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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.

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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.