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External Buildings Retrofit: Employing Guillotine Cuts for Aesthetic Envelopes

A.F. Barco¹, M. Aldanondo¹, É. Vareilles¹, P. Gaborit¹

¹Industrial Engineering Lab, Mines Albi, Toulouse University, France
({abarcosa, aldanond, vareille}@mines-albi.fr)

Abstract - The design of façades insulating-envelopes based on rectangular configurable panels is addressed via guillotine cuts. This design is treated as a two-dimensional orthogonal packing problem which considers the specific geometry and structure of each facade. Among the various packing algorithms dedicated to this particular design problem, the cutting approach is the most appropriated to design aesthetic insulating envelopes by including architects aesthetics criteria. The proposed solution exploits human knowledge and expertise to provide consistent envelopes solutions, in competitive computational time and with aesthetics aspects. Our work aims to assist architects in decision-making.

Keywords -2D-Packing, Building Retrofit, Guillotine

I. INTRODUCTION

In the aim of reducing energy consumption, buildings may be externally retrofitted by covering them with insulating envelopes [1, 13]. These insulating envelopes are based on the technical concept of insulating panels: wood-made rectangular structures which are configurable in the sense that their size and their position over the facade are defined at design time prior to their manufacturing. The envelope design is subject to the following general conditions:

1. The number and size of panels to design an insulating envelope for a given façade are not known in advance.
2. Due to manufacturing limitations, frames (windows and doors) over the façade are meant to be covered by one and only one panel.
3. No hole and no overlapping between panels are allowed in the envelopes.
4. To minimize the retrofit global cost and achieve a good thermal insulation, envelopes should be composed of the minimum number of panels.
5. Given the architectural conditions of façades, the designed insulating envelopes must consider aesthetics aspects.

The envelopes design is in essence a Cutting and Packing problem [6]. It presents a challenge to academics and practitioners given the wide range of façade geometries and structures. In regard of these conditions, one of the key problems of this retrofit is to propose a computation process that allows configuring the specific set of configurable panels with respect to each façade.

In two previous works, we have already developed consistent algorithmic solutions to the problem: the first using a greedy approach [2] and the second using a

constraint-based approach [3]. However, the generated envelopes solutions from these algorithms do not count with aesthetic aspects needed for the retrofit (such as symmetry). In fact, tacit knowledge as aesthetics is a major challenge for both the modeling and implementation of solutions. Further, it is known that aesthetics flair has no universally agreed standard. Nonetheless, properties like symmetry are well accepted as aesthetic concept in different domains such as human beauty [9], web design [12], computer interfaces [5] and art [10]. In this paper we assume a direct relationship between symmetry and aesthetics of façades.

The work presented in this article deals with the need of designing envelopes with a more “pleasant” aesthetic appearance. We do so by developing a rule-based heuristic, called *Casye*, based on the well-known technique of guillotine cuts [7]. Cutting is a technique from operations research widely used to solve different industrial problems [6, 7, 14] and it has been applied to problems where symmetry is relevant for the final output: for instance, arranging items in a newspaper [11], automatic mosaic generation [4] and aesthetics photo post-processing [8]. We use the guillotine approach and show that it generates aesthetic (symmetric) insulating envelopes not generated by the two other approaches [2, 3], thus satisfying this crucial architectural requirement.

The document is structured as follows. In Section II, more details about the packing problem are given. In Section III, the design of the proposed solution is introduced. In Section IV, the *Casye* algorithm and its complexity are discussed. In Section V, a comparison against the existing solutions is presented and some conclusions and remarks are drawn.

II. External Insulating Envelopes

The design problem addressed here raises when retrofitting buildings to reduce their energy consumption levels. The retrofit is done by attaching a new insulating envelope composed of rectangular insulating panels over buildings façades. Panels are rigid 2D rectilinear rectangles and their sides are therefore parallel to the façade reference axis. Panels are configured by setting their size (width pw and height ph) and setting the position of their bottom-left corner (x,y) . Panels have a given orientation: if the ratio pw/ph is less than one, the panel is vertical, otherwise, it is horizontal. This information impacts the inner structure of the panel and its laying direction onto the façade, even more pertinent if the panel contains frames. Panels’ position must be set

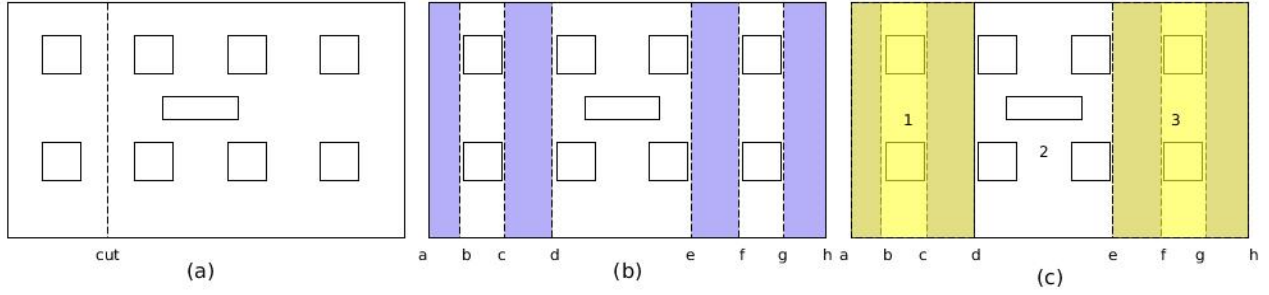


Fig. 1 - Guillotine cuts for intervals and sub-façades definition

in such a way that all existing frames over the façade are covered by one and only one panel, without any partial overlapping. In addition, due to the manufacturing, transportation and working-site conditions of the retrofit, panels have specific size lower and upper bounds that must be respected when instantiating them.

According to the previous description, the parameters needed for designing an envelope are:

Façade size: width ($facw$) and height ($fach$)

For every frame,:

- Coordinates: bottom-left corner (frx, fry)
- Size: width (frw) and height (frh)

Panel bounds:

- Width lower and upper bounds ($minw, maxw$),
- Height lower and upper bounds ($minh, maxh$)

Conversely, the main decision variables of panels refer to:

Panel width $pw \in [minw, maxw]$,

Panel height $ph \in [minh, maxh]$

Panel Coordinates bottom-left corner (x, y).

III. Casye Algorithm Phases

The main idea behind our solution is to generate envelopes aesthetically pleasant by considering their symmetry while respecting the manufacturing, transportation and working-site conditions. To do so, the set of panels in an envelope is configured according to a given orientation (vertical or horizontal). Then, for a given façade, the algorithm tries as much as possible to design panels using the preferred orientation. If due to the geometry of the façade, a portion of the envelope cannot be designed using the preferred orientation, the algorithm creates a sub-façade and tries to design that sub-façade by changing the panel orientation. This means, on the one hand, that insulating envelopes may contain only vertical panels, only horizontal panels or a combination of both. And, on the other hand, that the insulating envelope corresponds to the set of panels belonging to every sub-façade no matter the orientation. As it is shown later in the document (section V), mixing panels orientation on the same envelope does not interfere with the aesthetics goal.

The algorithmic solution is divided in three phases executed sequentially.

Phase 1: Make a pre-process to determine if the envelope can be designed using the preferred orientation (sub-

section A). It does so by finding the areas in which panels can be attached (i.e., those places with no conflicts with frames). In the case a portion of the envelope cannot be designed with the chosen orientation, a sub-façade is created. This sub-façade is later designed by changing the orientation.

Phase 2: For an envelope designed using vertical (respectively horizontal) panels, find the columns (respectively rows) where panels are to be placed (sub-section B). These columns (respectively rows) are generated by taking into account panels upper bounds and available areas to attach panels generated by Phase 1.

Phase 3: For an envelope designed using vertical (respectively horizontal) panels, allocate panels over the columns (respectively rows) (sub-section C). Panels' allocation is done one by one following a greedy approach to assign the final size and to solve remaining conflicts with the frames over the façade.

A. Phase 1: Pre-Process

The goal of the pre-process phase is to determine whether the envelope can be designed using vertical panels, horizontal panels, both or to identify the sub-façades and characterize them, within the façade. Intuitively, when using guillotine cuts to design an envelope with vertical panels, for instance, the horizontal axis of the façade is traversed looking for points with absence of frames. When there are no frames in a given horizontal point, a vertical guillotine cut may trace from the bottom to the top of the façade (see Fig. 1.a). A set of consecutive cuts makes an interval (see Fig. 1.b). These lines or intervals, termed as Zones Free of Conflicts (*ZoFCo*), are later used to place panels' borders. If the necessary vertical intervals are present in the façade, then the envelope is designed using vertical panels. The pre-process is similar for horizontal panels.

At the end of the pre-process, every sub-façade is marked as *Vertical* or *Horizontal*, and *NotVertical* and *NotHorizontal*. Now, if a given sub-façade is marked both *NotVertical* and *NotHorizontal*, the sub-façade has no solution with the proposed algorithm. Ergo, the entire envelope cannot be designed.

B. Phase 2: Inner-process

After the pre-process phase 1, the second phase is executed for each sub-façade. In this phase, the columns

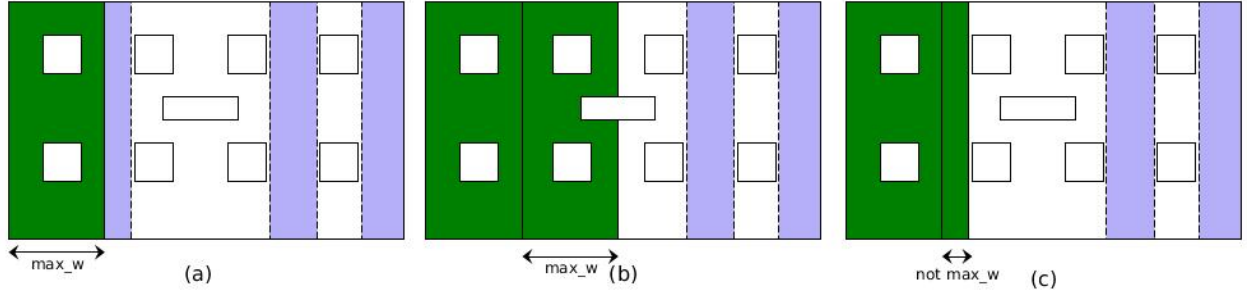


Fig. 2 - Guillotine cut for columns definition

(respectively rows) for the vertically (respectively horizontally) designed envelope must be defined. It is at these columns or rows that panels will be placed. For convenience, let us continue our solution description using vertical panels. First, it is necessary to determine where the left and right borders of panels will be placed. As the entire façade must be covered, it is the case that the end of the column i must be equal to the start of column $i+1$. Further, as we have found intervals (*ZoFCo*), then it suffices to determine the start and end of columns only within the defined *ZoFCos*. Taking into account that envelopes should be composed of the minimum number of panels, the definition of the columns is made using the upper bounds for panel's width (respectively height). The idea is to place the left and right edge of the panel in a given *ZoFCo* in such a way that its width is maximal (see Fig. 2.a). If using the width upper bound makes the column enter in conflict with a frame (see Fig. 2.b), then the upper bound cannot be used for the current column. In consequence, the width of the column is reduced as less as possible while solving the conflict (see Fig. 2.c). The algorithm for the phase 2 is applied to every sub-façade independently.

At the end of the inner process, every sub-façade has been divided into columns (respectively rows) where panel's borders will be located. The last phase sets the final position and size of panels over these columns/rows.

C. Phase 3: Allocation-process

The allocation of panels is executed for each of the columns and rows generated in the inner-process. As commented above, this last stage aims to set the final position and size of panels. Additionally, this phase handles potential conflicts with frames by executing guillotine cuts in non-conflictive zones. Likewise the previous phases, the allocation starts by an extreme of the sub-façade until its end. In the case of an envelope designed using vertical panels, the allocation process starts in the bottom of each column by extending the panel in its maximum allowed height. If a frame blocks the horizontal cut as in Fig. 2.b, the panel size must be reduced to the first place in which no conflict exists, see Fig. 2.c. The allocated panels in a given column will have the width of the column and the height defined by the horizontal guillotine cut. Again, a similar process is carried on in rows when designing envelopes with horizontal panels.

At the end of this phase, each column (respectively row) has been covered by panels. The resulting insulating envelope for the façade is the union of all panels of every sub-façade (if any). Now, let us discuss how these three phases are merged together to assist architects design.

IV. Casye Algorithm and Complexity

The phases of pre-process, inner-process and allocation-process are executed sequentially to generate a given envelope. This sequential process is executed twice in order to generate two different solutions (if the façade geometry allows it): one for vertical panels design and one for horizontal panels design.

Fig. 4 presents the flowchart of the Cutting Algorithm for Symmetrical Envelopes or *Casye*. The behavior of the *Casye* algorithm is as follows. The main loop of the algorithm is executed while there are still some sub-façades to be designed. It contains two blocks: a block for designing vertical panels (*guillotine('vertical', unknown, solution)* box) and another for horizontal ones (*guillotine('horizontal', unknown, solution)* box). Initially, the envelope for the inputted façade (*unknown = [façade]*) is meant to be designed using vertical panels only (*guillotine('vertical', unknown, solution)* box). Thus, the pre-process (sub-section A) finds the set of *ZoFCo* to design the envelope and it will find and mark the sub-façades that cannot be designed using vertical panels, if any. For all sub-façades found that are marked as *vertical*, execute the inner-process (sub-section B) and allocation-process (sub-section C). Note here that if the whole envelope for the inputted façade can be designed using vertical panels, with no partitions, then there is only one sub-façade to be processed; only one sub-façade marked as *vertical*.

In the case that there exist sub-façades marked as *notVertical*, these ones are saved for a further processing using horizontal panels only (*guillotine('horizontal', unknown, solution)* box). Once the first block is executed, the algorithm tries to design the envelopes for the sub-façades that are label as *notVertical*. The behavior of the second block is then similar to the first one. A solution with all designed panels is returned at the end of the loop when no more sub-façades are left.

Now, when processing vertical or horizontal designed envelopes, sub-façades may be created iteratively. Considering the diamond “Any sub-façades marked

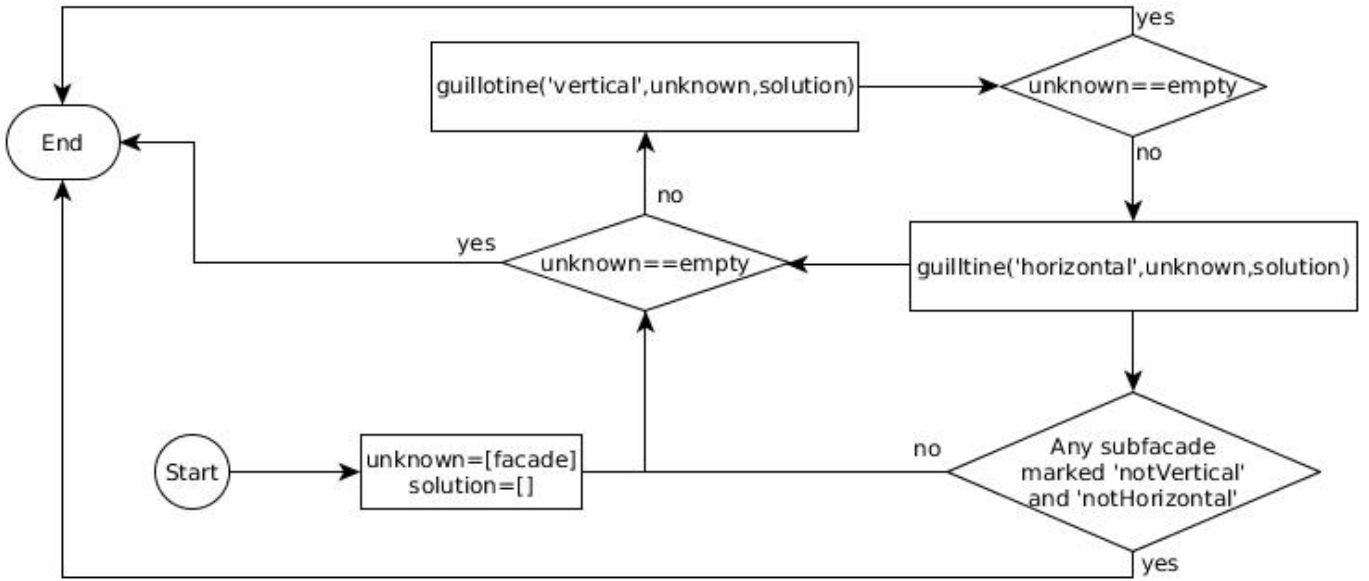


Fig. 3 – *Casye* Flowchart

notVertical and *notHorizontal*”, if the answer is ‘no’, then there is potentially more sub-façades to be processed. In that case, these new sub-façades are processed later using the corresponding orientation. However, it may be the case that a given sub-façade cannot be designed using any orientation. If this is the case, i.e., if a given sub-façade has been marked both *notVertical* and *notHorizontal*, the *Casye* algorithm fails at designing the façade (‘yes’ answer). This is due to the third condition for generating envelopes: no holes are allowed in a solution. Ergo, if a given portion of the inputted façade cannot be designed, then the façade has no solution. Nevertheless, in an attempt to overcome this situation, the algorithm is executed twice: one is starting the design vertically and another starting the design horizontally. Thus, a given façade has, potentially, two different solutions.

The algorithm complexity is determined by Phase 1 and Phase 2 as it is in these phases that the frames are iterated over. The *Casye* algorithm complexity is bounded. In the worst case, the algorithm will find sub-façades for every iteration, for both vertical and horizontal design, and then its complexity would be $O(Nfr \times (facw/minw + fach/minh))$, where Nfr is the number of frames in the façade. On the other hand, the best case scenario happens when the envelope for the inputted façade is designed entirely with one orientation, and then its complexity would be $O(Nfr)$.

V. Comparison and Conclusion

The goal of the *Casye* algorithm is to generate insulating envelopes as symmetrical as possible in order to satisfy the aesthetics need of the retrofit. The algorithm has been tested on several façades to analyze the results. As well, the greedy solution [2] and the constraint-based one [3] have been executed against the same examples to compare the resulting envelopes. We have summarized the output results in Table 1.

The first four lines in Table 1 are dedicated to the performance of the algorithms for finding all solutions to a standard façade of 18×10 meters (less than one second of CPU time), completeness of search, whether the optimal solution is reached (minimum number of panels), if the algorithm generates diversity of solutions and aesthetics (symmetry of the solutions).

As the table shows, the constraint-based algorithm [3] is the more robust solution for the design problem although it takes more time due to the search space exploration. However, it lacks of mechanisms to generate symmetrical solutions as the modeling of aesthetics under constraint satisfaction is intricate. The guillotine cutting approach implemented in the *Casye* algorithm presents symmetrical insulating envelopes not generated by the greedy [2], nor constraint-based [3] algorithms. As illustration of the aesthetic difference, the same façade insulation envelop generated by each one of the algorithms is presented in Fig. 4.

TABLE I
COMPARISON OF CASYE WITH TWO OTHER ALGORITHMS

	Greedy [2]	Constraints [3]	<i>Casye</i>
Performance	+	-	+
Complete	-	+	-
Optimal	-	+	-
Diversity	+	+	-
Aesthetics	-	-	+

The proposed solution tries to artificially behave as a human in the sense that conflicts with frames are avoided while attempting to provide a pleasant appearance. Further, the architect may use a generated insulating envelope as a good basis for designing a new solution: the relevant envelope can be therefore adapted and tuned by adding some tacit knowledge (really difficult to formalize), such as his/her own artistic flair, in order to

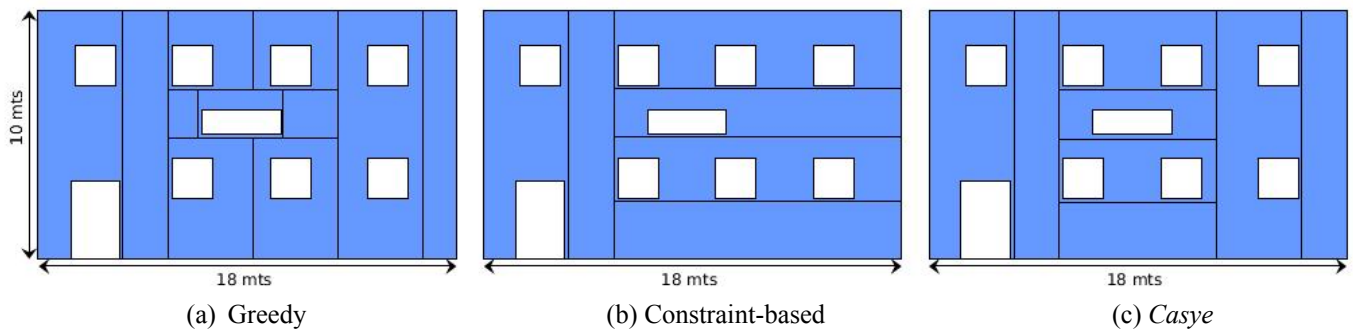


Fig. 4 – Greedy, Constraint-based and *Casye* Solutions

turn the renovation more pleasing to the eye or give it an architectural expression. A future direction of this work is then to improve the solutions generated by the algorithm *Casye* using other known techniques, for instance, using a meta-heuristic technique that allows the solution to evolve either to a more symmetrical solution or to an optimal one. Inclusion of different aesthetics concepts is as well open to future work. The design of insulating envelopes for façades is then supported by our work.

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REFERENCES

- [1] M. Aldanondo, A. F. Barco, E. Vareilles, M. Falcon, P. Gaborit, and L. Zhang, 'Towards a bim approach for a high performance renovation of apartment buildings', in *Product Lifecycle Management for a Global Market*, eds., S. Fukuda, A. Bernard, B. Gurumoorthy, and A. Bouras, volume 442 of IFIP Advances in Information and Communication Technology, 21–30, Springer Berlin Heidelberg, (2014).
- [2] A. F. Barco, E. Vareilles, M. Aldanondo, and P. Gaborit, 'A recursive algorithm for building renovation in smart cities', in *Foundations of Intelligent Systems*, volume 8502 of Lecture Notes in Computer Science, 144–153, Springer-Verlag, (2014).
- [3] A.F. Barco, J.G. Fages, E. Vareilles, M. Aldanondo, and P. Gaborit, 'Open packing for facade-layout synthesis under a general purpose solver', in *Principles and Practice of Constraint Programming*, ed., G. Pesant, volume 9255 of Lecture Notes in Computer Science, 508–523, Springer International Publishing, (2015).
- [4] S. Battiato, A. Milone, and G. Puglisi, 'Artificial mosaic generation with gradient vector flow and tile cutting', *JECE*, 2013, 8:8–8:8, (January 2013).
- [5] M. Bauerly and Y. Liu, 'Effects of symmetry and number of compositional elements on interface and design aesthetics', *International Journal of Human-Computer Interaction*, 24(3), 275–287, (2008).
- [6] J. A. Bennell, J.F. Oliveira, and G. Wascher, 'Cutting and packing', *International Journal of Production Economics*, 145(2), 449–450, (October 2013).
- [7] N. Christofides and E. Hadjiconstantinou, 'An exact algorithm for orthogonal 2-d cutting problems using guillotine

cuts', *European Journal of Operational Research*, 83(1), 21 – 38, (1995).

[8] L. Greco and M. Cascia, *Image Analysis and Processing–ICIAP 2013: 17th International Conference*, Naples, Italy, September 9-13, 2013, Proceedings, Part II, chapter Saliency Based Aesthetic Cut of Digital Images, 151–160, Springer Berlin Heidelberg, Berlin, Heidelberg, 2013.

[9] T. Jacobsen and L. Hofel, 'Descriptive and evaluative judgment processes: Behavioral and electrophysiological indices of processing symmetry and aesthetics', *Cognitive, Affective, & Behavioral Neuroscience*, 3(4), 289–299.

[10] I. C. McMannus, 'Symmetry and asymmetry in aesthetics and the arts', *European Review*, 13, 157–180, (10 2005).

[11] T. Strecker and L. Hennig, *Operations Research Proceedings 2008: Selected Papers of the Annual International Conference of the German Operations Research Society (GOR)* University of Augsburg, September 3-5, 2008, chapter Automatic Layouting of Personalized Newspaper Pages, 469–474, Springer Berlin Heidelberg, Berlin, Heidelberg, 2009.

[12] A. N. Tuch, J. A. Bargas-Avila, and K. Opwis, 'Symmetry and aesthetics in website design: It's a man businesses, Computers in Human Behavior, 26(6), 1831 – 1837, (2010). Online Interactivity: Role of Technology in Behavior Change.

[13] E. Vareilles, A.F. Barco, M. Falcon, M. Aldanondo, and P. Gaborit, 'Configuration of high performance apartment buildings renovation: A constraint based approach', in *IEEM 2013 International Conference*, pp. 684–688, (Dec 2013).

[14] G. Wascher, H. Haußner, and H. Schumann, 'An improved typology of cutting and packing problems', *European Journal of Operational Research*, 183(3), 1109–1130, (December 2007).