse and distribution systems cannot be avoided. Some of the reasons to have warehouses are following (Hompel, Schmidt 2007):

- optimizing the supply chain performance;
- securing the continuation of productivity;
- value-added services;
- reduction of transport expenses;
- buffering differences between production and demand quantities.

Modern warehouse and distribution systems constitute highly complex nodes within the value-added chain and have to meet a variety of requirements with regard to time, costs and quality. The efficient operation of such a system is a continuous and great challenge for anyone in charge. Recent developments of advanced computer and control technologies have provided the necessary control and management systems (Warehouse Management Systems – WMS) (Foster 1970).

Nevertheless, due to the high complexity, users often find it hard to handle these kinds of systems.

---

*Corresponding author. E-mail: *tone.lerher@um.si*

While designing warehouse systems, designers are frequently facing adversarial influential factors. Therefore, it is very important to evaluate the one that prevails in every individual case, which is considered. If influential factors are not precisely estimated, there is a chance that one of the uneconomical solutions is selected (Zrnić, Savić 1990).

Automated warehouses. The Automated Storage and Retrieval System (AS/RS) is a major category of material handling equipment. There are two major types: unit load AS/RS (Figure 1) and mini-load AS/RS. AS/RS in most cases is comprised of conveyors, Storage Racks (SR) and automated Storage/Retrieval (S/R) machines. Although they usually mean high investment costs to begin with, automated storages make sense in countries with high wages, expensive land, or in competitive markets. If fast delivery and precision in order filling are extremely important, they can outweigh high initial investments.

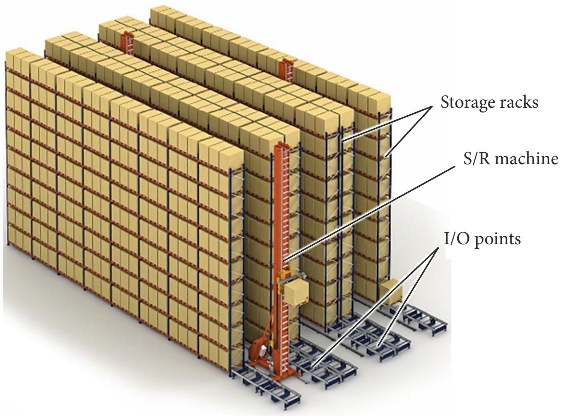

Figure 1. Unit load AS/RS illustration

In this paper, we propose a model that can help warehouse designers in early stages of planning of AS/RS. Finding the best compromise between investment expenses and required throughput, while still thinking about energy consumption (and at the same time operational cost of the warehouse) is crucial, as the changes in a warehouse layout in later phases are expensive, and often not possible.

In Chapter 1, we discuss what other authors have done in the past, and provide overview of literature. Chapter 2 provides theoretical background on simulation and Pareto optimization. In Chapter 3, three objective functions and input variables are defined, and in Chapter 4, we define our model. Chapter 5 contains analyses of a theoretical example of a warehouse, and results. In Chapter 6 we discuss results and in the last chapter we make conclusions.

1. Literature review

Over the past decades, many researchers have performed studies of AS/RS. As the informational and computer science were developing, so to was the research in Intralogistics field intensifying. In following chapter, major publications will be noted.

Gudehus (1973) placed foundations in research, and formed principles for calculations of the S/R machines cycle times, both for the Single Command Cycle (SCC) and as well for Dual Command Cycle (DCC). SCC is a simple cycle where the S/R machine can only derive one storage or retrieval request at a time. Combining storage and the retrieval requests to be done simultaneously by the S/R machine, represents a more advanced DCC. Unlike other cycle time expressions in earlier publications, he considered the impact of the acceleration and deceleration on travel times. Hausman *et al.* (1976) and Graves *et al.* (1977) presented publications, in which travel time models for AS/RS are assuming that the SR is so-called "Square In Time" (SIT), which meant that times to the most distant column $t_x = \frac{L_{SR}}{v_x}$ and tier $t_y = \frac{H_{SR}}{v_y}$ were both equal ($t_x = t_y$). They analysed different storage strategies, e.g. randomised, turnover-based and class-based storage assignment rules. Bozer and White (1984) presented an analytical approach for cycle time model for calculating the SCC and DCC for the so-called non-SIT racks. Authors based their models of S/R with various Input–Output (I/O) locations and configurations of the input queue on random strategy. Presupposition that the S/R machine travels all the time at constant velocity, is main characteristic of their analytical travel time model. Hwang and Lee (1990) included the operating characteristics of the S/R machines for AS/RS and non-SIT racks in their model. Lerher (2005), Lerher and Potrč (2006), like Hwang and Lee (1990), also included the operating characteristics of the S/R machines for AS/RS, but considered multi-aisle AS/RS in their analytical travel time model. By using the suggested analytical travel time model, realistic average travel times can be evaluated. Gu *et al.* (2007) presented a detailed review paper of publications that research warehouse operation. Roodbergen and Vis (2009) presented a comprehensive elucidation of the current state-of-the-art in AS/RS. Rouwenhorst *et al.* (2000) presented a comprehensive review paper of warehouse design and control policies. Lerher *et al.* (2014) presented simulation analysis of a mini-load multi-shuttle AS/RS. Vasili *et al.* (2012) presented a comprehensive review on travel time models and control policies. Bortolini *et al.* (2015a) published an addition for analytical models when calculating the average travel time for the SCCs and DCCs of AS/RS in three-class-based warehouse systems. Later the same year, Bortolini *et al.* (2015b) published a paper with non-conventional configuration for unit load warehouses containing diagonal cross-aisles. In addition, Bortolini *et al.* (2017) introduced assignment strategy based on energy and time for unit-load AS/RS warehouses. Janilionis *et al.* (2016) published a work with a comparison between different routing algorithms for S/R mechanisms in cylindrical AS/RS. Marchet *et al.* (2013) investigated main design trade-offs between two types of AVS/RS configurations. Tappia *et al.* (2015) presented model, which compares AVS/RSs and its natural alternative AS/RS, and Tappia *et al.* (2017) presented design insights for shuttle-based compact multi-deep unit-load storage systems.

Publications, which discuss the multi-objective studies are following.

Diao *et al.* (2011) researched a compromise issues between three objective functions: cost, cycle time, and material handling quality, which determined performance of a system. A multi-objective Pareto optimisation approach using Non-dominated Sorting Genetic Algorithm II (NSGA II) was utilized for solving compromise issues. The approach can help searching near the reality Pareto-optimal set while not receiving any information on the stakeholders' preference for time, cost and quality. Based on the developed approach, decision-making can become easy according to the sorted non-dominated solutions and project preferences. Lerher *et al.* (2013) researched multi-objective optimization for a Class Based S/R Systems (CBS/RS), and the three proposed objective functions were: (1) minimisation of average cycle times, (2) costs, and (3) maximization of quality of material handling. Just like research of Diao *et al.* (2011), NSGA II algorithm was used for finding optimal solutions on Pareto line, which is the main reason for utilizing the evolutionary algorithm. Later Lerher (2013) and Borovinšek *et al.* (2017) researched Shuttle-Based S/R Systems (SBS/RS) by taking into account energy efficiency. Their objective functions were (1) average cycle times of transactions (average throughput time), (2) amount of energy (electricity) consumption, and (3) total investment cost. During the optimization procedure, considered were seven design variables: (1) number of aisles, (2) number of tiers, (3) number of columns, (4) velocities of shuttle carriers, (5) acceleration/deceleration of shuttle carriers, (6) velocity of the elevators lifting tables, and (7) acceleration/deceleration of the elevators lifting tables. Due to the non-linear property of the objective function, also was utilized the NSGA II, and Pareto optimal solutions were searched. Bekker (2013) published a work for economic approach for computation, to optimize the throughput rate and allocated buffer space. The cross-entropy method was earlier applied to a variety of optimisation problems with single objectives, and in this paper it was extended to the multi-objective case and proposed as a computationally economic approach to optimise at least two conflicting objectives of the buffer allocation problem, namely (1) throughput rate and (2) allocated buffer space, while using computer simulation as evaluation function of small to large stochastic queuing networks of unreliable resources. General solution for obtaining the network-related Pareto front is proposed. The results for test networks indicate that reasonable Pareto fronts can be obtained via a low number of multi-objective solution evaluations using the modified cross-entropy method. Smew *et al.* (2013) published a simulation study of compromises among the conflicting objectives of maximising customer service quality and minimising working activities. It was demonstrated as an optimisation framework that will provide solutions with an accuracy that is acceptable for decision makers and computationally less demanding than simulation based optimisation. A simulation model to process a single product was developed in order to explore the impact of some essential input factors on customer service level and average work in process, through Design Of Experiments (DOE), Gaussian Process (GP) modelling and Metamodel-Based Optimisation using the Desirability Function. The precision of the results from this approach was determined by comparison to results from Simulation-Based Optimisation by means of Genetic Algorithms (GA). Lerher *et al.* (2015a, 2015b) performed additional studies of SBS/RS by taking into account the energy efficiency of S/R machines within the storage system's design. The presented models gave several different suggestions for warehouse designs along with their respective performances. Ries *et al.* (2017) considered the environmental impact of warehousing for the United States. Colicchia *et al.* (2016) presented a supply chain network design framework that is based on multi-objective mathematical programming and that can identify "eco-efficient" configuration alternatives that are both efficient and ecologically sound.

Majority of the researchers and their publications in the material handling field, have presented models with optimization of different decision variables, but with single objective function only. Most common are: minimum travel time, maximum throughput capacity, minimum cost, maximum energy efficiency, etc. In this paper however, the multi-objective optimization model with three objective functions and four constraints will be presented.

2. Simulation and optimization

There is a constant aspiration towards maximizing efficiency of material handling and storage systems. This conditions necessity for use of simulation methods for analysis of material flow. Simulation of processes enables that separate elements and the whole material flow chain is analysed in detail. Advantage of simulation over analytical methods is in the fact that it gives far more precise results, and also, it does not require expensive and long testing and confirmations of results obtained in exploiting conditions. Simulation offers broad possibilities, especially because it allows study of processes, which could occur in theoretical conditions, and as well as those that exist in real cases (Zrnić, Savić 1990).

Optimization problems search for a point in which a particular function is minimal or maximal. Frequently, this point has to fulfil some limitations as well.

Adding several objective functions simultaneously into an optimization problem adds to its complexity. For instance, one would desire a stacker crane that is both fast and energy efficient. When these two objectives are conflicting, a compromise must be made. Fast crane, means more powerful motors are required, and those utilize more electricity. There could be one crane, which is fastest, one which is maximally energy efficient, but slow; and an infinite number of cranes that are some compromise between speed and energy efficiency. The set of solutions with made compromises, which cannot be improved upon according to one criterion without deteriorating another

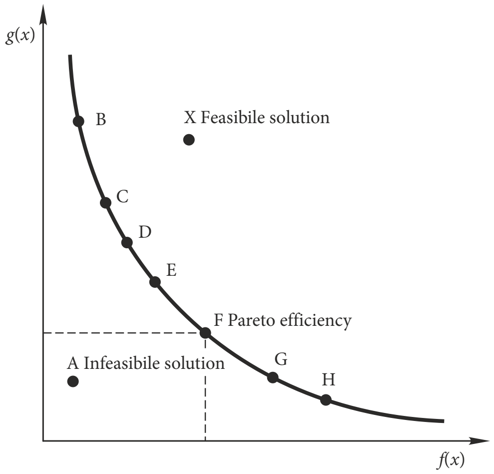

Figure 2. Pareto set of solutions on Pareto frontier (Gu *et al.* 2007)

criterion is known as the Pareto set. The curved line created plotting velocity solutions (motor power) against energy efficiency solutions is known as the Pareto frontier – Figure 2 (Gu *et al.* 2007).

3. Definition of the optimisation model of the AS/RS

Like mentioned earlier, majority of the researchers in material handling field had performed optimization with only one objective function: Ashayeri *et al.* (1985), Bafna and Reed (1972), Altintas *et al.* (2010).

This model simultaneously minimizes "investment expenses", "cycle time", and "CO_2 footprint" of a storage system according to project restraints and conditions.

3.1. Minimizing investment expenses

Investment expenses are comparable relative to cycle time. It is logical that if we want to use material handling devices with more powerful motors, which will allow for higher movement and hoisting velocity, this will undoubtedly increase the initial investment expenses of the warehouse, but also the expenses for material handling devices in the exploitation phase. More powerful motors will add to expenses in the exploitation phase as they will consume more energy. The objective is to minimize the investment expense, which is described as follows:

function:

$$\min f_{IE}\left(x_i\right),\ i \in \left[1, 8\right]. \quad (1)$$

3.2. Minimizing cycle time

Cycle time in majority of material handling facilities gives information about movement of various material handling devices like forklifts, S/R machines, etc. While some researchers prefer analytical cycle time models, it is already explained what advantages discrete simulation provides. Reducing cycle times is achievable by using more powerful motors to get better acceleration performances and to reach projected top speed faster. Aside from the more powerful motors, the length and the height of the SR should be in the corresponding relationship. To determine the necessary number of Material Handling Device (MHD) (S/R machines) it is required to know throughput capacity, and to calculate cycle time. The goal is to minimize the cycle time, which is described as follows:

function:

$$\min f_{CT}\left(x_i\right),\ i \in \left[1, 8\right]. \quad (2)$$

3.3. Minimizing CO_2 footprint

This model deals with minimization of energy consumption of AS/RS equipment. Therefore, if we decrease number of cranes, we reduce energy consumption, and cut down cost for buying and operating cranes, but we enhance cycle time, because, less cranes means more utilization for the existing ones. If we have, for instance, one crane for every two hallways, we increase warehouse surface for the zone in which cranes change lanes, increasing the cost for land, building, and operating warehouse, etc.

The goal is to minimize the energy consumption, that is, CO_2 footprint (emission), which is described as:

function:

$$\min f_{FP}\left(x_i\right),\ i \in \left[1, 8\right]. \quad (3)$$

In our model, we are also introducing the independent variables, which have their lower and upper limitation. Variables are used in the f_{IE}, f_{CT} and f_{FP} functions, and are defined as follows:

real:

$$0 < x_1, x_2, x_3, x_4, x_5, x_6 \le 1; \quad (4)$$

integer:

$$1 < x_7, x_8 \le N, \quad (5)$$

where: variables x_1, x_2, …, x_8 are defined in Chapter 5.

The functions f_{IE}, f_{CT} and f_{FP} effect each other, and best solutions will form a Pareto line. From these various solutions design engineers will be able to choose one, depending on which one of the functions they consider to be a priority to the investor/future owner of the warehouse.

4. Definition of the design model

The proposed model contains known operational parameters, decision variables, costs of MHD, land and materials and workforce for building a warehouse. When defining the model, some assumptions and known facts had been applied:

1) the SR, logically, has a rectangular shape; the I/O location of the SR is placed as seen on Figure 3 (Lerher *et al.* 2013);
2) the warehouse building is split into segments, which contain aisles with SR on both sides; the I/O location of the storage zone is located as can be seen on Figure 4 (Lerher *et al.* 2013);

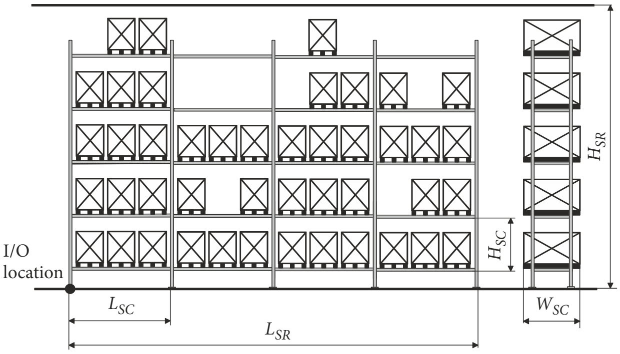

Figure 3. The SR with storage compartments – side view (Lerher *et al.* 2013)

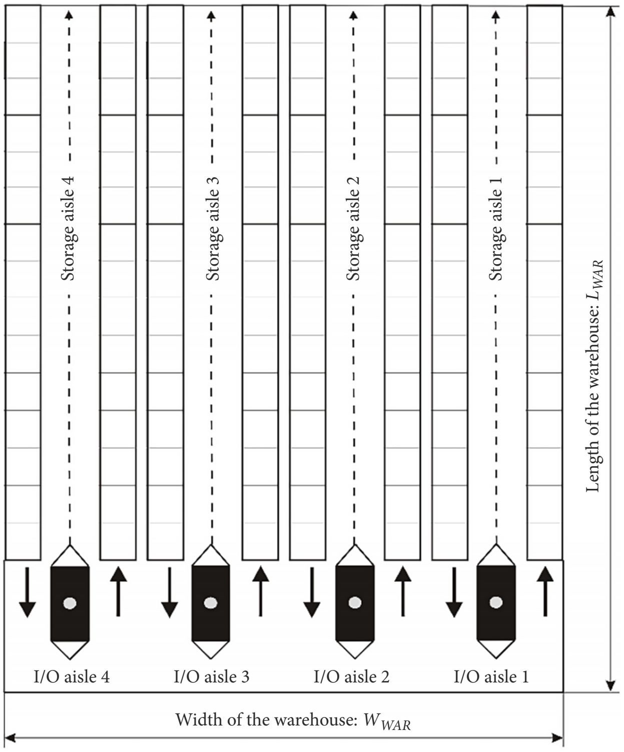

Figure 4. The SR with storage compartments – top view (Lerher *et al.* 2013)

3) there is one type of MHD with its working width A_{st};
4) there can be MHD only as much, or less, than there are storage aisles ($S \leq R$);
5) warehouse contains space for the cross-warehouse aisle, allowing the MHD to change storage aisles (Figure 4);
6) the MHD performs both SCC and DCC, and to which a share of travel time is added for MHD's travelling in the cross aisle;
7) drive performances of the MHD (velocity v, acceleration a, etc.) are known;
8) the length and height of the SR are known;
9) the SR's height and length are long/high enough for the MHD to reach its maximum velocity $v_{\max}$, both in the horizontal and vertical direction as well;
10) random storage strategy is used, meaning that any place in the SR is equally likely to be selected for the storage (if empty) or retrieval (if full) assignment.

Along with these assumptions, it is further necessary to explain abbreviations, functions, variables and parameters:

Abbreviations:

AS/RS – automated storage and retrieval systems;
AVS – autonomous vehicle system;
CBS/RS – class based S/R systems;
CO_2 – carbon dioxide;
DCC – double command cycle;
I/O – input and output location;
MHD – material handling device;
S/R – storage and retrieval;
SBS/RS – shuttle-based S/R systems;
SC – storage compartment;
SCC – single command cycle;
SIT – square in time;
SR – storage rack;
SRD – number of S/R machines;
$T(DCC)$ – mean dual command travel time;
$T(SCC)$ – mean single command travel time;
WMS – warehouse management system.

Objective functions:

$f_{IE}(x_i)$ – objective function "investment expenses";
$f_{CT}(x_i)$ – objective function "cycle time";
$f_{FP}(x_i)$ – objective function "CO_2 footprint" (emission).

Design variables:

R – number of aisles in the AS/RS;
Y – number of single deep racks;
S – number of MHD;
v_x – velocity in the horizontal direction;
v_y – velocity in the vertical direction;
a_x – horizontal acceleration of the MHD;
v_y – vertical acceleration of the MHD.

Operational parameters:

x_i – variable;
g_i – constraint;
b – shape factor;
Q – warehouse volume (capacity);
m – mass (weight) of the pallet;
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 SR;
L_{SC} – length of the SC;
H_{WAR} – height of the warehouse;
H_{SR} – height of the SR;
H_{SC} – height of the SC;
W_{WAR} – width of the warehouse;
W_{SR} – width of the SR;
W_{SC} – width of the SC;
Ast – aisle working width;
P – total motor 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;
ε – efficiency of the warehouse;
E_{CO_2} – amount of emitted CO_2 into atmosphere;
S_{fores} – surface of forest;
ρ – factor based on measurements of German Environment Agency (*Umweltbundesamt* – UBA (UBA 2016));
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;
$F(t)$ – solutions front;
N_x – number of SC in the horizontal direction;
v – velocity;
v_{pi} – velocity profile;
$v_{\max}$ – maximum velocity;
t_x – travel time in the horizontal direction;
t_y – travel time in the vertical direction;
P_x – required motor power for traveling in x axis;
P_y – required motor power for lifting in y axis;
P_{Tax} – required motor power for acceleration in x axis;
P_{Tay} – required motor power for acceleration in y axis;
P_{Tvx} – required motor power for traveling at constant velocity in x axis;
P_{Tvy} – required motor power for lifting at constant velocity in y axis;
P_B – required motor power for stopping S/R machine (breaking);
t_{accx} – time in which S/R machine accelerates from 0 to max velocity;
$t_{convelx}$ – time during which S/R machine travels at constant velocity;
t_{deccx} – time in which S/R machine breaks from max velocity to 0;
t_{accy} – time in which S/R machine acceleration from 0 to max velocity in y axis;
$t_{convely}$ – time during which S/R machine lifts loads in y axis at constant velocity;
t_{deccy} – time in which S/R machine breaks from max velocity to 0 in y axis;
$S_{acc\ x,y}$ – distance travelled during acceleration;
$S_{convel\ x,y}$ – distance travelled at constant velocity;
$S_{dec\ x,y}$ – distance travelled during breaking;
w – width of the pallet;
g – length of the pallet;
h – height of the pallet;
b_1 – safety addition to the width of the SC;
b_2 – safety addition to the height of the SC;
b_3 – width of the upright frames of SR;
b_4 – width of the upright frame;
b_5 – thickness of the upright frame;
b_6 – height of rack beams;
b_7 – height of the SC from the floor;
b_8 – safety spacing between SR that are assembled in close proximity to each other;
b_9 – safety addition to the height of the warehouse;
b_{10} – addition to the width of the palette at input buffer;
b_{20} – addition to the end of the warehouse;
n – number of pallets in SC;
t_{01} – additional time for SCC;
t_{02} – additional time for DCC;
$n(SCC)$ – number of SCC;
$n(DCC)$ – 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;
L_v – length of the rack beam;
S_{TV} – number of lift trucks;
S_{RV} – number of pedestrian runners.

Operational cost parameters:

I_1 – investment for purchasing the land;
I_2 – investment for building foundations;
I_3 – investment for building walls;
I_4 – investment for building roof;
I_5 – investment for buying upright frames of SR;
I_6 – investment for purchasing beams of SR;
I_7 – investment for purchasing buffers;
I_8 – price of montage of SR;
I_9 – investment for buying fire safety equipment;
I_{10} – investment for heating and ventilation equipment;
I_{11} – investment in multi-aisle AS/RS;
I_{12} – investment in accumulating conveyor;
I_{13} – price of WMS software;
C_1 – cost of purchasing 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 purchasing upright frames;
C_6 – cost of purchasing rack beams;
C_7 – cost of purchasing buffers;
C_8 – cost of the assembly;
C_9 – cost of purchasing the fire safety equipment;
C_{10} – cost of purchasing the air ventilation system;
C_{11} – cost of purchasing S/R machine;
C_{12} – cost of purchasing accumulating conveyor;
C_{13} – cost of purchasing the diverted element.

4.1. Investment expenses definition

The investment in buying the land per square meter I_1:

$$I_1 = \left(P_{LAND} \cdot \frac{100}{P_{EFF}} \right) \cdot C_1, \tag{6}$$

where: P_{LAND} represents the available surface of the land [m^2]; P_{EFF} represents the surface share that warehouse occupies [m^2]; C_1 represents the land cost [EUR/m^2].

The required investment for laying foundations of the warehouse building I_2:

$$I_2 = \left(\left(\left(w \cdot n + \left(n+1\right) \cdot b_1 + b_4\right) \cdot N_x + \right.\right.$$
$$\left. +b_5 + b_{20}\right) + L_{TZ} \cdot \left(R \cdot W_{RD} + Y \cdot g + \right.$$
$$\left.\left.\left(R-1\right) \cdot b_8\right)\right) \cdot C_2, \tag{7}$$

where: N_x, R and Y are decision variables, defined in Chapter 5; n represents the number of pallets in SC; w, g and h represent the width, length and height of the pallet [mm]; W_{RD} represents the width of the SR machine [mm]; L_{TZ} represents the length of the transport zone [mm]; safety additions: b_1 width of the SC [mm], b_4 width of upright frame [mm], b_5 the thickness of the upright frame [mm], b_8 the spacing between racks that are placed close to each other [mm], b_{10} the width of the palette at the input buffer [mm], b_{20} the addition to the end of the warehouse [mm]; C_2 represents the cost of laying the foundations of the warehouse building [€/m^2].

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

$$I_3 = \left(\left(\left(\left(w \cdot n + \left(n+1\right) \cdot b_1 + b_4\right) \cdot N_x + \right.\right.\right.$$
$$\left. b_5 + b_{10} + b_{20} + b_5 + b_{10} + b_{20}\right) + L_{TZ} +$$
$$\left.\left(R \cdot W_{RD} + Y \cdot g + \left(R-1\right) \cdot b_8\right)\right) \times$$
$$\left.\left(\left(h + b_2 + b_6\right) \cdot N_y + b_7 + b_9\right)\right) \cdot 2 \cdot C_3, \tag{8}$$

where: N_y is the decision variable; safety additions: b_2 height of the SC [mm], b_6 the height of rack beams [mm], b_7 the distance of the SC from the floor [mm], b_9 height of the warehouse [mm]; C_3 is the expense of building the walls of the warehouse [€/m^2].

The investment cost for placing the roof I_4:

$$I_4 = \left(\left(\left(w \cdot n + \left(n+1\right) \cdot b_1 + b_4\right) \cdot N_x + \right.\right.$$
$$\left. b_5 + b_{10} + b_{20}\right) + L_{TZ} \times$$
$$\left.\left(R \cdot W_{RD} + Y \cdot g + \left(R-1\right) \cdot b_8\right)\right) \cdot C_4, \tag{9}$$

where: C_4 represents the cost of placing the roof of the warehouse [€/m^2].

The investment for purchasing columns of SR I_5:

$$I_5 = \left(\left(N_x + 1\right) \cdot 2 \cdot Y\right) \cdot C_5, \tag{10}$$

where: C_5 represents the cost of purchasing upright frames [€/m].

The investment cost for purchasing rack elements and an appendix for the reinforcing of the SR structure I_6:

$$I_6 = \left(N_x \cdot N_y \cdot 2 \cdot Y \cdot L_v\right) \cdot C_6, \tag{11}$$

where: L_v is the length of the rack beam [mm]; C_6 indicates the cost of purchasing rack elements [€/m].

The investment in purchasing buffers I_7 and the assembly of the SR structure I_8:

$$I_7 = 2 \cdot R \cdot C_7; \tag{12}$$
$$I_8 = Q \cdot C_8, \tag{13}$$

where: C_7 represents the cost of purchasing buffers [€]; C_8 the cost of SR elements assembly [€].

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

$$I_9 = \left(\left(N_x \cdot N_y\right) \cdot 3 \cdot 2\right) \cdot C_9; \tag{14}$$
$$I_{10} = \left(L_{WAR} \cdot H_{WAR} \cdot W_{WAR}\right) \cdot C_{10}, \tag{15}$$

where: C_9 represents the cost of fire-safety [€/PM]; C_{10} the cost of air ventilation equipment [€/m^3].

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

$$I_{11} = S_{RD} \cdot C_{11}, \tag{16}$$

where: S_{RD} represents the number of SR machines (and is decision variable); C_{11} cost of purchasing the S/R machine [€].

The investment in the accumulating conveyor I_{12}:

$$I_{12} = C_{12} + 2 \cdot R \cdot C_{13}, \tag{17}$$

where: C_{12} indicates the cost of the accumulating conveyor (the controls, the control system) [€]; C_{13} indicates the cost of the diverted element [€].

The price of WMS software I_{13}:

$$I_{13} = 245000\ €. \tag{18}$$

The objective function $\min f_{IE}$ refers to all the costs of building the warehouse, and purchasing the material-handling equipment. In the objective function, the costs represent the variable value and change depending on the geometry of the warehouse. Fire safety and air, and ventilation systems costs are dependent of the warehouse volume. In some future research could be interesting to compare these costs, with double-deep AS/RS, since saving in floor space will result in overall volume reduction, and therefore, reduction in these costs. The expression for the objective function $\min f_C$ is following:

$$f_{IE} = \left(I_1 + I_2 + I_3 + I_4 + I_5 + I_6 + \right.$$
$$I_7 + I_8 + I_9 + I_{10} + I_{11} + I_{12} + I_{13} +$$
$$\left. I_9 + I_{10} + I_{11} + I_{12} + I_{13}\right) / Q. \tag{19}$$

4.2. Cycle time definition

Presented model is based on the SCC and DCC. The throughput capacity λ and the cycle time are inverse and dependant of each other. To perform calculations of the cycle time of the SCC and DCC, in our analytical cycle time model, we considered the real driving characteristics of the S/R machine, by using expressions of Gudehus (1973).

Expression for SCC by Gudehus (1973):

$$T\left(SCC\right) = \begin{cases} Tscc_1, \text{ when } b \le 1; \\ Tscc_2, \text{ when } b > 1, \end{cases} \tag{20}$$

where:

$$Tscc_1 = t_{01} + \frac{L_{SR}}{v_x} + \frac{2 \cdot v_x}{a_x} + \frac{A \cdot v_x}{L_{SR}^2 \cdot a_y} +$$
$$\frac{A^2 \cdot v_x}{3 \cdot L_{SR}^3 \cdot v_y^2} - \frac{A \cdot v_x^2}{L_{SR}^2 \cdot a_x \cdot v_y};$$

$$Tscc_2 = t_{01} + \frac{A}{L_{SR} \cdot v_y} + \frac{2 \cdot v_y}{a_y} + \frac{L_{SR}^2 \cdot v_y}{A \cdot a_x} + \frac{L_{SR}^3 \cdot v_y}{3 \cdot A \cdot v_x^2} - \frac{L_{SR}^2 \cdot v_y^2}{A \cdot a_y \cdot v_x}.$$

Expression for DCC by Gudehus (1973):

$$T(DCC) = \begin{cases} Tdcc_1, \text{ when } b \le 1; \\ Tdcc_2, \text{ when } b > 1, \end{cases} \tag{21}$$

where:

$$Tdcc_1 = t_{02} + \frac{4 \cdot L_{SR}}{3 \cdot v_x} + \frac{3 \cdot v_x}{a_x} + \frac{3 \cdot A \cdot v_x}{2 \cdot L_{SR}^2 \cdot a_y} + \frac{A^3 \cdot v_x^2}{30 \cdot L_{SR}^5 \cdot v_y^3} + \frac{A^2 \cdot v_x}{2 \cdot L_{SR}^3 \cdot v_y^2} - \frac{3 \cdot A \cdot v_x^2}{2 \cdot L_{SR}^2 \cdot a_x \cdot v_y};$$

$$Tdcc_2 = t_{02} + \frac{4 \cdot A}{3 \cdot L_{SR} \cdot v_y} + \frac{3 \cdot v_y}{a_y} + \frac{3 \cdot L_{SR}^2 \cdot v_y}{2 \cdot A \cdot a_x} + \frac{L_{SR}^5 \cdot v_y^2}{30 \cdot A^2 \cdot v_x^3} + \frac{L_{SR}^3 \cdot v_y}{2 \cdot A \cdot v_x^2} - \frac{3 \cdot L_{SR}^2 \cdot v_y^2}{2 \cdot A \cdot a_y \cdot v_x};$$

$$b = \frac{H_{SR}}{L_{SR}} \cdot \frac{v_x}{v_y}. \tag{22}$$

More literature concerning analytical cycle time models, that are considering the real operating characteristics of the S/R machine, is recommended. Earlier, we mentioned paper of Hwang and Lee (1990), but we also recommend papers by Vössner (1994) and Vidovics (1994).

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

$$\lambda(p) = \frac{2 \cdot T_{shift}}{p \cdot T(DCC) + 2 \cdot (1-p) \cdot T(SCC)} \cdot n_{MHD}. \tag{23}$$

The expression for the objective function $\min f_{CT}$ is following:

$$f_{CT} = \frac{n(SCC) \cdot T(SCC) + n(DCC) \cdot T(DCC)}{n(SCC) + n(DCC)}. \tag{24}$$

4.3. CO$_2$ footprint (emission) definition

Mechanical model of the S/R machine with the hoisted carriage. Sum of required motor power P for travelling of the S/R machine, equals the next expression:

$$P = P_x + P_y \ [\text{kW}], \tag{25}$$

where: P_x is power required for S/R machine to travel in the horizontal direction; P_y is required power for hoisting material in vertical direction. These are calculated as follows:

$$P_x = \sqrt{\frac{P_{Tax}^2 \cdot t_{accx} + P_{Tvx}^2 \cdot t_{convelx} + P_B^2 \cdot t_{decx}}{t_{accx} + t_{convelx} + t_{decx}}}; \tag{26}$$

$$P_y = \sqrt{\frac{P_{Tay}^2 \cdot t_{accy} + P_{Tvy}^2 \cdot t_{convely} + P_B^2 \cdot t_{decy}}{t_{accy} + t_{convely} + t_{decy}}}. \tag{27}$$

Cycle time t in x axis, can be divided into three parts. First one is time for accelerating of the S/R machine to reach maximum velocity t_{accx}. Then, the S/R machine is traveling with constant velocity $t_{convelx}$, and lastly, t_{decx} is time needed for the S/R machine to decelerate from maximal speed, until it stops at the storage location. The expressions for calculation of the above-mentioned times are described in the following equations:

$$t_{accx} = \frac{v_x}{a_x^+};$$

$$s_{accx} = \frac{v_x^2}{2 \cdot a_x^+};$$

$$t_{decx} = \frac{v_x}{a_x^-};$$

$$s_{accx} = \frac{v_x^2}{2 \cdot a_x^-};$$

$$t_{convelx} = \frac{s_{convelx}}{v_x};$$

$$s_{convelx} = \left(\left(\frac{2}{3} \cdot L \right) - s_{accx} + s_{deccx} \right). \tag{28}$$

Cycle time t in y axis, is also dividable in three parts. First is the time for acceleration of the lifting mechanism of the S/R machine to reach maximum velocity t_{accy}. Next, there is time needed for traveling of lifting mechanism with constant velocity $t_{convely}$. Lastly, time for decelerating of lifting mechanism until it stops at the storage location is t_{decy}. The expressions for calculation of the above-mentioned times are described in the following equations:

$$t_{accy} = \frac{v_y}{a_y^+};$$

$$s_{accy} = \frac{v_y^2}{2 \cdot a_y^+};$$

$$t_{decy} = \frac{v_y}{a_y^-};$$

$$s_{accy} = \frac{v_y^2}{2 \cdot a_y^-};$$

$$t_{convely} = \frac{s_{convely}}{v_y};$$

$$s_{convely} = \left(\left(\frac{2}{3} \cdot L \right) - s_{accy} + s_{deccy} \right). \tag{29}$$

Energy consumption W will be calculated and expressed on an annual basis. It expression is the following:

$$W = P \cdot T_{shift} \cdot n_{WD} \cdot n_{weeks} \cdot \varepsilon \ [\text{kWh/year}], \tag{30}$$

where: P is total motor power; T_{shit} is number of working hours in one shift; n_{wd} is number of working days in a work week; n_{weeks} is number of weeks in a year; ε is efficiency of the warehouse (distribution centre).

The amount of CO$_2$, which is released into the atmosphere is directly dependant of the energy consumption W:

$$E_{CO2} = W \cdot \rho \ \left[\text{kgCO}_2/\text{year}\right]. \tag{31}$$

The symbol ρ represents the factor, which is obtained from the German Environment Agency (*Umweltbundesamt* – UBA (UBA 2016)), and it is based on the actual measurements.

In nature, 100 m^2 of the forest consume from the atmosphere, approximately 1 tonne of CO_2 in a period of 10 years, in the process known as photosynthesis. This fact can be used when we want to express CO_2 emission as a footprint. In this case, we want to calculate the needed surface of forest, with the goal objective to annul CO_2 emission in period of 1 year. If the amount of the CO_2 emission is measured in kgCO_2/year, then the next expression is valid:

$$S_{Forest} = E_{CO_2} \cdot 0.1 \ \left[\text{m}^2 \text{ of forest/10years}\right]. \tag{32}$$

Finally, we will express the function f_{FP} as acres of forest required to consume emitted CO_2 in one year:

$$f_{FP} = S_{Forest} \cdot 2.471 \cdot 10^{-4} \ \left[\text{acres of forest/year}\right]. \tag{33}$$

In general, major factors, which determine the overall efficiency of the AS/RS are mainly the geometry of the SR (L_{sr} and H_{sr}), velocity performances of the S/R machine and the control strategy and policy, which has a significant influence on the average cycle time.

5. Analysis: an example of designing AS/RS

The decision variables x_i are defined as follows:

- $x_1 = N_x$ – number of SC in the horizontal x direction;
- $x_1 = N_y$ – number of SC in the vertical y direction;
- $x_3 = v_x$ – speed of S/R machine in the horizontal x direction;
- $x_4 = a_x$ – acceleration and deceleration of S/R machine in the horizontal x direction;
- $x_5 = v_y$ – speed of S/R machine in the vertical y direction;
- $x_6 = a_y$ – acceleration and deceleration of S/R machine in the vertical y direction;
- $x_1 = R$ – number of storage aisles in a warehouse;
- $x_8 = S$ – number of S/R machines.

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

- L_{WAR} (20…120 m) – the length of the warehouse;
- W_{WAR} (20…100 m) – the width of the warehouse;
- H_{WAR} (10…30 m) – the height of the warehouse.

Furthermore, four constraint functions are added:

- $g_1 = \min Q < Q$ – capacity of the warehouse has to be bigger than the minimum required capacity;
- $g_2 = \min \lambda < \lambda$ – throughput capacity has to be higher than the minimum required throughput capacity;
- $g_3 = Q < \left(\min Q + 20\%\right)$ – capacity of the warehouse must not be more than 20% higher than the required capacity;
- $g_4 = S \le R$ – number of S/R machines has to be lower or equal to the number of hallways.

Input data for this example is based on information from real AS/RS system. The analysis refers to the chosen model of the AS/RS, which is determined by the following parameters:

1) ***Entry-level parameters:*** maximum storage capacity of the warehouse Q = 20000 pallets, throughput capacity of the warehouse $P_f = 600$ pallets/day;
2) ***Operational parameters of the AS/RS:*** w = 800 mm, g = 1200 mm, h = 1200 mm, m = 1000 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 s, t_{02} = 10 s, $n(SCC) = 200$, $n(DCC) = 400$, $L_{TZ} = 20000$ mm, $W_{RD} = 1500$ mm, $L_{RD} = 2000$ mm;
3) ***Material handling equipment:*** the single-aisle AS/RS (*Stöklin AT RGB 0-Q*): $G_{RD} = 1250$ kg, $H_{RD} = 22000$ mm, $W_{RD} = 1400$ mm, $v_x = 3$ m/s, $v_y = 2$ m/s, $v_i = 0.6$ m/s, $a_x = 1$ m/s^2, $a_y = 0.1$ m/s^2;
4) ***Investment expenses:*** C_1 = 500 €/m^2, C_2 = 165 €/m^2, C_3 = 22 €/m^2, C_4 = 25 €/m^2, C_5 = 30 €/m^2, C_6 = 24 €/m^2, C_7 = 190 €/piece, C_8 = 10 €/RO, C_9 = 5 €/PM, C_{10} = 10 €/m^3, C_{11} = 431750 €/piece, C_{12} = 40 €/m, C_{13} = 500 €/m.

Based on the performed analysis of the optimization of the decision variables in the $\min f_{IE}\left(x_i\right)$, $\min f_{CT}\left(x_i\right)$ and $\min f_{FP}\left(x_i\right)$ with the method of GA, the main results, which are shown in the Table, can be presented. The following Table shows the results of the optimization of the decision variables N_x, N_y, v_x, a_x, v_y, a_y, R, S, with the number of generations $n(gen) = 100$ and $n(pop) = 100$ in the GA.

The diagram in Figure 5 shows results and the relation between functions f_{FP} (minimum "CO_2 footprint") and f_{CT} (minimum "cycle times").

The diagram in Figure 6 shows results and the relation between functions f_{CT} (minimum "cycle times") and f_{IE} (minimum "investment expenses").

Lastly, the diagram in Figure 7 shows results and the relation between functions f_{FP} (minimum "CO_2 footprint") and f_{IE} (minimum "investment expenses").

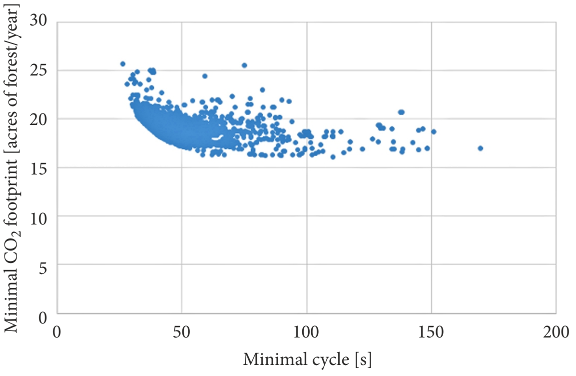

Figure 5. Results relation of minimal "CO_2 footprint" and minimal "cycle times"

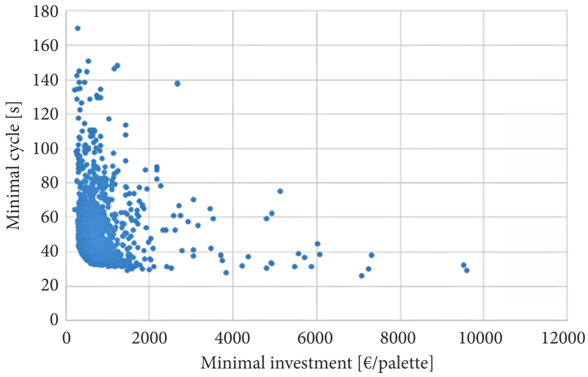

Figure 6. Results relation of minimal "cycle times" and minimal "investment expenses"

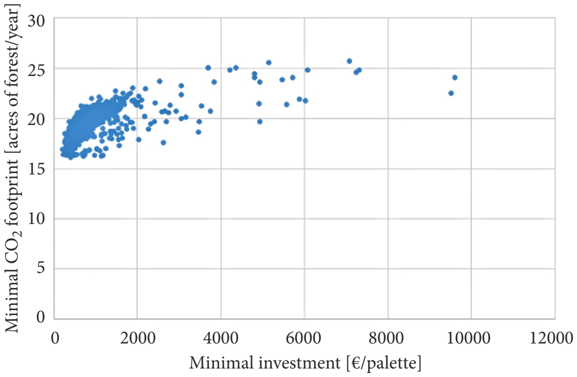

Figure 7. Results relation of minimal "CO_2 footprint" and minimal "investment expenses"

Table. Top 5 solutions for each objective function after optimization

ID	N_x	N_y	v_x [m/s]	a_x [m/s^2]	v_y [m/s]	a_y [m/s^2]	R	S	f_{CT} [s]	f_{IE} [€/TUL]	f_{FP} [acres of forest/year]
Cycle time – best five solutions sorted by cycle time											
9871	9.28	13.51	3.00	1.00	2.00	1.00	14.24	3.75	34.04	601.13	20.26
8933	9.28	13.50	3.00	0.99	2.00	1.00	14.24	3.75	34.05	601.13	20.26
8595	9.28	13.51	2.99	1.00	2.00	0.99	14.24	3.75	34.06	601.13	20.26
7357	9.28	13.51	3.00	0.98	2.00	1.00	14.24	3.71	34.07	601.13	20.26
7179	9.28	13.51	3.00	0.98	2.00	0.98	14.12	3.71	34.09	601.13	20.26
CO_2 footprint – best five solutions sorted by minimum CO_2 footprint											
9320	27.59	13.03	3.00	1.00	1.99	1.00	6.60	6.54	48.37	589.62	17.80
9410	26.83	13.03	3.00	1.00	2.00	1.00	6.60	6.54	47.35	608.36	17.88
9954	19.38	18.37	3.00	1.00	2.00	1.00	6.21	4.78	42.80	538.35	17.96
8341	26.44	12.25	3.00	0.99	1.99	0.99	8.01	6.54	47.28	593.37	18.03
8188	24.93	12.94	3.00	0.98	2.00	1.00	7.57	6.49	45.59	595.23	18.05
Investment expenses – best five solutions sorted by minimum investment expenses											
9911	18.75	14.23	3.00	0.99	2.00	1.00	8.60	4.21	40.74	520.92	18.53
8966	18.89	17.25	3.00	0.99	2.00	1.00	6.97	4.56	42.48	521.07	18.06
9749	17.33	16.61	3.00	1.00	2.00	1.00	7.87	4.10	40.58	521.96	18.42
8828	9.34	15.37	3.00	0.97	2.00	1.00	14.94	3.73	35.38	522.65	19.99
7044	9.58	13.71	2.98	0.96	2.00	0.99	14.18	3.68	35.48	523.70	19.88

6. Discussion

For optimization, *Optimax* v0.6.1 program, developed by fourth author of this paper – Matej Borovinšek. Optimization process took about 2.5 h on laptop *Asus* X750LB (*Intel* i7-4500U, 8GB DDR3 1866Mhz, *Samsung* 840EVO 240GB SSD). Optimization with 100 generations, and population of 100, will generate 10.000 solutions. Those that do not meet the requirements set by the constraint functions g_1, g_2, g_3 and g_4 are discarded. Once those are disregarded, we are still left with thousands of results, all of which can theoretically be selected, but not all of them are optimal. Figures 5–7 are giving us a visual presentation of all of solutions, and it can clearly be seen that optimal solutions have formed a Pareto line. Those on the right from the Pareto line are selectable, but not optimal. If a solution would appear on the left from the Pareto line, it would mean, that this solution is now optimal, and solutions on the right from, it are not.

Results in Table, as expected, show that better performances of S/R machine, usually mean lower energy efficiency and higher investment cost.

One of the first steps for a warehouse planner would be to choose number of storage compartments N_x and N_y and number of aisles R, to set the physical size of the AS/RS system. Once this is known, investment expenses for building can be precisely calculated. Then, choosing the S/R machine in regard to the operating performances, according to the selected solutions, and thus the required number of S/R machines, will make investment expenses for S/R machines known. Then, it is possible to program each individual S/R machine (v_x, v_y, a_x, a_y) through WMS software to achieve cycle times and CO_2 footprint in accordance to selected solutions. Warehouse planners can decide if they wish to achieve better performances, but higher energy consumption, or the other way around.

What is not presented in the Table, are the worst solutions. We will just mentions that, one of the worst solutions for function f_{CT} is cycle time of over 170 s, while at the same time cost is very low at 282 €/TUL, and footprint is 16.96 acres of forest/year. This cycle is more than 136 s worse than the best solution, so, even though investments are very low, this cycle time is way too big for this solution to be considered. Worst solution for f_{IE} is 9.597 €/TUL, but cycle is very low at 29.37 s, and footprint is 24.10 acres of forest/year. This solution provides extremely low cycle times, but is extremely more expensive than the best. Worst solution for f_{FP} is 25.68 acres of forest/year (some 8 acres worse than the best solution), while cycle is excellent at 26.32 s, and investments are at very high 7.071 €/TUL. This comparison shows us, that even though we could actually choose from any of physically possible solutions to build an AS/RS, we can make an enormous mistake, and pick a solution, which is a lot more expensive, with much longer cycle time, and higher energy consumption, than the optimal. We can see, that, even though, individual functions can achieve better solutions than those presented in Table, it would seriously deteriorate solutions of other two functions. This is the essence of this model: not just achieving best results in any individual functions, but finding the best compromise between all three functions.

Conclusions

New multi-objective optimization model for designing AS/RS was presented in the paper. Since modern AS/RS are increasing in complexity, designing and optimizing them using conventional design analysis and processes is extremely demanding. As could be seen in discussion, the margin for error is quite high, and AS/RS planners, using this model, can achieve significant saves in investments, time and energy consumption. Once the AS/RS system is build, any organizational or changes in layout are extremely hard, and often not possible. Even if changes could be made, they will most certainly be very costly. It is therefore very important, to carefully plan the system, right in the initial stage of planning.

We could see in literature review chapter, that majority of researchers who built optimization models, optimized single objective function only, and it was only in later work, that real operating characteristics of S/R machines were considered. This work is based on research by Lerher (2005) and Lerher *et al.* (2013). Direct result comparison is possible, and both models provide results using NSGA II, but this model is improved, and adds energy efficiency into consideration. In difference to mentioned paper by Lerher *et al.* (2013) and Borovinšek *et al.* (2017), the suggested design model simultaneously optimizes different three objective functions named minimum: (1) "investment expenses", (2) "cycle time", (3) "CO_2 footprint", while results are limited by four constraint functions. The objective functions are described with a mathematical model, which contains decision variables x_i, $i \in \left[1, 8\right]$. This model also considers all relevant operational and physical parameters of the S/R machine, and investment and operating costs of the AS/RS. Since the problem is not linear, the method of NSGA II has been applied in order to optimize decision variables.

Further improvements of the presented model are possible by adding more variables and constraints, to achieve more precision by eliminating excess solutions. Model could be modified to optimize AS/RS with double-deep SR, since no similar models implement cycles for double-deep SR. A comparison of results could be made between single-deep and double-deep AS/RS to see how depth of SR influences cycle times, expenses and energy consumption. Lerher (2016), studied travel time models for double-deep SR, and influence of fill-grade factor on cycle times, which could be implemented in the presented model.

References

Altintas, O.; Avsar, C.; Klumpp, M. 2010. Change to green in intralogistics, in *The 2010 European Simulation and Modelling Conference: Proceedings*, 25–27 October 2010, Ostend, Belgium, 373–377.

Ashayeri, J.; Gelders, L.; Van Wassenhove, L. 1985. A microcomputer-based optimization model for the design of automated warehouses, *International Journal of Production Research* 23(4): 825–839. https://doi.org/10.1080/00207548508904750

Bafna, K. M.; Reed, R. 1972. An analytical approach to design of high-rise stacker crane warehouse systems, *Journal of Industrial Engineering* 4(10): 8–14.

Bekker, J. 2013. Multi-objective buffer space allocation with the cross-entropy method, *International Journal of Simulation Modelling* 12(1): 50–61. https://doi.org/10.2507/IJSIMM12(1)5.228

Borovinšek, M.; Ekren, B. Y.; Burinskienė, A.; Lerher, T. 2017. Multi-objective optimisation model of shuttle-based storage and retrieval system, *Transport* 32(2): 120–137. https://doi.org/10.3846/16484142.2016.1186732

Bortolini, M.; Accorsi, R.; Gamberi, M.; Manzini, R.; Regattieri, A. 2015a. Optimal design of AS/RS storage systems with three-class-based assignment strategy under single and dual command operations, *The International Journal of Advanced Manufacturing Technology* 79(9–12): 1747–1759. https://doi.org/10.1007/s00170-015-6872-1

Bortolini, M.; Faccio, M.; Gamberi, M.; Manzini, R. 2015b. Diagonal cross-aisles in unit load warehouses to increase handling performance, *International Journal of Production Economics* 170: 838–849. https://doi.org/10.1016/j.ijpe.2015.07.009

Bortolini, M.; Faccio, M.; Ferrari, E.; Gamberi, M.; Pilati, F. 2017. Time and energy optimal unit-load assignment for automatic S/R warehouses, *International Journal of Production Economics* 190: 133–145. https://doi.org/10.1016/j.ijpe.2016.07.024

Bozer, A. Y.; White, J. A. 1984. Travel-time models for automated storage/retrieval systems, *IIE Transactions* 16(4): 329–338. https://doi.org/10.1080/07408178408975252

Colicchia, C.; Creazza, A.; Dallari, F.; Melacini, M. 2016. Eco-efficient supply chain networks: development of a design framework and application to a real case study, *Production Planning & Control: the Management of Operations* 27(3): 157–168. https://doi.org/10.1080/09537287.2015.1090030

Diao, X.; Li, H.; Zeng, S.; Tam, V. W.; V.; Guo, H. 2011. A Pareto multi-objective optimization approach for solving time-cost-quality tradeoff problems, *Technological and Economic Development of Economy* 17(1): 22–41. https://doi.org/10.3846/13928619.2011.553988

Foster, D. 1970. *Automatic Warehouse*. Iliffe. 272 p.

Graves, S. C.; Hausman, W. H.; Schwarz, B. L. 1977. Storage-retrieval interleaving in automatic warehousing systems, *Management Science* 23(9): 935–945. https://doi.org/10.1287/mnsc.23.9.935

Gu, J.; Goetschalckx, M.; McGinnis, L. F. 2007. Research on warehouse operation: a comprehensive review, *European Journal of Operational Research* 177(1): 1–21. https://doi.org/10.1016/j.ejor.2006.02.025

Gudehus, T. 1973. *Grundlagen der Kommissioniertechnik. Dynamik der Warenverteil- und Lagersysteme*. Cornelsen Verlag GmbH. 214 S. (in German).

Hausman, W. H.; Schwarz, L. B.; Graves, S. C. 1976. Optimal storage assignment in automatic warehousing systems, *Management Science* 22(6): 629–638. https://doi.org/10.1287/mnsc.22.6.629

Hompel, M.; Schmidt, T. 2007. *Warehouse Management: Automation and Organisation of Warehouse and Order Picking Systems*. Springer. 357 p. https://doi.org/10.1007/978-3-540-35220-4

Hwang, H.; Lee, S. B. 1990. Travel-time models considering the operating characteristics of the storage and retrieval machine, *International Journal of Production Research* 28(10): 1779–1789. https://doi.org/10.1080/00207549008942833

Janilionis, V. V.; Bazaras, Ž.; Janilionis, V. 2016. Comparison of routing algorithms for storage and retrieval mechanism in cylindrical AS/RS, *Transport* 31(1): 11–21. https://doi.org/10.3846/16484142.2014.995130

Lerher, T. 2016. Travel time model for double-deep shuttle-based storage and retrieval system, *International Journal of Production Research* 54(9): 2519–2540. https://doi.org/10.1080/00207543.2015.1061717

Lerher, T. 2005. *Model načrtovanja regalnih skladiščnih sistemov*. Doktorska disertacija. Univerza v Mariboru, Slovenija. 192 s. (in Slovenian).

Lerher, T. 2013. Modern automation in warehousing by using the shuttle-based technology, in D. Arent, M. Freebush (Eds.). *Automation Systems of the 21st Century: New Technologies, Applications and Impacts on the Environment & Industrial Processes*, 51–86.

Lerher, T.; Borovinšek, M.; Šraml, M. 2013. A multi objective model for optimization of automated warehouses, in J. Cheung, H. Song (Eds.). *Logistics: Perspectives, Approaches and Challenges*, 87–110.

Lerher, T.; Edl, M.; Rosi, B. 2014. Energy efficiency model for the mini-load automated storage and retrieval systems, *The International Journal of Advanced Manufacturing Technology* 70(1–4): 97–115. https://doi.org/10.1007/s00170-013-5253-x

Lerher, T.; Ekren, B. Y.; Dukic, G.; Rosi, B. 2015a. Travel time model for shuttle-based storage and retrieval systems, *The International Journal of Advanced Manufacturing Technology* 78(9–12): 1705–1725. https://doi.org/10.1007/s00170-014-6726-2

Lerher, T.; Ekren, Y. B.; Sari, Z.; Rosi, B. 2015b. Simulation analysis of shuttle based storage and retrieval systems, *International Journal of Simulation Modelling* 14(1): 48–59. https://doi.org/10.2507/IJSIMM14(1)5.281

Lerher, T.; Potrč, I. 2006. The design and optimization of automated storage and retrieval systems, *Strojniški vestnik – Journal of Mechanical Engineering* 52(5): 268–291.

Marchet, G.; Melacini, M.; Perotti, S.; Tappia, E. 2013. Development of a framework for the design of autonomous vehicle storage and retrieval systems, *International Journal of Production Research* 51(14): 4365–4387. https://doi.org/10.1080/00207543.2013.778430

Ries, J. M.; Grosse, E. H.; Fichtinger, J. 2017. Environmental impact of warehousing: a scenario analysis for the United States, *International Journal of Production Research* 55(21): 6485–6499. https://doi.org/10.1080/00207543.2016.1211342

Roodbergen, K. J.; Vis, I. F. A. 2009. A survey of literature on automated storage and retrieval systems. *European Journal of Operational Research* 194(2): 343–362. https://doi.org/10.1016/j.ejor.2008.01.038

Rouwenhorst, B.; Reuter, B.; Stockrahm, V; Van Houtum, G. J.; Mantel, R. J.; Zijm, W. H. M. 2000. Warehouse design and control: framework and literature review, *European Journal of Operational Research* 122(3): 515–533. https://doi.org/10.1016/S0377-2217(99)00020-X

Smew, W.; Young, P.; Geraghty, J. 2013. Supply chain analysis using simulation, Gaussian process modelling and optimisation, *International Journal of Simulation Modelling* 12(3): 178–189. https://doi.org/10.2507/IJSIMM12(3)4.239

Tappia, E.; Marchet, G.; Melacini, M.; Perotti, S. 2015. Incorporating the environmental dimension in the assessment of automated warehouses, *Production Planning & Control: the Management of Operations* 26(10): 824–838. https://doi.org/10.1080/09537287.2014.990945

Tappia, E.; Roy, D.; De Koster, R.; Melacini, M. 2017. Modeling, analysis, and design insights for shuttle-based compact storage systems, *Transportation Science* 51(1): 269–295. https://doi.org/10.1287/trsc.2016.0699

UBA. 2016. *Umweltbundesamt – UBA*. Dessau-Roßlau, Deutschland. Available from Internet: http://www.umweltbundesamt.de (in German).

Vasili, M. R.; Tang, S. H.; Vasili, M. 2012. Automated storage and retrieval systems: a review on travel time models and control policies, in R. Manzini (Ed.). *Warehousing in the Global Supply Chain*, 159–209.

Vidovics, H. 1994. *Die Systemanalyse und Umschlagleistungen von Regalförderzeugen mit Mehrfachlastaufnahmemitteln*. Dissertation. Technische Universität Graz, Österreich. 213 S. (in German).

Vössner, S. 1994. *Spielzeit Berechnung von Regalförderzeugen*. Dissertation. Technische Universität Graz, Österreich. (in German).

Zrnić, Đ.; Savić, D. 1990. *Simulacija procesa unutrašnjeg transporta*. Univerzitet u Beogradu, Srbija. 251 p. (in Serbian).