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A simulated annealing approach for optimizing layout design of reconfigurable manufacturing system based on the workstation properties

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Abstract: The problem studied focuses on facility layout problems (FLP) that arise in reconfigurable manufacturing systems. The goal is to reduce the distance traveled by an automatic guided vehicle (AGV) to move products between several workstations. The proposed solving approach takes into account the empty and loaded travels made by this vehicle as well as the machine's properties (i.e. layout, orientations, shapes of workstations). We use simulated annealing to optimize this problem. The findings demonstrate the impact of the modification of the layout, the orientation, the shape, and the benefits of using the three together. In addition, we study two different ways to optimize the solution: each property independently (i.e. sequentially) or all properties together. Preliminary results show that the sequential method outperforms the latter in terms of distance gain.

Keywords: Layout design, Reconfigurable Manufacturing System, optimization, simulated annealing

1. INTRODUCTION

The problem studied belongs to the Facility Layout Problem (FLP) arising in the reconfigurable manufacturing system (RMS) (Yelles-Chaouche et al., 2020)(Maganha et al., 2019). Let us start by defining some terms commonly used in the field: the layout is the placement of the workstations; the reconfiguration is the transition from one layout to another.

This problem has been introduced in 1957 by Koopmans and Beckmann (Koopmans and Beckmann, 1957). Facility layout problems are defined as the assignment of departments or workstations by considering the minimization of material handling. Between 20 and 50% of the total operating expenses within manufacturing are attributed to material handling. Furthermore, it is generally agreed that effective facilities planning can reduce these costs by at least 10 to 30% (Tompkins, 2010). Recent studies are oriented towards using sustainability criteria in the reconfiguration of production systems (Khezri et al., 2021).

FLP is a large paradigm that integrates several research domains (Drira et al., 2007) (Al-Zubaidi et al., 2021). We are interested in some of them such as the formulation of the problem, the constraints, and the solving approach.

The formulation of a Facility Layout Problem can be done in two different ways. The first is the continued formulation. Some papers represent it in a planar plan with facilities including different sizes or shapes (Ghassemi Tari and Neghabi, 2015). The second is the discrete formulation where the plant site is divided into several sites in which facilities or workstations will be installed (Wang et al., 2005). Sites can even be divided into smaller squares to take into account the irregular shape of the facility (Bock and Hoberg, 2007). Guan et al. (2012) use a graph-based representation of the plant to minimize handling and reconfiguration costs. The authors take into account the empty and the loaded travels made by automatic guided vehicles (AGVs) to transport products between workstations. They propose an electromagnetic mechanism (REM) heuristic method to find good solutions.

FLP can have several constraints. One of them is to determine the place of pick-up and delivery points on the workstation (Friedrich, 2018) (Kim and Goetschalckx, 2005). Kim and Kim (2000) minimize the total distance of material flows between the pick-up and delivery points by taking into account the rotation of facility. They develop a two-phase algorithm in which an initial layout is generated in the construction phase and is improved using four improvement methods applied iteratively in the improvement phase.

The FLP is an NP-hard problem so it is difficult to find optimal solutions (Garey and Johnson, 2009). Therefore, two possible solving approaches exist for FLP. The first one is the exact method, to find the optimal solution (Kouvelis and Kim, 1992). The second one is the approximated approach. An optimal solution method can be used for small problems, but not for large problems, especially because the computation time is too long. It is therefore necessary to use an approximated method such as a metaheuristic (Hao et al., 1999). Chwif et al. (1998) optimize the FLP using Simulated Annealing (SA). This metaheuristic has been introduced in 1983 by Kirkpatrick (Kirkpatrick et al., 1983). The interest of this algorithm lies in the fact that it can, under certain conditions, find the best solution (Aarts et al. 2005).

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The problem we are interested in is the reduction of the distance traveled by an AGV to move products between several workstations. We take into account in our solving approach the empty trips made by this vehicle. We suppose that the workstations can be moved in the workshop. In addition to the layout of the workstations, we also take into account the orientation and the shape of the workstations. Given the complexity of this problem, we are using metaheuristic SA to solve our problem so that it will be possible to tackle larger problems in terms of the number of workstations.

In the next section, we describe the problem with the possible shapes and orientations of the workstations. In section three, we explain how we model and solve the problem. In the last section, we show the preliminary results.

2. DEFINITION OF THE PROBLEM

The transportation demand will be represented by a product flow from one workstation to another. An AGV is used to transport the products. The goal is to travel the shortest distance with the AGV. To achieve this, we consider the possibility of modifying the layout of all the workstations as well as their orientation and shape.
A site is a place where a workstation is assigned. These workstations are linked together by bidirectional paths used by the AGV.
Two kinds of travel are made by the AGV:

- Travels carrying a product are also called product flow. The AGV will start from a pick-up node (P) and go to a delivery node (D).
- Travels without product are also called empty transport flow. The AGV will move from a delivery node to a pick-up node.

2.1. *Working hypotheses*

To delineate our study, we make the following assumptions:

- The number of workstations is the same as the number of sites.
- A site can receive only one workstation and a workstation can be assigned to only one site.
- The path segments (i.e. edges) are bidirectional and the AGV travels along the shortest path.
- An AGV can transport only one product at a time.
- Workstations can be oriented.
- A workstation has one entry: the delivery node (D) and one exit: the pick-up node (P). These nodes are not mixed up.

2.2. *Orientation and shape of workstations*

The originality of our work is to take into account the orientation of the workstations set in the workshop. By setting the orientation of the workstations, we aim to reduce the distances covered by the AGV. The nodes of delivery (D) and pick-up (P) are represented by triangles oriented towards the outside (P) or the inside (D) of the workstation. 5 workstation shapes will result from the location of these nodes:

1. U and U' shapes. In this case, the pick-up (P) and delivery (D) nodes are located on the same edge. If we successively rotate the workstation by 90° three times, we get four different orientations. If we start again by swapping the points P and D, we get four more orientations. We call U (figure 1) the shape with P on the left and D on the right in orientation 1 and U' (figure 2) the shape with P on the right and D on the left in orientation 1.

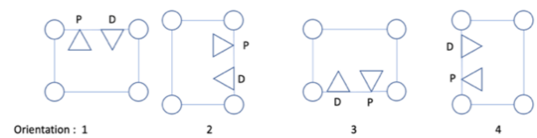

Figure 1. Possible orientations for a U-shape

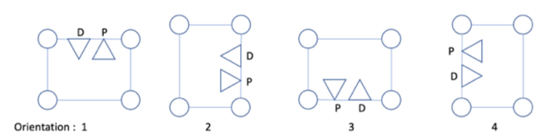

Figure 2. Possible orientations for an U'-shape

2. L and L' shapes. In this case, the pick-up (P) and delivery (D) nodes are located on two adjacent edges. As for the U-shape, we have two series of four possible orientations: the L-shape with P on top and D on the right for orientation 1 (figure 3) and the L' with P on the right and D on top for orientation 1 (figure 4).

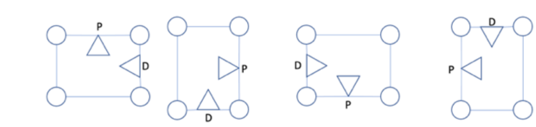

Figure 3. Possible orientations for an L-shape

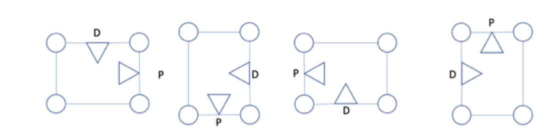

Figure 4. Possible orientations for an L'-shape

3. I-shape. In this case, the pick-up (P) and delivery (D) nodes are located on opposite edges of each other. Therefore, we have four possible orientations (figure 5).

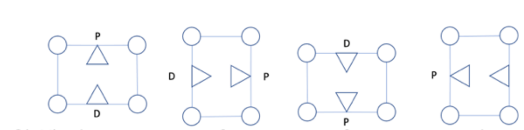

Figure 5. Possible orientations for an I-shape

Let us consider a set of n sites; the following notation is used to describe the sites, the workstations, and their properties:

- w_j: layout of the workstation on-site j, $w_j \in \{1, .., n\}$
- o_j: orientation of workstation on-site j, $o_j \in \{1, .., 4\}$
- s_j: shape of workstation on-site j, $s_j \in \{U, U', I, L, L'\}$

3. PROBLEM MODELING AND SOLVING

3.1. Problem modeling

The problem studied is modeled by a graph. First, we start with an empty graph on which we add the sites delimited by path segments. The example of figure 6 shows 9 rectangular sites between nodes identified by values 1 to 16.
Then, we add the workstations on each site with their pick-up and delivery nodes. The nodes of pick-up node (P) will be associated with the orange triangles and the delivery node (D) will be associated with the blue triangles. Each site of figure 6, contains the pick-up and delivery nodes (identified by values 17 to 34) of the 9 workstations. As explained in section 2.2, orientation and shape are defined by the position of the nodes P and D. For example, in the first site, workstation 1 has L-shape, orientation 4.

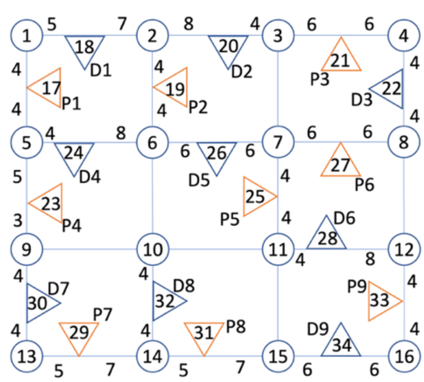

Figure 6. Graph with the workstations

3.2. Solving approach

The mathematical model of the optimization problem is based on the formulation of Guan et al. (2012) which we have extended to take into account the orientation and shape of the machines.
In a simplified way, the solving approach has two main components:
- The objective function computes the distance traveled by the AGV starting from a given solution.
- The simulated annealing mechanism search for a good solution.

3.3. Objective function

The objective function is divided into two parts:
-The first one consists of minimizing the flow of products corresponding to the transportation demands.
-The second one consists of minimizing the empty transport flow and it is solved as a standard transport problem.

3.4. Coding of the solutions

We are working on a finite set of solutions, so we have chosen to code the solution with the matrix in figure 7. Each line corresponds to a level of the solution.

	Sites			
Layout (level 1)	w_1	w_2	...	w_n
Orientation (level 2)	o_1	o_2	...	o_n
Shape (level 3)	s_1	s_2	...	s_n

Figure 7. Solution coding matrix

Level 1 is the layout of the workstations. In the example (figure 7), workstation w_1 is on the first site, workstation w_2 is on the second site, etc.

Level 2 corresponds to the orientation of the workstations as shown in the corresponding part of figure 7. In our example (figure 7), workstation w_1 has orientation o_1, workstation w_2 has orientation o_2, etc.

Level 3 corresponds to the shape of each workstation. In the example (figure 7), workstation w_1 has a shape s_1, and workstation w_2 has a shape s_2.

3.5. Loaded and empty flows

The AGV routes are composed of alternating loaded (i.e. from pick-up to delivery nodes) and unloaded moves (i.e. from delivery to pick-up nodes); the latter are also called empty flow.

3.6. The metaheuristic: the simulated annealing

Two neighborhood operators are used by the SA, depending on the part of the solution which is concerned:

- Regarding the layout of the workstations, the classical swap operator is used: two different random values between one and n are selected (n corresponds to the number of sites) and then the workstations corresponding to these values are swapped (figure 8a).

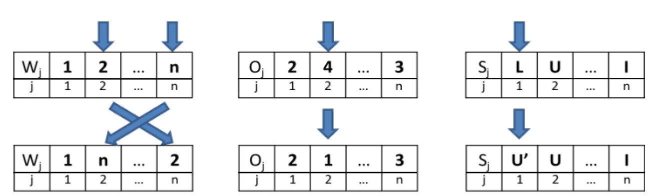

Figure 8: Neighborhood operators for workstation's (a) layout, (b) orientation, and (c) shape

-Concerning the orientation or the shape part, the operator chooses a random value between one and n corresponding to a site and selects a random value among the possible value (figure 8b & 8c). Our orientations are coded from 1 to 4 and the shapes are coded with the following values: I, U, U', L and L'.

These two methods can be performed by the SA to search for a new neighbor of a given solution.

4. EXPERIMENTATIONS AND RESULTS

The implementation of the proposed algorithm was done in Julia. The following packages are used: JuMP and GLPK for the optimization of the transport problem; SimpleWeightedGraphs and LightGraphs for the construction of graphs. The experiments were run on a Macbook Pro Intel Core i7 at 2,2 GHz with 6 cores (16 GB RAM).

4.1. Instances and design of experiments

We use 7 instances of two different sizes. The two first instances are composed of 9 workstations (9_A and 9_B) and the five other instances are composed of 25 workstations (25_A, 25_B, 25_C, 25_D, and 25_E). The values of each flow are uniform random numbers between 1 and 300. The results presented below are an average of five runs.

There are three possible configurations for the optimization flow:

- Single level optimization labeled 'OptLv_i' with i∈ {1, 2, 3}, being the selected level of the coding matrix.
- All levels optimization labeled 'OptAllLv'
- Multiple optimizations of a single level sequentially labeled 'OptSeq' according to a given sequence of levels

The first optimization configuration (OptLv_i) starts from the same initial solution and searches neighbors by changing values at level i only; the second (OptAllLv) aims at optimizing all levels of the solution at the same time; and the third (OptSeq) optimizes sequentially each level of the solution according to the result found in the previous level with the following order: layout, orientation, and shape.
The performance gap between two configurations 'a' and 'b' is measured by indicator G_{a-b} (Equation 1) calculated as follows with F_{cfg} being the objective value of configuration 'cfg':

$$\left(\frac{F_a-F_b}{F_a}\right) \times 100 = G_{a-b} \qquad (1)$$

For instance, in figure 9, the gap $G_{\text{Guan-OptLv\_2}}$ from the blue value (Guan configuration) to the orange value (Optlv_2 configuration) on instance 9_A, is equal to 32,6%.

4.2. Parameters of the Simulated Annealing

Four main parameters are used: the stopping criterion, the initial temperature, the cooling ratio and the number of iterations performed at each temperature. The values of the parameters are summarized in table 1.

The computation time limit in sections 3.2 to 3.5, is one hour (SA_Cfg_1).
To be able to compare the sequential (OptSeq) and all level optimization (OptAllLv), the total computation time must be equal. Therefore, the sequential optimization duration (Table 1) is three hours (SA_Cfg_2).

Table 1. Parameters of simulated annealing

	SA_Cfg_1	SA_Cfg_2
Computation time	1h	3h
Temperature	188 413	188 413
Cooling ratio	0.92	0.96
Number of iterations	3400	6059

4.3. Comparison with Guan et al. (2012)

In this section, we use the 9-workstations instances presented in the paper by (Guan et al., 2012)
In figure 9, the first column in blue represents the optimal solution obtained by the authors with only the possibility of moving the workstation (level 1), *i.e.* without taking into account the orientation and shape of the workstations. In the second column (i.e. orange), we keep the same layout found by the authors and we optimize the orientations of the workstations (level 2). Finally, for the last column (i.e. grey), we keep the previous layout and orientation found and we optimize the shape of the workstations (level 3).

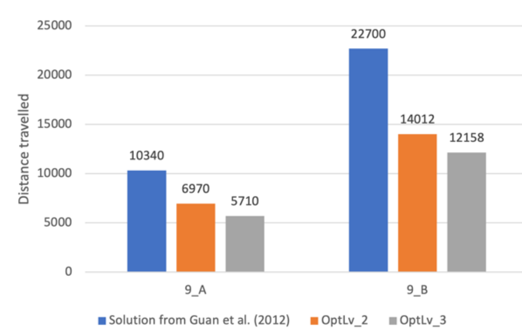

Figure 9. Impact of the orientation and the shape of workstations.

Regarding the orientation of workstations, the solution improvement labeled $G_{\text{Guan-OptLv\_2}}$ is 32,6%, for instance, 9_A and 38,3% for instance 9_B. Regarding the shape of workstations in addition to their orientation, the solution improvement labeled $G_{\text{Guan-OptLv\_3}}$ is 44,8% for instance 9_A and 46,4% for instance 9_B.

4.4. Comparison of single level and all levels optimizations

4.4.1. Workstations instances (9_X)

The values obtained (figure 10) correspond to a configuration of 9 sites with 9 workstations. All instances values of loaded flows are taken from the article written by (Guan et al., 2012). The initial solution for all instances is composed of all

workstations placed in ascending order (1, 2, 3, 4, …, n), with the orientation 1 (1, 1, 1, 1, …, 1) and the shape of L (L, L, L, L, …, L).
The first column (in light blue) is the result of the initial layout; columns 2, 3, and 4 are the respective results of OptLv_1, OptLv_2, and OptLv_3 as described in part 4.1; the last column (in yellow) is the optimization of all levels labeled OptAllLv.
The results of OptLv_1 are not identical to those from figure 9 because in the article the pick-up and delivery points are fixed with the site and don't move. In our case, the pick-up and delivery nodes can be moved.

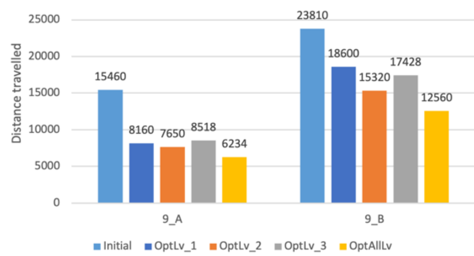

Figure 10. Impact of all levels of the solution coding with 9 workstations

Figure 10 shows the impact of each level of the solution. With 9 workstations, OptLv_1 and OptLv_3 have respectively the less impact on experiments 9_A and 9_B. In both experiments, OptLv_2 has a larger impact on the results. But the best result is obtained with OptAllLv.

4.4.2. Workstations instances (25_X)

The values obtained (figure 11) correspond to a layout problem with 25 sites and 25 workstations.
The columns in figure 11 are the same as the columns in figure 10.

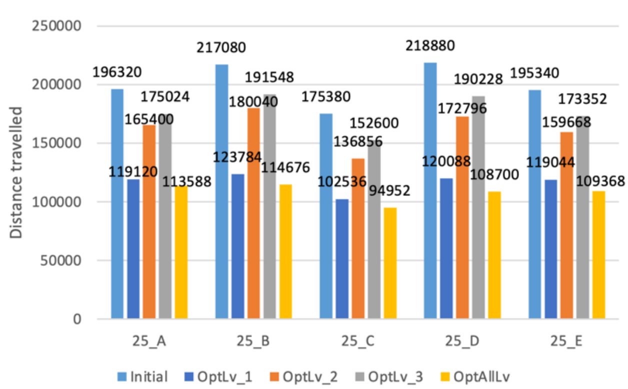

Figure 11. Impact of all levels of the solution coding with 25 workstations

Figure 11 shows that OptLv_1 has the most impact on the solution ($G_{Initial\text{-}OptLv\_1}$ between 39% and 45%) followed by the OptLv_2 ($G_{Initial\text{-}OptLv\_2}$ between 16% and 22%); OptLv_3 has the less impact ($G_{Initial\text{-}OptLv\_3}$ between 11% and 13%) in comparison to the initial result. Notice that OptAllLv gives the best result for each instance ($G_{Initial\text{-}OptAllLv}$ between 42% and 50%).

4.5. Optimization of all levels vs. sequential

We test two different ways to optimize the solution, OptAllLv, and OptSeq.
The comparison between those two methods is represented in figure 12.

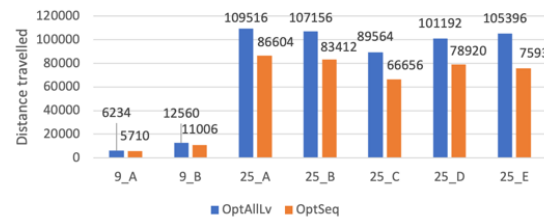

Figure 12. Comparison between OptAllLv and OptSeq

Figure 12 shows that OptSeq gives better results than OptAllLv. $G_{OptAllLv\text{-}OptSeq}$ varies from 8.4% to 12.4% for models with 9 workstations and from 22% to 28% for models with 25 workstations.
An explanation of the best performances of OptSeq could be that, for each optimization level, there are fewer solution combinations. It is, therefore, easier to find a better solution at each level.

4.6. Synthesis results

Table 2 shows the synthesis of all the results and improvements obtained for each instance compared to each initial solution. According to our results for a single-level optimization, for instances with few workstations (9), OptLv_2 provides better results. Then with larger problems (25 workstations), OptLv_1 gives better results. A potential explanation comes from the distance increase between the sites with 25 sites in comparison with 9 sites. OptAllLv gives better results than OptLv_i, but the best result is obtained with OptSeq.

Table 2. Resume of the results

Optimization	Improvement				
9 machines					
	9_A		9_B		
OptLv_1	33,12 %		21,88 %		
OptLv_2	50,52 %		35,66 %		
OptLv_3	44,90 %		26,8 %		
OptAllLv	59,68 %		47,25 %		
OptSeq	**63,07 %**		**53,78 %**		
25 machines					
	25_A	25_B	25_C	25_D	25_E
OptLv_1	39,32 %	42,98 %	41,53 %	45,14 %	39,06 %
OptLv_2	15,75 %	17,06 %	21,97 %	21,05 %	18,26 %
OptLv_3	10,85 %	11,76 %	12,99 %	13,09 %	11,26 %
OptAllLv	42,14 %	47,17 %	45,86 %	50,34 %	44,01 %
OptSeq	**55,89 %**	**61,58 %**	**61,99 %**	**63,94 %**	**61,13 %**

5. CONCLUSION AND FUTURE RESEARCH

These preliminary results confirm that taking into account the orientation and the shape of the workstations reduces the total distance traveled by AGVs. This study also shows that the results are significantly improved with sequential optimization (OptSeq). Thus, the best improvement for the problem with 25 machines and 25 sites (i.e. instance 25_D) is 63,94% ($G_{Initial-OptSeq}$). The following improvements will be considered in future work:

- Taking into account several time periods. The goal is to optimize the layouts over many time periods by taking into account several parameters such as the cost of moving workstations, the possibility of setting or not certain workstations in a certain site, or even looking at whether a reconfiguration is relevant according to the following periods;
- Taking into account the effort cost. The cost could be evaluated in "ton.km" to encompass the effort required for the removal.

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REFERENCES

Aarts, E., Korst, J., Michiels, W., 2005. Simulated Annealing, in: Burke, E.K., Kendall, G. (Eds.), Search Methodologies. Springer US, Boston, MA, pp. 187–210.

Al-Zubaidi, S.Q.D., Fantoni, G., Failli, F., 2021. Analysis of drivers for solving facility layout problems: A Literature review. Journal of Industrial Information Integration 21, 100187.

Bock, S., Hoberg, K., 2007. Detailed layout planning for irregularly-shaped machines with transportation path design. European Journal of Operational Research 177, 693–718.

Chwif, L., Barretto, M.R.P., Moscato, L.A., 1998. A solution to the facility layout problem using simulated annealing. Computers in Industry 36, 125–132.

Drira, A., Pierreval, H., Hajri-Gabouj, S., 2007. Facility layout problems: A survey. Annual Reviews in Control 31, 255–267.

Friedrich, C., 2018. Integrated slicing tree approach for solving the facility layout problem with input and output locations based on contour distance. European Journal of Operational Research 15.

Garey, M.R., Johnson, D.S., 2009. Computers and intractability: a guide to the theory of NP-completeness, 27. print. ed, A series of books in the mathematical sciences. Freeman, New York [u.a].

Ghassemi Tari, F., Neghabi, H., 2015. A new linear adjacency approach for facility layout problem with unequal area departments. Journal of Manufacturing Systems 37, 93–103.

Guan, X., Dai, X., Qiu, B., Li, J., 2012. A revised electromagnetism-like mechanism for layout design of reconfigurable manufacturing system. Computers & Industrial Engineering 63, 98–108.

Hao, J.-K., Galinier, P., Habib, M., 1999. Méthaheuristiques pour l'optimisation combinatoire et l'affectation sous contraintes 40.

Khezri, A., Benderbal, H.H., Benyoucef, L., 2021. Towards a sustainable reconfigurable manufacturing system (SRMS): multi-objective based approaches for process plan generation problem. International Journal of Production Research 59, 4533–4558.

Kim, J.-G., Kim, Y.-D., 2000. Layout planning for facilities with fixed shapes and input and output points. International Journal of Production Research 38, 4635–4653.

Kirkpatrick, S., Gelatt, C.D., Vecchi, M.P., 1983. Optimization by Simulated Annealing. Science 220, 671–680.

Koopmans, T.C., Beckmann, M., 1957. Assignment Problems and the Location of Economic Activities. Econometrica 25, 53.

Kouvelis, P., Kim, M.W., 1992. Unidirectional Loop Network Layout Problem in Automated Manufacturing Systems. Operations Research 40, 533–550.

Maganha, I., Silva, C., Ferreira, L.M.D.F., 2019. The layout design in reconfigurable manufacturing systems: a literature review. Int J Adv Manuf Technol 105, 683–700.

Tompkins, J.A. (Ed.), 2010. Facilities planning, 4th ed. ed. J. Wiley, Hoboken, NJ.

Wang, M.-J., Hu, M.H., Ku, M.-Y., 2005. A solution to the unequal area facilities layout problem by genetic algorithm. Computers in Industry 56, 207–220.

Yelles-Chaouche, A.R., Gurevsky, E., Brahimi, N., Dolgui, A., 2020. Reconfigurable manufacturing systems from an optimisation perspective: a focused review of literature. International Journal of Production Research 1–19.

[i] https://www.ez-wheel.com/fr