2nd International Conference on Engineering Optimization
September 6 - 9, 2010, Lisbon, Portugal

Accessibility in Layout Optimization

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Abstract
Component and facility layout plays an important role in the design and usability of many engineering products and systems as mechanical design, facility layout, process plan, management and architecture including ship compartment layout. In real-world applications, all designer's requirements can not be formulated as simple mathematical expressions. The accessibility to components is one of these requirements which can not easily be taken into account in the layout optimization process. Firstly, this accessibility deals with the required vacant space located around the component and used to guarantee the correct mechanism of the component. This space is described, in this paper, as a virtual component with particular attributes. Moreover, the accessibility requirement means that each component has to be attainable from the container's entry. In order to consider it in the layout optimization process, designers usually use their expertise to modify the layout problem description and satisfy a priori all the accessibility specifications. This paper proposes an alternative approach based on the integration of the accessibility to components in the layout problem formulation. The accessibility is considered as a design constraint or an objective of the optimization problem. This method is applied on a two dimensional real-world problem which deals with the layout optimization of components inside a shelter. Some research leads are also described in order to use this approach for the three dimensional layout problems.
Keywords: Design optimization, Layout problems, Accessibility.

1. Introduction

Layout problem is inherently a multidisciplinary task [1]. It covers all the aspects of the product design life cycle from the conceptual to the detailed stage and makes necessary the collaboration between experts of technical and economical disciplines. In layout design literature, one finds some different definitions of layout problems [2, 3]. The key idea is always the same: given a set of free form components and an available space, a layout problem consists of finding the best arrangement (location and orientation) of components satisfying geometrical and functional constraints and achieving design objectives. This generic definition can be adapted to all real-world applications. For example, Drira et al. [4] and Wascher et al. [5] have adapted the definition of a layout problem to their respective research domain i.e. facility layout design and cutting and packing problems.

One finds multiple search algorithms to solve layout optimization problems in two or three dimensions. Traditional optimization approaches for three dimensional layout problems are described by Jonathan Cagan et al. [2]. They use genetic algorithms [3], simulated-annealing algorithms [6] or extended pattern search algorithms [7]. Most search algorithms are developed for a specific problem and they provide an effective optimization strategy for it. Therefore, they are not generic and can not be adapted to a lot of layout problems. Some of recent studies deal with the search of efficient generic algorithms for solving layout problems [8].

In most layout problems, the design constraints and the objectives are multiple: non-overlap, alignment of components, mass distribution, minimum or maximum distance between components. Moreover, in most real-world applications, the translation of all designer’s requirements into simple mathematical expressions is a very hard task. These requirements need specific computation processes which can be time consuming.

This paper focuses on one of these particular layout requirements, which deals with the accessibility to components from the container’s entry. This designer’s requirement can be found in some real-world applications as facility layout problems (to be sure that facilities are accessible from the plant’s entry) or the mechanical assemblies (to be sure that a part can be accessible for maintenance).

In fact, in a layout problem, the designer has two possibilities in order to take into account the accessibility to components:

- by inserting his expertise in the problem description in order to guarantee the accessibility to all components (for example by adding a free corridor in the middle of a room),
- by integrating the accessibility requirement in the problem formulation, by inserting the accessibility to components in the design constraints or the objectives.

The first approach can easily be used by the designer. However, this method does not encourage the innovation and the search of new solutions because the designer, by modifying the problem description, angles the search of

feasible designs (it means that respect all the design constraints) to some existing solutions a priori intended by the designer. Consequently, this paper points up the second approach and proposes two strategies in order to consider the accessibility to components as a constraint or an objective of the layout optimization process.
As far as we know, this approach has not been developed for layout problems yet. However, the different methods performed for path planning problems, especially in robotics, can be used. Trajectory planning deals with the determination of the optimal path in a workspace, where the start and end points of the trajectory are predefined and fixed. A review of trajectory planning techniques is given in [9]. In layout design problems, the accessibility to components has to be represented by a numerical value in order to rank the designs according to this accessibility. The methods, proposed in this paper, achieve this requirement.
This paper is organized as follows: section 2 presents two methods for characterizing the accessibility to layout components in a layout optimization process. The next section describes the optimization simulation realized on a real-world application and introduces the concept of "virtual component" used to define the space of accessibility of a layout component. The application deals with the layout problem of a shelter [10]. Eight components have to be located in the shelter including four electrical and energetic cabinets, two desks and two electrical boxes. The layout optimization problem of this shelter is a three dimensional optimization problem. Because the cabinets are full height of the shelter and prevent a superposition of elements, the model is simplified in two dimensions. This simplified model is represented in the figure 1. Actually, sections 4 and 5 are dedicated to an outlook on future work and the conclusion of this paper.

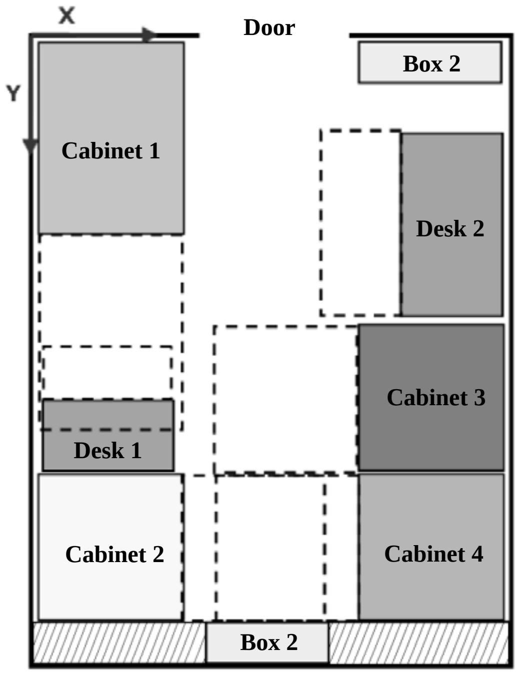

Figure 1: Description of the shelter in 2D

2. Accessibility analysis
This section presents two approaches for computing the accessibility to components in order to consider the problem of accessibility as a constraint or an objective of a two dimensional layout optimization problem. In fact, the two methods return a value that characterizes the accessibility to components inside the container. The two methods are explained and compared, according to the layout problem of the shelter.

2.1. "Inner-Fit Polygon"-based approach
This method uses the computation of the Inner-Fit Polygon (assimilated to IFP in the next sections). The IFP is derived from the No-Fit Polygon (assimilated to NFP in the next sections) [11]. The NFP determines all arrangements that two arbitrary polygons may assume such that the shapes touch but so that they can not be moved closer together without intersection.
For the layout problem of the shelter, firstly let us consider that the employee, who usually works in the shelter, is modeled by a circle C, with a radius equal to R. The center of the circle is represented by a point A. The shelter is modeled by a rectangular polygon P and the components, located inside the shelter, are considered in two dimensions as holes in this rectangle.

The method suggests calculating the IFP between the circle C and the polygon P, it means all the feasible positions of the point A such as the circle C is inside the shelter and do not overlap with the components located in the shelter. The IFP can be composed of several polygons.
Then, the polygon of the IFP that is linked to the entry of the shelter is selected. For each component, the distance D_i between the center of the component's entry i and this polygon is measured. If the distance is equal to the radius of the circle C, the component is then accessible from the shelter's entry. Otherwise, the employee can not reach to this component from the shelter's entry. The figure 2 illustrates this IFP-based approach. The components are represented by hatched rectangles and their entry is symbolized by a thicker line.
In order to integrate this accessibility requirement in the layout optimization process, we compute the value Acc, defined by:

$$Acc = \max(D_i - R),\ pour\ i \in [1,..,n] \quad (1)$$

where n represents the number of components taken into account in the computation of the accessibility requirement.
For the simulations which have been realized and whose results are presented in the next sections, the diameter of the circle C, that represents the employee, is fixed to 50 cm. The underlying fluctuation range step used to model the circle C is fixed to 10°.

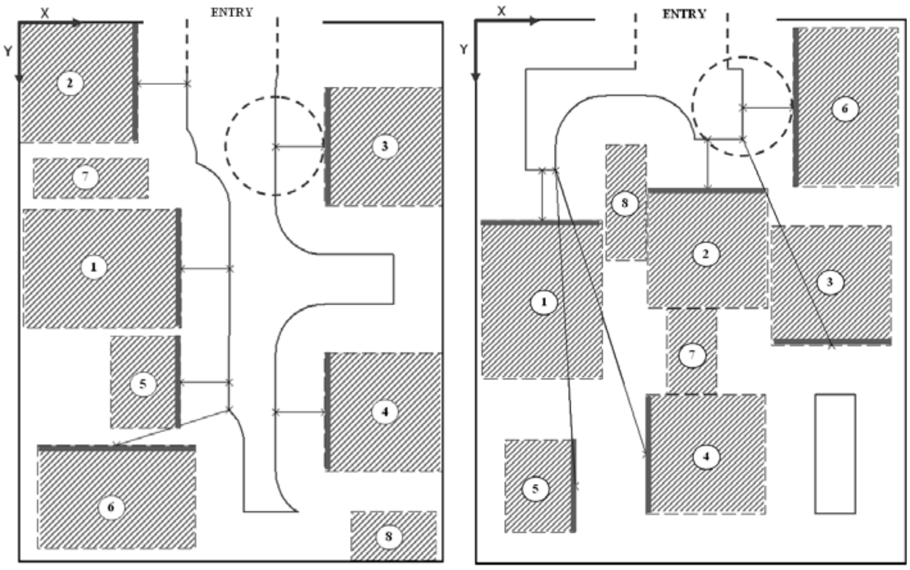

Figure 2: Illustrations of the IFP-based approach

2.2 Path optimization-based approach
This approach is based on a path optimization process that is realized between two points: the point A that is located at the center of the shelter's entry and the point B, located at the center of the component's entry. The path is composed of n_p butt joint rectangular sections. These rectangles represent the path taken by the employee inside the shelter, in order to reach to the component from the shelter's entry.
The path optimization process is an under constrained single-objective problem. The constraint deals with the respect of non-overlap constraints between the path and the components. Because we consider this layout problem in two dimensions and because of the rectangular shape of the path and the components, we can formulate the overlap between a section j of the path and a component i as the area intersection between the two elements. It is mathematically formulated as:

$$\begin{aligned} A_{ij} &= \max[0, \min(x_{pj} + \frac{l_{pj}}{2}, x_{fi} + \frac{l_{fi}}{2}) - \max(x_{pj} - \frac{l_{pj}}{2}, x_{fi} - \frac{l_{fi}}{2})] \\ &\times \max[0, \min(y_{pj} + \frac{L_{pj}}{2}, y_{fi} + \frac{L_{fi}}{2}) - \max(y_{pj} - \frac{L_{pj}}{2}, y_{fi} - \frac{L_{fi}}{2})] \end{aligned} \quad (2)$$

where (x_{pj}, y_{pj}) and (l_{pj}, L_{pj}) respectively define the coordinates and the dimensions (width and length) of the section j of the path. By the same way, (x_{fi}, y_{fi}) and (l_{fi}, L_{fi}) respectively define the coordinates and the dimensions (width and length) of the component i.
The design objective is to minimize the length of the path, it means the sum of the lengths of the different sections

of the path. The design variables are the variables that drive the position of the rectangular sections of the path, it means a continued parameter for the length of the rectangle and a discreet variable for its orientation which can take four values: 0°, 90°, 180° or 270°. Moreover, the last two sections result from the position of the $(n-2)^{th}$ section of the path. Consequently, there are $2 \times (n-2)$ design variables in this path optimization problem.

In order to characterize the accessibility to a component, the sum of non-overlap constraints, between the path and all the components located inside the shelter, is computed:

$$A_i = \sum_{i=1}^{i=n} \left(\sum_{j=1}^{j=n_p} A_{ij} \right) \tag{3}$$

If this sum is equal to zero, the component is then accessible from the entry of the shelter. It is also important to mention that the designer has to realize a path optimization simulation for each component.

In order to integrate this accessibility requirement in the layout optimization process, we compute the value Acc, defined by:

$$Acc = \sum_{i=1}^{i=n} A_i \tag{4}$$

where n represents the number of components taken into account in the computation of the accessibility requirement.

The figure 3 illustrates this path optimization-based approach, for the computation of the accessibility for the layout components 4 and 6. For the simulations which have been realized and whose results are presented in the next sections, the path is composed of 5 rectangular sections. The algorithm, used in the path optimization process, stops after a certain number of iterations, which is fixed to 100 in this paper. The vector of initial optimization variables is fixed to [L, L, L, 0, 0, 0], where L is arbitrarily chosen by the designer.

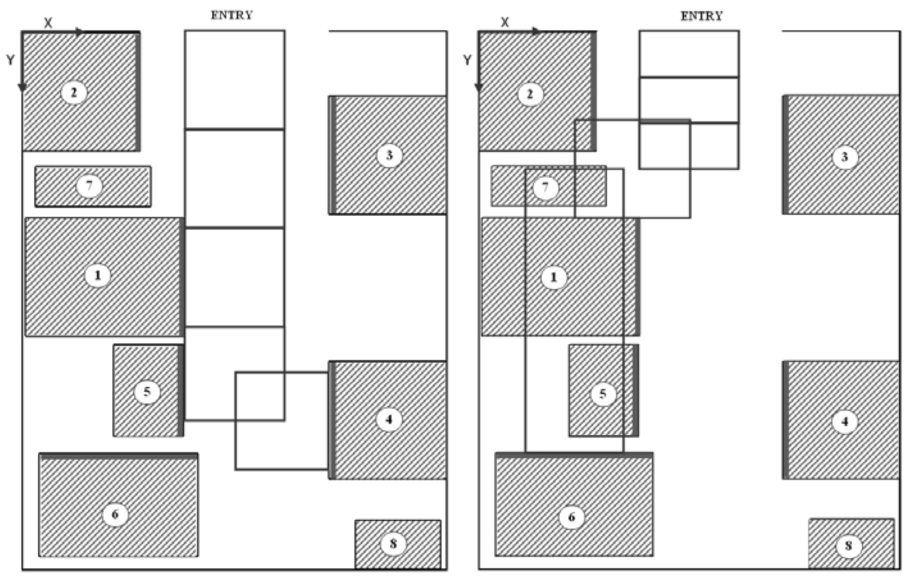

Figure 3: Illustrations of the path optimization-based approach

2.3 Comparison of the two approaches

This subsection compares the two approaches, previously described, on ten different layout designs of the shelter. For each layout configuration, the two methods are used to compute the accessibility to six components located inside the shelter. These components are those which are represented in the figure 2 and the figure 3 with a number ranged from 1 to 6, it means the cabinets and the desks. For each layout design, the calculation time and the accessibility value for each component are saved.

The accessibility values obtained for each approach show that the two methods detect, for each layout configuration the same components accessible from the shelter’s entry. The two methods are then comparable according to the relevance of the results.

The difference between the two methods is underlined with the calculation time. The simulations, realized on these ten layout designs, show that the mean calculation time of the IFP-based approach (0,41s) is shorter than the mean calculation time of the path optimization-based approach (0,99s). This difference can have a significant repercussion on the global calculation time of the layout optimization process.

Moreover, these simulations show that, for the IFP-based approach, the calculation time does not fluctuate much, so that the global calculation time of the layout optimization process can be predicted. The calculation time of the path optimization-based approach fluctuates more, because of the optimization process. It means that the convergence of the path optimization process depends on the arrangement of the components inside the container. Actually, the IFP-based approach is used for the two dimensional layout optimization process of the shelter, described in the next section.

3. Application

This section is dedicated to the layout optimization process of the shelter. The main objective of this problem is to find the best arrangement (location and orientation) of eight layout components in a shelter, satisfying geometrical and functional constraints and achieving design objectives. The accessibility to components is one of these design objectives.

3.1 Problem description

The layout problem of the shelter has already been described by Benabes et al. in [10]. The particularity of the problem description is that the layout components can be classified in two categories:

- the “material” components: have a mass and can not overlap with other material components. Layout components are generally considered as material components in layout literature [12,7],
- the “virtual” components: have no mass and can overlap with some material or virtual components, according to the designer’s requirements. The passages, described in the layout problem presented in [13], can be considered as virtual components.

As shown in the figure 1, the virtual components are used to define the spaces of accessibility of some components (cabinets and desks). They are represented by dotted rectangles. For example, the space of accessibility of a cabinet is the required space to insert some materials into a cabinet. Two spaces of accessibility can overlap, considering that operations of material loading are not simultaneously made.

3.2 Problem formulation

The layout problem of the shelter is an under constrained multi-objective problem. 24 design variables are defined, it means that each layout component is represented by 3 optimization variables (X, Y, α) : the coordinates of each element (a continued variable along X axis and an other one along Y axis) and the orientation (one discrete variable along Z axis).

The design constraints are non-overlap constraints, meaning only geometrical constraints. These non-overlap constraints are estimated by the computation of the area intersection between components.

Moreover, the layout problem of the shelter is a multi-objective optimization problem. The decision on the preferences between objective functions is delayed so that the designer can use the Pareto-front in order to select the most appropriate solution. Three design objectives have been defined for this layout problem:

- one objective to minimize the distance between the center of gravity of components and the geometric center of the shelter, in order to balance the masses inside the shelter (O1),
- one objective to maximize the distance between the energetic networks (cabinet 1) and the electrical networks (cabinet 3, cabinet 4, electrical box 2),
- one objective to evaluate the accessibility to each component from the shelter’s entry (O3). This accessibility is computed by the IFP-based approach.

3.3 Layout optimization algorithm

As most real-world applications, the layout problem of the shelter is a complex problem. The geometrical shape of the layout components is simple. The detection of collision between elements is not time consuming. However, the density of the problem is important if we consider the material and the virtual components. Moreover, this problem is also complex because of the problem formulation. The designed space, meaning the set of feasible designs, is parceled. In order to pass to a feasible region to an other one, traditional gradient-based optimization approaches can not be used. Instead, stochastic algorithms, as the genetic algorithm, have to be employed.

Consequently, we decide to use the layout optimization approach proposed by Jacquenot et al. in [8]. This optimization strategy uses a Genetic Algorithm coupled with a Separation Algorithm. The structure of this generic algorithm is very close to a generational genetic algorithm. The separation algorithm is nested in the genetic algorithm, and modifies components positions so that proposed solutions respect non-overlap constraints. Before evaluating a solution, the algorithm checks if placement constraints are satisfied. If so, the different objectives of the solution are evaluated and the algorithm moves to the next solution. Otherwise, the separation algorithm is run and modifies the solution so that placement constraints are respected. The solution is then evaluated. The optimization process is illustrated in the figure 5.

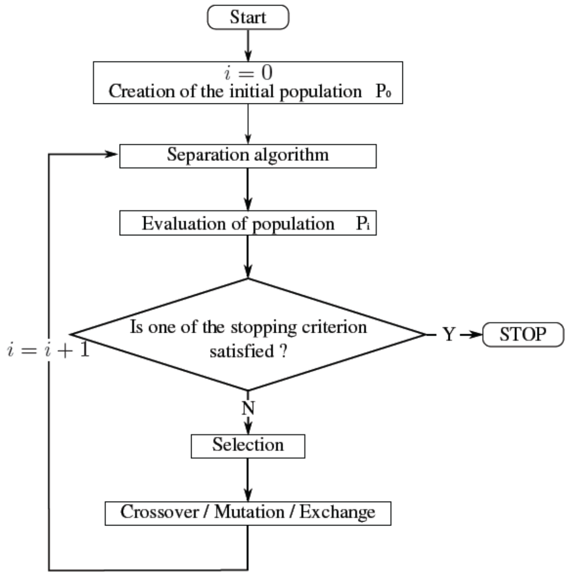

Figure 4: Hybrid layout optimization algorithm [11]

3.4 Interactive decision making

In design optimization, the designer is always the only person who is able to make the final decision on optimal solutions. The optimization strategy described in this paper suggests using an interactive environment in order to allow the designer to:

- select a Pareto-optimal solution generated by the algorithm,
- visualize the solution in two or three dimensions,
- manually and locally modify the solution, by changing the position and the orientation of some components and visualizing the new values of the constraints and the objectives which result from these modifications.

The main objective of this interactivity with the designer is to improve the performances of the optimal solutions proposed by the algorithm, by inserting in the decision making the personal judgment of the designer. This interactivity between the designer and the optimization process needs an efficient graphical and numerical environment.

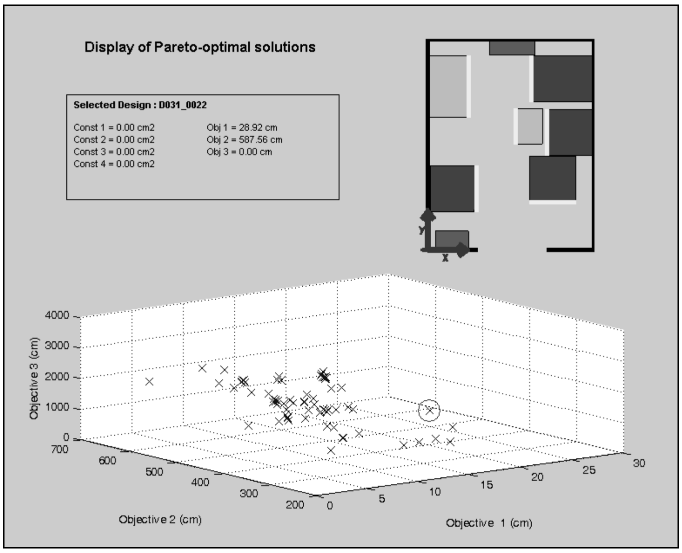

Figure 5: Interactive environment for decision making

The figure 5 represents an example of interactive environment which allows the designer to visualize the set of Pareto-optimal solutions. The designer can click on a point on the graph and visualize the layout design, the constraints and the objectives related to this solution.

3.5 Results

This subsection presents the results obtained by using the optimization strategy previously described. Firstly, the hybrid optimization algorithm has been randomly initialized by 200 individuals Then, after 100 iterations, the algorithm has computed 20 000 designs.

Among these designs, 72 are Pareto-optimal "variants". A design j is a new variant if it differs from the design i by at least one of the following criteria:

- one of the components of the layout has been displaced from at least Δ mm along one of the axis (Δ is set to 500 mm in this application),
- one of the components has been rotated,
- the minimum difference between the objective values of the two designs is bigger than a limit for example fixed to 10 cm.

As it is explained in the previous subsection, the designer has to select one of these Pareto-optimal variants. For example, let us consider that the designer chooses the design represented in the figure 5 and the figure 6 (b). Then, by locally modifying the position of some components, according to the personal judgment of the designer, the solution represented in the figure 6 (c) is obtained.

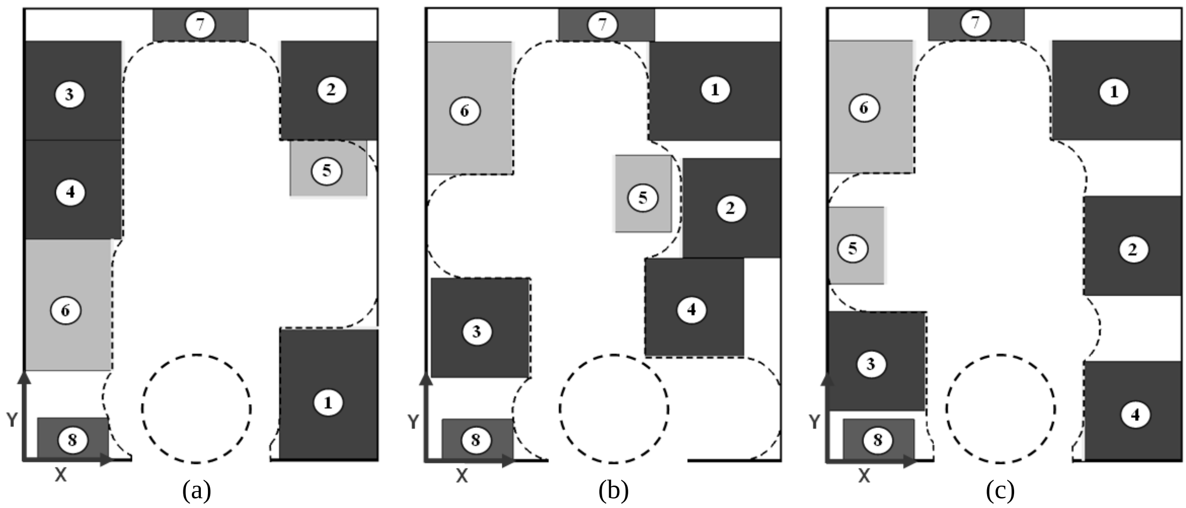

Figure 6: Graphical results

If we consider the values of the three objectives formulated in this layout problem, this solution is better than the initial one, proposed by the designer and represented in the figure 6 (a). It is important to mention that this initial configuration is an intuitive solution which has been generated only by considering geometric aspects. The table 1 represents the values of the three objectives for the three solutions illustrated in the previous figure.

Table 1: Numerical results

	Initial design (a)	Selected design (b)	Modified design (c)
Obj. 1 (min,cm)	25,41	28,92	22,90
Obj. 2 (max,cm)	604,88	587,56	669,03
Obj. 3 (min,cm)	0	0	0

4. Outlooks

This paper proposes two approaches to take into account the accessibility to components in the layout problem formulation. These two approaches are different. One method uses the Inner-Fit-Polygon (IFP), whereas the other one performs a path optimization process for each design. One of the main outlooks is the adaptation of these approaches to the three dimensional layout problems.

On the one hand, in order to use the IFP-based approach, the method has to be modified. A suggestion is to transform the problem into a two dimensional problem. Firstly, according to the designer's requirements, the components which are located below a certain plan, fixed by the designer, can be deleted for the computation of the accessibility to components. It means that the designer is able to step over a component if the component is, for example, a small object fixed to the floor. By the same way, the components located above a certain plan can be deleted. It means that the designer is able to pass below these components. These components can be for example a ceiling light or a ventilator. Then, all the other components have to be projected in two dimensions and the

IFP-based approach, previously described, can be used. This approach can be used for most three dimensional layout problems.

On the other hand, in order to use the path optimization-based approach, a suggestion is to transform the rectangular sections of the path into parallelepipeds. Then, the method, adapted to three dimensional applications, has to compute intersection volumes between the components and the path's sections. As it is explained for the path optimization-based method in two dimensions, if the intersection volume between a component and the path is equal to zero, then the component is accessible from the container's entry.

Moreover, it is important to mention that the accessibility requirement that guarantees that all components are accessible from the container's entry differs from the accessibility condition which guarantees that a component can be taken out from the container. One finds this second requirement in mechanical assemblies, when the designer wants to maintain a part. Consequently, the strategies, presented in this paper, have to be adapted to these specific layout problems.

5. Conclusion

Accessibility in layout optimization can have two different meanings. Firstly, this accessibility can refer to the space located near a layout component and required to insert some materials into the component. The layout optimization strategy, proposed in this paper, defines this space of accessibility as a "virtual" component.

Secondly, accessibility means also that all components have to be accessible from the container's entry. This paper proposes two methods to consider this accessibility requirement as either a design constraint or an objective of the optimization problem. These approaches suggest simplified models in order to compute the accessibility to layout components, without being time consuming. Then, it allows the designer to use these methods in layout optimization processes.

Actually, this paper proposes innovative approaches which allow the designer to explore more alternative solutions to his layout problem. It is a very good way to encourage the innovation. The designer is not forced to modify the problem description and the optimization algorithm can find original solutions.

Acknowledgment

The authors would like to acknowledge THALES for the application study.

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