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Constraint-Based Feedback for the Interactive Design of Buildings Thermal Insulating Envelopes

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Abstract

This paper discusses how to support the manual interactive design of buildings thermal insulating envelopes by means of a decision support system. The system provides visual feedback to the user design actions thus assisting its decision-making in real-time. The design problem has been modeled as a constrained two-dimensional packing problem that acts as foundation for an algorithmic solution for designing envelopes. Both model and implementation choices are discussed.

Keywords: Building renovation; constraint satisfaction; interactive design; product configuration; decision-support systems;

1. Introduction

Two-dimensional packing problems consist in allocating a set of two-dimensional items into a set (possibly a singleton) of two-dimensional larger objects in such a way that items are completely contained in the objects without overlapping [1]. A particular instance of two-dimensional packing problem arises in the context of thermal building renovation [2]. This special case deals with the design of an *insulating envelope* by packing a set of rectangular and parameterizable panels (items) over rectangular facade (objects). The insulating envelope is used to reduce the thermal transfer between the interior and the exterior of the building in the aim of reducing the building's energy consumption and thus deal with the countries' green development policies.

In order to help the person in charge of the thermal renovation, referred to as user or architect, to design the insulating envelopes, a decision-support system (DSS) with several algorithmic solutions has been developed [3]. The DSS can solve this particular design problem by the use of two different algorithms: The first, named *GaLaS*, using an on-the-fly greedy approach [4] and the second one, named *OpackS*, using a filtering-based approach [5]. Each generated envelope may be tuned by the architect and thermal performance is computed for each design solution. However, the proposed algorithms do not allow a manual design but rather automatic ones.

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In this paper, the focus is made on a third algorithm, named *InDie*, which allows a manual and constructive way to design consistent insulating envelopes: The architect draws, i.e. places and sizes, one by one the panels in order to completely cover the facades. To avoid inconsistent panels and consequently insulating envelopes, the architect needs feedback to be sure when drawing panels that they can effectively be manufactured, transported to the working site, assembled and mounted on the walls. It is then the task of the DSS to aid the construction process by informing the architect of constraint conflicts. This design may be seen as a guided design, meaning that the reactions of the DSS to the user's actions (interaction) must be clearly identified. These identified actions are built on the top of a constraint-based model stating the limitations of the insulating envelope design.

The solution presented in this paper implements the constructive approach to interactively guide the architect in his/her design and see, in real-time, the impact of his/her own panels' dawning in regard to the renovation conditions. We do so by developing validation functions for each of the constraint in the model. The solution may be implemented in any functional language without relying on complex black-box tools as constraint solvers, linear programming libraries or meta-heuristics. Further, we propose a web-oriented Java-script implementation that gives the possibility to have a real-time interaction with the user by evading potential network traffic and delays.

The remaining of the paper is divided as follows. In Section 2, the facade and insulating envelope elements are introduced. In Section 3, the constraint-based definition of the problem is presented. In Section 4, the general scheme of the solution is discussed. Finally, some conclusions are discussed in Section 5.

2. Building thermal renovation

The addressed problem appears in a large French multi-partner project that aims to industrialize buildings thermal renovation in order to reduce energy consumption of buildings [2,6]. This renovation is firstly based on a complete, true and accurate description of each of the facades in terms of geometry (position and size of old openings) and structure (position and of the façade's supporting areas able to support panels weight) and, secondly, on a precise description of the configurable panels (bounded size and weight). This first-hand knowledge enriched by the user's expectations about the renovation leads to an insulating envelope taking into account all the stakeholders' requirements. In this section, the problem from the industrial point of view is presented.

2.1. Elements

A facade is represented by a rectangular 2D coordinate plane with origin of coordinates at the bottom-left corner of the facade (fac_{xo}=0, fac_{yo} = 0), and contains rectangular zones defining precisely (around 1 mm):

- Perimeter of facade with it size (height and width in meters).
- Openings (old single-glazed openings over the facade) defined with:
  - Origin point (x,y) with respect to origin of facade.
  - Width and height (in meters).
- Supporting areas, such as slabs and shear walls, defined with:
  - Origin point (x,y) with respect to origin of facade.
  - Width and height (in meters).

Panels are rectangular, of varying sizes and may include new openings (replacing the existing ones) and have:

- Size (height and width in meters). Height and width are constrained by a given lower and upper bound related to manufacturing, environmental and transportation limitations.
- New openings (replacing the existing ones). Given internal structure of rectangular panels, new openings must respect a parameterizable minimum distance (d) with panel's borders.

2.2. Design limitations

The problem subject of our study has five particularities. First, unlike most packing problems in the literature, the number of panels used to create an insulating envelope is not known before the design process starts. In addition, the size of panels is bounded to a given interval product of manufacturing and transportation conditions. Second, new openings must be completely included, and therefore overlapped, by panels. Any of these openings must be covered with only one panel, meaning that the partial overlapping of openings by panels is forbidden. Third, panels are directly mounted on the walls, attached in supporting areas, which will uniformly distribute their weight thus preventing them to fall and the facades to collapse. As expected panels overlapping are forbidden and, given the renovation context, holes are impractical for the thermal insulation then panels must be adjacent to each other.

3. Constraint model

In this section, the packing problem is formalized as a constraint satisfaction problem. Now, in order to give limit to variables, a set of parameters containing geometrical and structural information linked to the facade is needed. Each renovation being unique, the problem has to be tuned considering some parameters:

- Perimeter of facade with it size (height and width in meters).
- Height fac_h and width fac_w in meters.
- Set *O* of openings and for each opening *j*:
  - Origin point (o_x^j,o_y^j) with respect to origin of façade (fac_{xo},fac_{yo}).
  - Width o_w^j and height o_h^j in meters.
- Set *Sa* of supporting areas and for each supporting area *k*:
  - Origin point (sa_x^k,sa_y^k) with respect to origin of facade (fac_{xo},fac_{yo}).
  - Width sa_w^k and height sa_h^k in meters.

Decision variables are linked to the position and size of panels in an envelope. Assume that *N* represents the number of panels in a given envelope. Then, each panel p^i with $1 \leqslant i \leqslant N$ is described by:

- Its width $p_w^i \in [min_w , max_w]$
- Its height $p_h^i \in [min_h , max_h]$
- Its coordinates (p_{x0}^i,p_{y0}^i), bottom-left corner of the panel w.r.t. the origin of facade (fac_{xo},fac_{yo}).

The knowledge extracted by stakeholders (e.g., architects and building renovation companies) have been mapped into the constraints presented in Table 1, stating the properties that consistent panels and envelopes must possess.

Table 1. Constraints for envelopes design in disjunctive form.

Number	Name	Disjunctive form
C1	Size constraint	$\forall p_i , 1 \leqslant i \leqslant N : min_w \leqslant p_w^i \leqslant max_w \wedge min_h \leqslant p_h^i \leqslant max_h$
C2	Panels and openings	$\forall o^j \in O, \exists p^i, 1 \leqslant i \leqslant N \mid p_{x0}^i + d \leqslant o_x^j \wedge o_x^j + o_w^j \leqslant p_{x0}^i + p_w^i + d$ $\wedge\ p_{y0}^i + d \leqslant o_y^j \wedge o_y^j + o_h^j \leqslant p_{y0}^i + p_h^i + d$
C3	Installation	$p^i , 1 \leqslant i \leqslant N$: $\exists sa^k \mid (sa_x^k \leqslant p_{x0}^i \wedge p_{x0}^i \leqslant sa_x^k + sa_w^k \wedge sa_y^k \leqslant p_{y0}^i \wedge p_{y0}^i \leqslant sa_y^k + sa_h^k)$ $\exists sa^l \mid (sa_x^l \leqslant p_{x0}^i \wedge p_{x0}^i \leqslant sa_x^l + sa_w^l \wedge sa_y^l \leqslant p_{y1}^i \wedge p_{y1}^i \leqslant sa_y^l + sa_h^l)$ $\exists sa^m \mid (sa_x^m \leqslant p_{x1}^i \wedge p_{x1}^i \leqslant sa_x^m + sa_w^m \wedge sa_y^m \leqslant p_{y0}^i \wedge p_{y0}^i \leqslant sa_y^m + sa_h^m)$ $\exists sa^n \mid (sa_x^n \leqslant p_{x1}^i \wedge p_{x1}^i \leqslant sa_x^n + sa_w^n \wedge sa_y^n \leqslant p_{y1}^n \wedge p_{y1}^n \leqslant sa_y^n + sa_h^n)$
C4	Non-overlapping	$\forall p^u,q^v \mid p_{x0}^u \geqslant p_{x0}^v + p_w^v \vee p_{x0}^v \geqslant p_{x0}^u + p_w^u \vee p_{y0}^u \geqslant p_{y0}^v + p_h^v \vee p_{h0}^v \geqslant p_{y0}^u + p_h^u$
C5	No holes	$\sum_{i=1}^{N} (p_w^i \times p_h^i) = fac_w \times fac_h$

4. Visual feedback interaction

As explained before, our efforts focus on providing to architects an interactive design of insulating envelopes in real-time. An interactive design refers to the system reactions to the user's actions in order to help him/her to reach her/his (design) goals [7]. Interactive behavior has been widely study in many knowledge areas and industry sectors [8-11]. Among other things, the human interface allowing the interactive communication is one of the major study topics in computer science and informatics [7].

On the other hand, we have real-time support. Real-time support refers to the capabilities of the DSS to react to the user's actions in “no time”. Real-time interaction is needed, mostly, when the user's actions require a response within the next 100 milliseconds (cf. Chapter 17 in [7]). For instance, for activities involving hand-eye coordination, the system must answer fast enough to not block the activity or deteriorate the results. In the envelopes design case, immediate support must be given to architects when designing each panel. This means that the underlying DSS must execute validation algorithms in such a way that the design process is continuously fed by the system responses.

Now, an alternative for doing manual design is to provide instantaneous feedback to the architect drawing. Essentially, this means that the manual design may be *interactively* guided by the DSS. When drawing a panel, the system may limit its size to the allowed one, visually inform of conflicts with openings and supporting areas, and ideally, completely avoid panels overlapping or inform about such overlapping. An interactive architect’s manual design of insulating envelopes would work as follows:

1. The system presents a drawing of the facade (blank page at the beginning).

2. The architect draws a panel over the facade while the system informs: If the size of the panel is oversized or undersized, if the panel is in conflict with some openings, if the panel cannot be installed because it cannot be attached and if the panel is in conflict with an already designed panel.
3. The architect iterates step 2 until satisfaction.

A given drawn panel may be re-designed by the architect as part of aesthetics considerations or as constraint conflicts may get solved. This means that inconsistent definition of panels should be possible. Further, stopping inconsistent panels' definitions may be counterproductive for the aesthetic expression of architects. The underlying algorithms inform the architect that constraints are being violated but it is the architect who decides lastly the position and size of panels. Among the set of alternatives to support architect's manual design, we have chosen:

- Informing about constraint conflicts is done visually: Our design choice is to set different colors for consistent panels (green) and inconsistent ones (red).
- As an invariant, for drawing a panel, each of the previously drawn panels must be consistent.
- When re-designing a panel, colors are changed interactively depending on constraint conflicts.
- Gaps between panels are not conflictive for the result. In other words, when doing manual interactive design, the area constraint *C5*, that implies no holes, is ignored.

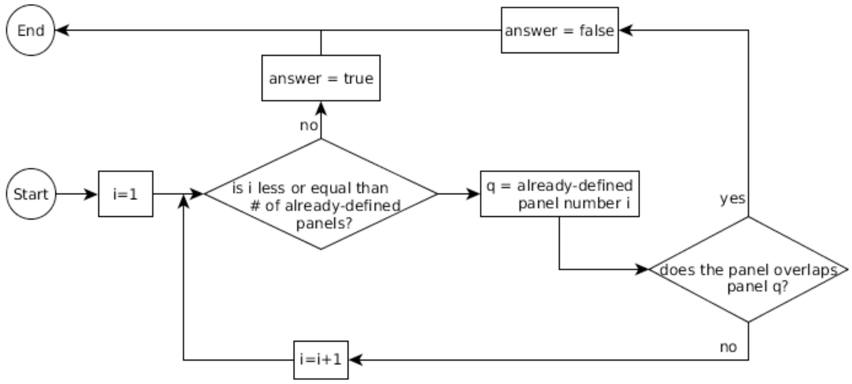

Fig. 1. Non-overlapping validation algorithm.

Thus, the DSS has two responsibilities: detecting that constraint conflict exists for the selected/drawn panel, and informing the user about those conflicts. The former responsibility is fulfilled by validation algorithms as the one presented in Fig. 1 for the non-overlapping constraint. The latter responsibility is fulfilled with the GUI capabilities. No details about the GUI capabilities are provided as they are of marginal interest to our work.

5. Conclusions

The industrial thermal renovation of buildings has to cope with a multiple and diverse set of requirements, guidelines and constraints coming from urban design guidelines, owners' expectations, tenders' wishes and architects' skills and ability in design art. Within these, two key functional requirements have been identified: Been able to do manual and automatic design of envelopes. In this paper, we have shown how the manual design of buildings insulating envelopes may be made interactive with a visual communication with the user. Then, we have discussed the fact that the interaction may be implemented as a visual feedback that allows the design support to be executed less than 100 milliseconds thus providing real-time interaction with the user. To get a better view of our solution, we encourage the reader to access a video presenting the decision support system, and the solution behavior, that we have implemented [12].

Perspectives. Two main perspectives emerge from our proposals: the first one deals with the explanation of the conflicts. Currently, the user is just informed visually that a conflict exists without any clue about the reasons of this conflict. Indeed, we consider that the user is quite an expert and is aware of all the model constraints. But in a case of a *lambda* user, the DSS needs to provide some information about the origin of the conflict. We have to notice that the origin of conflicts can be linked to several reasons: a panel can be at the same time over-sized, in conflict with an opening and in conflict with another panel. This kind of information is essential to help a non-expert user to solve a conflict and make the panel consistent. The second perspective deals with the conflict solving. When a conflict occurs, several solving possibilities exist: resize the panel, move it, etc. The DSS should be able to help the user by proposing some solutions consistent with the model constraints, such as one solution keeping the position of the panel and resizing it to become consistent or another one retaining the size (if consistent with the size constraint) of the inconsistent panel and moving it to a relevant position, etc.

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