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Multi-objective optimization model for double-deep automated storage and retrieval systems

In the following paper, a new multi-objective optimization model for optimizing performances, costs and energy consumption of an automated storage and retrieval system with double-deep storage rack, will be presented. While majority of literature considers single objective function at a time, this model simultaneously optimizes three objective functions (minimum: investment costs, cycle time, CO_2 emission) for a double-deep AS/RS. Analyses are performed in regard to different fill-grade factor of SR. For optimization, NSGA II algorithm is used as a tool to find Pareto optimal solutions. Since AS/RS require high initial investments, and are not flexible in terms of layout or other organizational changes once to system is built, this model could potentially be a very useful tool for warehouse designers in initial stages of planning.

Keywords: *Automated storage and retrieval systems, double-deep storage racks, multi-objective optimization, performance analysis.*

1. INTRODUCTION

Warehouses are a crucial part of the supply chain. Some of their major functions are: the optimization of supply chains, securing the continuation of productivity and supplying, performing various value-added services, reducing transport expenses, buffering differences between production and demand quantities, etc. Reducing the initial investments, and as well the operating cost of warehouses is a neverending job performed by warehouse designers.

AS/RS are usually comprised of storage rack (SR), storage and retrieval machines (S/R machines), and accumulating conveyors. Two major types are mini-load, and unit-load AS/RS (Figure 1).

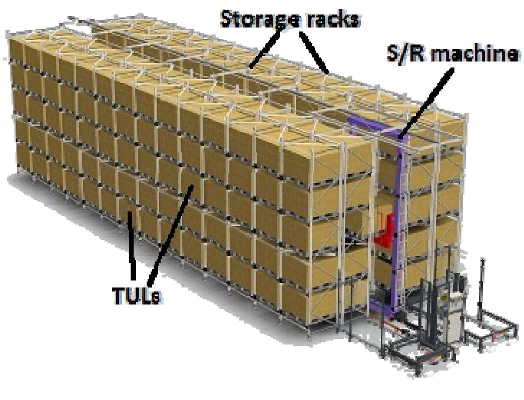

Figure 1. Illustration of double-deep unit-load SR

In countries with high wages, land and energy prices, high initial investment in automated storage and retrieval system (AS/RS) is logical, since reduced expences on wages and energy consumption will cause the investment return quickly through lower operating costs.

Further, if high throughput of the system is not extremely important, placing double deep SR will additionaly cut down on costs. A save of up to 50% of floor space for aisles (and therefore a land required) will be achieved [1]. In warehouses where a temperature regime is important, reduced volume of storage rack (SR) zone will allow further savings in energy consumption for heating and cooling systems.

AS/RS has been a matter of interest for many researchers over the last few decades. Since the 1973 and Gudehus [2] who was first to present formulas for SCC and DCC, while considering the impact of accelaration and decceleration on cycle times (unlike earlier authors), many authors have published papers in this field. Hausman et al. [3] in 1976, Graves et al. [4] in 1977, Bozer et al. [5] in 1984, Hwang and Lee [6] in 1990, Lerher et al. in 2005 [7], and 2006 [8], etc. are among the authors who published research of AS/RS.

Only a handfull of publications research double deep SR. Oser et al. [9] in 1998, and 2004 [10] presented travel time models for double-deep mini-load AS/RS. Sari et al. [11] in 2005 presented travel time models for 3D flow-rack AS/RS. Bartholdi and Hackman [12] in 2007, presented a configuration, where double-deep AS/RS has two single deep SR, placed one next to the other, and pallets are stored in first or second storage lane of SR. Each lane is independently accessible, and pallets can be stored in any lane, or at any level. Lerher et al. [1] in 2010 presented a travel time model for calculation of cycle times for unit-load double-deep AS/RS, considering real operating characteristics of S/R machine.

Multi-objective optimization was studied by following authors:

Diao et al. [13] in 2011 introduced three objective functions: cost, cycle time, and material handling quality as a way of grading the performance of a system. Pareto optimisation approach utilizing NSGA II algorithm was used to find solutions. Lerher et al. [14], [15] in 2013 researched multi-objective optimization for

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a CBS/RS and introduced energy efficiency. Bekker [16] in 2013 published a economic approach to optimize the throughput rate and allocated buffer space. Smew et al. [17] also in 2013 published a simulation study of maximising customer service quality and minimising working activities.

While there are many publications concerning AS/RS, not many consider double-deep racks or multi objective optimization of several objective functions simultaneously. Since there are no publications which simultaneously optimize investment costs, cycle times and CO_2 emmision of AS/RS with double-deep SR, the presented model will provide a useful tool for a warehouse planners who consider the benefits of double SR mentioned in this chapter. AS/RS systems are not very flexible after they are built, and any changes in layout, even if possible, are very expensive. Therefore, a careful planning in the initial phase is extremely important.

2. SIMULATION AND OPTIMIZATION

Like it is mentioned in the introduction, warehouse planners have a constant goal towards maximization of efficiency by reducing costs and increasing quality. Complexity of modern AS/RS, conditions necessity for use of simulation methods for analysis of material flow within the system. Advantage of simulation over analytical methods is that it provides more precise results, and it does not require expensive and long tests to be performed, and results obtained in exploiting conditions to be confirmed. Simulation offers variety of possibilities, especially because it allows study of processes which could occur in theoretical conditions, and as well as those that exist in real cases [18].

Optimization problems seek a point where a particular function is minimal or maximal. Quite often, it is required for this point to be within some limitations.

Introducing more than one objective function into an optimization problem at once, will add to higher complexity. For example, when selecting an electric reach-truck, one would want it to be energy efficient, and fast. Better performances cause higher energy consumption, therefore making these two objectives conflicting. Therefore, a compromise must be made. Two solutions could be found: one where the reach-truck is maximally energy efficient, but has low performances; and one with maximum performances, but low energy efficiency. In optimization, we have these two, and an infinite number of solutions, where reach-truck is some sort of compromise between performances and energy efficiency. The entire set of these solutions, that can't be improved is known as the Pareto set. The curved line created plotting energy efficiency solutions against performance solutions is known as the Pareto frontier [12].

The presented model minimizes three objective functions of an unit-load AS/RS with double-deep SR at once: investment costs, cycle time, and CO_2 emission. Optimization of objective functions is in accordance with project restraints and conditions.

3. MODEL FOR DESIGNING UNIT-LOAD DOUBLE-DEEP AS/RS

For the multi-objective optimization of functions: investment costs - cycle time - CO_2 emission, the method with genetic algorithms was used. In order to find the Pareto optimal solutions on the Pareto line, the NSGA II algorithm was used [19].

3.1 Minimizing investment costs

Investment cost are comparable to cycle time and energy efficiency. Reduction of cost could be achieved by purchasing S/R machines with lower performances and lower energy efficiency. Minimizing the investment costs are described as follows:

$$\text{function: } \min f_c(x_i); \qquad i \in [1,8] \tag{1}$$

NOTE: Variables x_i are defined in chapter 5.

3.2 Minimizing cycle time

At the same time, more powerful motors of S/R machines will shorten cycle times, but increase expenses in the exploitation phase as they will consume more energy (lower energy efficiency). To minimize cycle times, following expression is presented:

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

NOTE: Variables x_i are defined in chapter 5.

3.3 Minimizing CO_2 emission

Lastly, if we want to achieve maximum energy efficiency, we will have to do so on the account of the performances, that is, cycle time. Energy efficient S/R machines, as a rule, are more expensive. Minimizing CO_2 emission is described with expression:

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

NOTE: Variables x_i are defined in chapter 5.

Therefore, we can see that these objective functions influence each other. Proposed model will provide Pareto set of solutions, which all are optimal, but engineers will have to choose, which one of the functions is more relevant than the other.

4. DEFINITION OF THE DESIGN MODEL

When designing the presented model, the following assumptions are applied:

1. The unit-load AS/RS is divided into picking aisles. On both side of aisles is double-deep storage rack.
2. The double-deep SR has rectangular shape. The I/O location is located on the lower right corner of the SR.
3. The S/R machine performs both SCC and DCC. It can manipulate one TUL at a time.
4. TUL's are stored in second storage lane of SR, as long as there are free locations. This will reduce

the number of re-arrangements in a retrieval cycle.

5. The number of MHD - S/R machines is equal to the number of picking aisles ($n_{MHD} = R$).
6. The S/R machine is equipped with attachments to reach both first and second lane in SR.
7. The S/R machine has performances which are known. The length and height of SR are also known.
8. The S/R machine performs movement through aisle and lifting/lowering simultaneously.
9. Dimensions of SR are enough for S/R machine to reach maximal velocity in both x and y axis.
10. Random storage/retrieval assignment rule has been applied.

4.1 Investment costs definition

The investment in buying the land per square meter I_1:

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

The investment for building foundations of the warehouse building I_2:

$$\begin{aligned} I_2 = \Big[\big(\left(nW_{pal} + 2a_1 + (n-1)a_2 + a_3 \right) N_x + \\ + a_4 + a_5 + L_{TZ} \big) \cdot \\ \cdot \left(R\left(2G_{RO} + W_{aisle}\right) + (R-1)b_4 + 2b_5 \right) \Big] \cdot C_2 \end{aligned} \tag{5}$$

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

$$\begin{aligned} I_3 = \Big[\big(\left(nW_{pal} + 2a_1 (n-1)a_2 + a_3 \right) N_x + \\ + a_4 + a_5 + L_{TZ} \big) \cdot \\ \cdot \left(c_1 + \left(H_{pal} + c_2 + c_3 \right) N_y - c_2 + c_4 \right) \Big] \cdot C_3 \end{aligned} \tag{6}$$

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

$$\begin{aligned} I_4 = \Big[\big(\left(nW_{pal} + 2a_1 + (n-1)a_2 + a_3 \right) N_x + \\ + a_4 + a_5 + L_{TZ} \big) \cdot \\ \cdot \left(R\left(2G_{RO} + W_{aisle}\right) + (R-1)b_4 + 2b_5 \right) \Big] \cdot C_4 \end{aligned} \tag{7}$$

The investment for buying upright frames of SR I_5:

$$I_5 = \left((N_x + 1) \cdot 8R \right) \cdot C_5 \tag{8}$$

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

$$I_6 = \left(N_x \cdot N_y \cdot 8R \cdot L_v \right) \cdot C_6 \tag{9}$$

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

$$I_7 = 4R \cdot C_7 \tag{10}$$

$$I_8 = Q \cdot C_8 \tag{11}$$

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

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

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

where:

$$\begin{aligned} L_{WAR} = \left(nW_{pal} + 2a_1 + (n-1)a_2 + a_3 \right) N_x \\ + a_4 + a_5 + L_{TZ} \end{aligned} \tag{14}$$

$$H_{WAR} = c_1 + \left(H_{pal} + c_2 + c_3 \right) N_y - c_2 + c_4 \tag{15}$$

$$W_{WAR} = R\left(2G_{RO} + W_{aisle}\right) + (R-1)b_4 + 2b_5 \tag{16}$$

The investment in purchasing electric pedestrian runners I_{11}, and electric forklift trucks I_{12}:

$$I_{11} = S_{TV} \cdot C_{11} \tag{17}$$

$$I_{12} = S_{RV} \cdot C_{12} \tag{18}$$

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

$$I_{13} = R \cdot C_{13} \tag{19}$$

The investment in the accumulating conveyor I_{14}:

$$I_{14} = C_{14} + 4R \cdot C_{15} \tag{20}$$

The price of WMS software I_{15}:

$$I_{15} = 245.000\,€ \tag{21}$$

The expression for the objective function Min. f_C is following:

$$f_C = I_1 + I_2 + \cdots + I_{11} \tag{22}$$

NOTE: All of the symbols are defined in nomenclature.

4.2 Cycle time definition

Proposed model is based on the SCC and DCC, which takes into account the real driving characteristics of the S/R machine. Following expressions for cycle times by Gudehus, 1973 [2] are utilized:

$$T(SCC) = \begin{cases} t_{01} + \frac{L_{SR}}{v_x} + \frac{2v_x}{a_x} + \frac{Av_x}{L_{SR}^2 a_y} + \\ + \frac{A^2 v_x}{3L_{SR}^3 v_y^2} - \frac{Av_x^2}{L_{SR}^2 a_x v_y} & b \le 1 \\ t_{01} + \frac{A}{L_{SR} v_y} + \frac{2v_y}{a_y} + \frac{L_{SR}^2 v_y}{Aa_x} + \\ + \frac{L_{SR}^3 v_y}{3Av_x^2} - \frac{L_{SR}^2 v_y^2}{Aa_y v_x} & b > 1 \end{cases} \tag{23}$$

$$T(DCC) = \begin{cases} t_{02} + \frac{4L_{SR}}{3v_x} + \frac{3v_x}{a_x} + \frac{3Av_x}{2L_{SR}^2 a_y} + \frac{A^3 v_x^2}{30L_{SR}^5 v_y^3} + \\ + \frac{A^2 v_x}{2L_{SR}^3 v_y^2} - \frac{3Av_x^2}{2L_{SR}^2 a_x v_y} & b \le 1 \\ t_{02} + \frac{4A}{3L_{SR} v_y} + \frac{3v_y}{a_y} + \frac{3L_{SR}^2 v_y}{2Aa_x} + \frac{L_{SR}^5 v_y^2}{30A^2 v_x^2} + \\ + \frac{L_{SR}^3 v_y}{2Av_x^2} - \frac{3L_{SR}^2 v_y^2}{2Aa_y v_x} & b > 1 \end{cases} \tag{24}$$

$$b = \frac{H_{SR}}{L_{SR}} \cdot \frac{v_x}{v_y} \tag{25}$$

In a double-deep AS/RS, SCC and DCC have additional times (t_{01}, t_{02}) for telescoping forks of the S/R machine, and for the re-arrangement of the TUL in the first row, when TUL in the second row is to be retrieved. Chance that the re-arrangement will occur, depends on the fill-grade factor. Our model implements the analysis of this additional cycle time for re-arrangement from publication by Lerher et al [1].

The throughput capacity for combined SCC and DCC equals the following expression:

$$\lambda(p) = \frac{2 \cdot T_{shift}}{p \cdot T(SCC) + 2(1-p) \cdot T(DCC)} \cdot n_{MHD} \tag{26}$$

4.3 CO_2 emission definition

E_{CO2} represents the amount of CO_2 emitted into the air, and function f_T expresses the surface of the forest required to neutralize this pollution in 10 years. To obtain more information on operating characteristics of the S/R machine, and it's influence on energy consumption and CO_2 emission, see paper by Lerher et al. [20].

Minimum CO_2 emission is expresed by following formula:

$$f_T = E_{CO_2} \cdot 100\text{m}^2 \left(\text{m}^2 \; of \; forest/10 years\right) \tag{27}$$

5. ANALYSIS: AN EXAMPLE OF DESIGNING ASRS

The decision variables x_i (N_x, N_y, V_x, a_x, V_y, a_y, R, S,) are defined as follows:

$x_1 = N_x$ – number of SC in the horizontal (x) direction,
$x_2 = N_y$ – 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,
$x_7 = R$ – number of picking aisles in a warehouse,
$x_8 = S$ – number of S/R machines ($S = R$).

The optimum design of the ASRS was searched for and it should suit the following project constraints:
L_{WAR} (20 – 100) m – the length of the warehouse
W_{WAR} (20 – 80) m – the width of the warehouse
H_{WAR} (10 – 25) 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,
$g_3 = Q <$ (min$Q$ + 20%) - capacity of the warehouse must not be more than 20% higher than the required capacity,
$g_4 = S = R$ - number of S/R machines is 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 = 15.000 pallets, throughput capacity, of the warehouse P_f = 200 pallets/day;
2. *Operational parameters of the AS/RS*: W_{pal} = 800 mm, L_{pal} = 1200 mm, H_{pal} = 1200 mm, m = 1000 kg, n = 3, $a_1 = a_2 = a_3$ = 120 mm, a_4 = 1065 mm, a_5 = 2000 mm, b_1 = 92,5 mm, b_2 = 1100 mm, b_3 = 150 mm, b_4 = 400 mm, b_5 = 500 mm, c_1 = 920 mm, c_2 = 300 mm, c_3 = 110 mm, c_4 = 1000 mm, t_{01} = 8 s, t_{02} = 12 s, n(SC) = 80, n(DC) = 120, L_{TZ} = 20.000 mm, W_{RD} = 1500 mm, L_{RD} = 2000 mm;
3. Material handling equipment: the single-aisle ASRS - Swisslog Vectura: G_{RD} = 1200 kg, H_{RD} = 24.000 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, v_z = 0,3 m/s^2;
4. Investment costs: 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} = 12.750 €/piece, C_{12} = 15.250 €/piece, C_{13} = 430.000 €/piece, C_{14} = 40 €/m, C_{15} = 500 €/m.

6. DISSCUSION OF THE RESULTS

Optimization of 100 generation, and 150 population provides 15.000 solutions. Those that do not meet the limitations of constraint functions g_1, g_2, g_3 and g_4, are disregarded. Best provided results in the Table 1, show us, as expected, that three objective functions are conflicting in regard to one another. Choosing AS/RS system with minimal initial investments, means that a compromise will have to be made, and S/R machines with lower performances and energy efficiency will have to be used.

In case where we decide that performances are important, bigger investments will have to be made, but will also cause higher energy consumption.

Lastly, if we decide that the most important aspect of AS/RS system will be its energy efficiency, results show that, a compromise will have to be made, and S/R machines with lower velocity performances will have to be selected.

7. CONCLUSION

In the presented paper, a new multi-objective optimization model of unit-load AS/RS with double-deep SR was presented. Literature review showed that, while many authors researched AS/RS, not many publications exist, where double-deep SR are introduced. On top of that, no existing models simultaneuosly optimize three objective functions: minimum investment cost - cycle times - CO_2 emission. Presented model provides warehouse designers with entire set of solutions, all of which are optimal, and one can be selected, depending on importance of individual objective function to the investor. Proper solution selection is very important, since AS/RS are not very flexible to changes.

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NOMENCLATURE

AS/RS	automated storage and retrieval system
SR	storage rack
S/R	storage and retrieval
SC	storage compartment
SCC	single command cycle
DCC	dual command cycle
T(SCC)	mean single command travel time
T(DCC)	mean dual command travel time
NSGA II	non-dominated sorting genetic algorithm II
CBS/RS	class based storage and retrieval systems
MHD	material handling device
I/O	input/output location
CO_2	carbon dioxide
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

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
E_{CO2} amount of CO_2 which is emitted
n_{MHD} number of material handling devices
S_{RD} number of S/R machine
R number of picking aisles
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
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
v_z velocity of telescoping the forks of MHD
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 pedestrian runners
I_{12} investment for buying electric forklift trucks
I_{13} investment in single aisle AS/RS
I_{14} investment in accumulating conveyor
I_{15} the price of warehouse management software
W_{pal} width of the pallet
H_{pal} height of the pallet
L_{pal} length of the pallet
m mass (weight) of the pallet
a_1, a_2 the safety addition to the width of the SC
a_3 the width of the upright frame
a_4 length of pick-and-deposit place in SR
a_5 the addition to the end of the warehouse
b_4 the safety spacing between racks that are placed close to each other
b_5 the addition to the end of the warehouse
c_1 the deviation of the SC from the floor
c_2 the height between TUL and next rack frame
c_3 the thickness of the rack frame
c_4 the safety addition to the height of the warehouse
n number of pallets in storage compartment
t_{01} additional time for SCC
t_{02} additional time for DCC
W_{RD} width of the S/R machine
L_{RD} length of the S/R machine
G_{RD} max 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 electric pedestrian runner
C_{12} cost of buying electric forklift truck
C_{13} cost of single aisle
C_{14} cost of buyng accumulating conveyor
C_{15} cost of buying diverted element

Table 1. Best 5 solutions for each objective function, with $n(pop)$=150, $n(gen)$=100, and fill-grade factor of α = 0,85

ID	*Nx*	*Ny*	V_x [m/s]	a_x [m/s²]	V_y [m/s]	a_y [m/s²]	V_z [m/s]	*S = R*	f_C [sek]	f_T [€/PM]	f_F [acres of forest/year]
min Cycle time (best five solutions sorted by minimum cycle time)											
11962	9,54	14,58	3,00	1,00	2,00	1,00	0,30	5,91	**57,22**	538,82	19,46
6172	10,11	14,68	3,00	0,97	1,98	0,88	0,30	5,93	**57,50**	538,82	19,46
12974	11,09	14,69	3,00	1,00	2,00	1,00	0,30	5,80	**58,09**	525,86	19,26
5170	11,35	14,56	2,99	0,98	1,99	0,82	0,30	5,53	**58,46**	525,86	19,26
4160	11,27	14,87	2,96	0,91	1,97	0,65	0,30	5,63	**59,00**	525,86	19,26
min CO_2 footprint (best five solutions sorted by minimum CO_2 footprint)											
12679	17,45	14,90	3,00	1,00	2,00	1,00	0,30	5,54	64,05	435,66	**18,34**
10296	18,22	13,47	3,00	1,00	2,00	1,00	0,30	4,89	64,75	441,40	**18,36**
11072	16,61	14,95	3,00	1,00	2,00	1,00	0,30	4,48	62,99	455,01	**18,47**
12346	14,89	13,51	3,00	1,00	2,00	1,00	0,30	5,87	61,53	468,83	**18,74**
12897	13,25	14,75	3,00	1,00	2,00	1,00	0,30	5,66	59,96	492,38	**18,91**
min Investments (best five solutions sorted by minimum investment cost)											
1683	17,16	14,58	2,72	0,04	0,49	0,55	0,26	5,62	80,41	**435,66**	18,34
1766	18,15	13,56	1,82	0,12	2,00	0,18	0,25	5,77	80,77	**441,40**	18,36
3979	16,47	14,70	2,48	0,95	1,80	0,77	0,30	5,20	66,30	**455,01**	18,47
2223	16,97	13,99	1,93	0,01	1,73	0,46	0,24	5,60	79,11	**459,88**	18,48
1359	14,21	14,94	1,54	0,10	1,76	0,12	0,14	5,74	86,32	**466,62**	18,75