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Interactive Configuration of High Performance Renovation of Apartment Buildings by the use of CSP

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Abstract

This paper is a prospective study which looks at the possibility of configuring high performance renovation of apartment buildings by the use of constraint satisfaction problem (CSP). This study is one part of a project called *CRIBA* which aims to industrialize high performance thermal renovation of mid-rise (up to seven stories) apartment buildings. The renovation is based on external rectangular panels, always comprising insulation and cladding, and sometimes including, in addition, doors, windows or solar modules. The panels can be fixed directly onto the walls or onto a metal structure around the whole building. With the new thermal envelope and equipment, the building must achieve a really low energy performance of $25\ kWh/m^2/year$. A configuration system, based on CSP approaches, will simultaneously enable the interactive definition of the renovation, the associated bill of material (BOM) and the building site assembly process. In Section two, we set out the industrial problem of residential buildings renovation and explain how a configurator can support it. Then, in the third section, the renovation configuration process is described. In the fourth and final section, we present how the renovation configuration can be addressed with constraints, and we introduce relevant CSP approaches. Through out the article, industrial examples illustrate our proposal.

1 Introduction

The global contribution from buildings (residential and commercial) towards energy consumption has steadily increased. Buildings account for around 20% and 40% of the total final energy consumption in developed countries: 37% in the EU [Perez-Lombard *et al.*, 2008], 36% in the USA [Council, 2013] and 31% in Japan [Center, 2012]. It has now exceeded the other major sectors: industry and transportation. Growth in population, enhancement of building services and comfort levels, together with the rise in time spent inside buildings assure the upward trend in energy demand will continue in the future. Therefore, reducing energy consumption of the building sector is one of our century's challenges. For this reason, it is a prime objective for energy policy at regional, national and international levels.

In several countries, research works are carried out on the efficient measures to take to reduce energy consumption of the building stock. Most states set regulations to improve the energy performance of new buildings. However, the annual rate of construction of new dwellings is only 1.1% in Europe [Poel *et al.*, 2007]. It is therefore very important to renovate the existing buildings to really reduce their energy consumption and to assist the retrofit process by the development of decision support systems [Juan *et al.*, 2010].

This study is one part of a research project called *CRIBA*, which aims to industrialize high performance thermal renovation of apartment buildings. In this project, a very innovative renovation system based on large timber frame panels will be designed. Moreover, all the tools needed to industrialize the renovation process will be developed:

- a new method for three-dimensional building survey and modelling,
- a configuration system for the design of the buildings new thermal envelope (bill of material and assembly process),
- a working site planning model with resource constraints.

The aim of this paper is to present a prospective study on the development of the interactive configuration system for the renovation of apartment buildings.

Therefore, the remainder of the paper is organized as follows. In Section 2, we present the building renovation problem and how the configurator can support apartment buildings renovation. In Section 3, we put forward some ideas on the generic renovation bill of material. In Section 4, we outline the building renovation configuration process. In Section 5, we identify the different kinds of constraints that are needed in order to make the apartment building renovation model.

2 Building Renovation Configuration Needs

In this section, we introduce the building renovation problem which is at the origin of our work. Then, we express what the configurator is expected to generate as results.

2.1 Building Renovation Problem

The industrialized high performance thermal renovation is based on external rectangular panels, always comprising insulation and cladding, and sometimes including, in addition, doors, windows or solar modules. Although the shape of the panels is a major limitation for the architectural creativity, this assumption is the key of renovation industrialization and matches most of apartment buildings.

The building sector is very dependent on hand-made methods which are not always synonymous with quality guarantee [Falcon and Fontanili, 2010]. Therefore, the aim of the *CRIBA* project is to prefabricate all the panels needed for a renovation, in a correct order, then to deliver them directly to the working site and finally to hang them on the faades. Therefore, the renovation process enables thermal renovations:

- at low cost, considering all the positive elements, fixed cost, logistic, etc,
- in a short time,
- of high quality,
- in a good environmental balance,
- without rehousing the inhabitants during the renovation works.

Depending on the building strength of materials, the panels can be fixed directly onto the faades or onto a metal skeleton around the whole building. With the new thermal envelope and equipment, the building must achieve a really low energy performance of $25kWh/m^2/year$. In order to reach such a low energy performance, the new thermal envelope has to wrap the whole building. All the faades are covered by non-overlapping panels and are space-partitioned.

2.2 Building Renovation Configuration

The interactive configuration system for the renovation of apartment buildings will simultaneously enable the interactive definition of the renovation thanks to the associated bill of material [Felfernig, 2007] and the building site assembly process.

The bill of material is a list of the components and sub-components, sub-assemblies, and the quantities of each needed to manufacture an end product. It can have multiple options and variants. In our case, we consider:

- the new thermal envelope as the end product;
- the facade new envelopes as the sub-assemblies;
- the complete panels as sub-components;
- the configurable components as leaves of the bill of material (BOM):
  - the panels, which are placed on the faades, include wood structure, insulation and cladding (three or four types at the moment), as shown in Fig. 1,
  - the angles, which make the junction between two faades. An angle is a specific type of panel which cannot include other components,
  - the windows, doors, solar modules and balconies,
  - the metal fasteners, which are used to fix either metal profiles or directly the panels onto the faades. There are several types of metal fastener depending on their type (fasteners to fix metal profiles, to hang panels or to provide wind bracing of panels), their load bearing capacity and the distance between the structural elements of the present facade and the panels,
  - the metal profiles, which are used when the structural elements of the present facade cannot support the load of the new envelope. They are fixed onto the metal fasteners and the panels are hung on them. There is only one type of metal profile but its length has to fit the facade height.

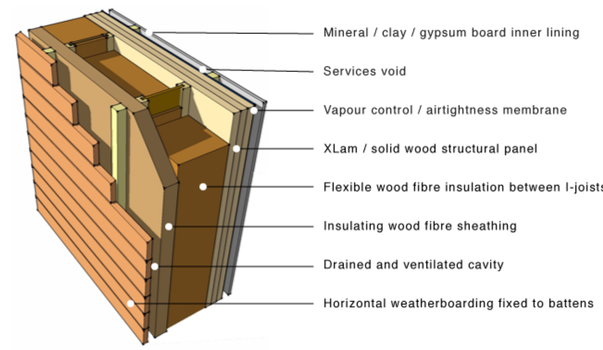

Figure 1: CRIBA Panels

The assembly process consists in a set of tasks to be carried out in order to assemble the new frame and envelope all around the building. It comprises some tasks that have always to be carried out, such as positioning and fixing metal fasteners, and some that are optional, such as fixing the metal profiles onto the metal fasteners.

At least, the configurator will give an idea of the renovation global cost which includes the costs of raw materials, transportation, labour and lifting devices.

On the first hand, in the configuration community, many authors (among them [Sabin and Weigel, 1998], [Soininen *et al.*, 1998]) have shown that product configuration could be efficiently modelled and aided when considered as a Constraints Satisfaction Problem (CSP) [Montanari, 1974]. On the other hand, in the civil engineering community and in the constraints community, many authors ([Honda and Mizoguchi, 1995], [Junker, 2006], [Medjdoub and Yannou, 2001], [Zawidzki *et al.*, 2011] or [Regateiro *et al.*, 2012]) have shown that spatial layout can be solved with CSP. Consequently, we address the building renovation configuration with constraints and filtering algorithms.

3 Generic BOM Model

In this paper, we focus on the interactive definition of the renovation bill of material. In this section, we highlight the main variables of the configurable components of the renovation BOM. We focus in this paper on the panels and the angles. At the end of the configuration, all the configurable components variables have a single value, given either by the user or deduced by the configurator.

3.1 Panels

The panels are rigid 2D rectilinear rectangles. That means that their sides are parallel to the facade reference axis. Let us consider one facade. All the panels covering it belong to a unique vertical plane. They are adjacent (they are at least one side in common) and are not overlapping themselves. By the way, they have all the same orientation. They cover completely the facade and make a partition of it.

The main variables of a panel refer to:

- its width $[min_w, max_w]$,
- its length $[min_l, max_l]$,
- its coordinates (abscissa and ordinate),
- its insulation thickness $[min_i, max_i]$,
- the insulation type (mineral wool or cellulose),
- its weight, which depends on its dimensions, the insulation type, and the components that are included in itself.

If the panel includes other components (windows, doors or solar modules), we need to know exactly for each of them:

- its width $[min_w, max_w]$,
- its length $[min_l, max_l]$,
- its relative position on the panel (x and y),
- its type and reference code.

A minimal distance is required between the sides of the panel and the position of other components: the distance cannot be lower than 90 mm in order to preserve the panel stiffness.

3.2 Angles

The prefabricated angles are rigid 3D L-polyomino tetracubes which are placed at the building corners. The corners are at the intersection of two consecutive and perpendicular facade planes. We assume then that the angles are right. Otherwise, a specific design task must be carried out in order to design the relevant angles.

Let us considering a corner. All the angles covering it belong to a unique vertical row. They are adjacent (they are at least one side in common) and are not overlapping themselves. By the way, they have all the same orientation. They covered completely the corner and make a partition of it.

The main variables of an angle refer to:

- its width $[min_w, max_w]$,
- its right length $[min_{rl}, max_{rl}]$,
- its left length $[min_{ll}, max_{ll}]$,
- its coordinates (abscissa and ordinate),
- its insulation thickness $[min_i, max_i]$,
- the insulation type (mineral wool or cellulose),
- its weight, which depends on its dimensions and the insulation type.

For the first version of the BOM, the prefabricated angle cannot include other components. The angles dimensions directly depend on the sizes of their adjacent panels, with a minimal length (right and left) equal to 90 mm in order to preserve the angle stiffness.

4 Building Renovation Configuration Process

The building renovation configuration is a top-down and multi-step process, which progressively converges from the working site to the configurable components. The user has to input some information and data in order to configure the renovation. After each user input, the configurator removes inconsistent values and guides progressively the user to a consistent solution. The user has to follow this process and gives information on:

- the whole working site. The working site description has an impact on the panels dimensions. Let us focus on the working site accessibility and its local atmosphere. Concerning its accessibility, if you can access the working site with special convoys, the panels can be as wide and long as needed. Otherwise, the dimensions of the panels are constrained by the size of the trucks which can access to the working site. Concerning the local atmospheric, if the working site area is very windy, wind speed peaks $\geq 80\ km.h^{-1}$, the panels have to be smaller in order to be fixed onto the faades, and the renovation lasts longer because of nonworking periods.
- the block of apartment buildings. The block description has directly an impact on the hoisting equipment and indirectly on the panels dimensions. If the block cannot be accessible with a tower crane, the panels have to be smaller in order to be conveying to the faades with an other suitable hoisting equipment, such as a telescopic boom lift.
- the apartment building. The apartment building description has an impact on the panels dimensions. Let us consider only the apartment building height. If the apartment building height is lower than twelve meters (four stories), the height of the panels can be the same as the building one so that the panels are fixed vertically on the faades.
- the faades. Let us focus on a facade.
  1. First of all, the user has to describe precisely the structure and the geometry of the facade. Considering the structure of the facade, (s)he needs to input where the metal fasteners can be fixed on the facade. A structural study has to be done in order to characterize the load bearing capacity of every area of the facade. Considering the geometry, the positions of windows, doors and balconies have to be known precisely. Only a topographic survey can provide these information.
  2. Regarding these areas and their characteristics, the decision of fixing the panels directly on the facade or on the metal profiles can be made. This decision has an impact on the BOM (metal fastener type and optional metal profiles) and on the assembly process (tasks devoted to metal profiles, such as delivery, assembly and adjustment).
  3. Having information about the working site, the block, the apartment building and the facade and the impact on the panels dimensions, the drawing of the facade layout can start. The user has now to

indicate what the aesthetic effect she/he wants for the facade. For instance, she/he can want continuous vertical joints, which means that the panels are fixed vertically or she/he can want a checkerboard effect with a lot of similar panels.

4. Knowing the facade layout, each panel has to be configured. If the panel is solid, one can decide to add solar modules or to add an exit door. If the panel has to include windows, doors and/or balconies, the suitable reference code has to be selected for each of them.

- the angles. The renovation configuration finishes by the configuration of the angles. At this step, only the height of angles has to be determined.

At any time in every step of the configuration process, the user can change her/his inputs and see their impact on the configuration solutions.

5 Building Renovation Configuration and Constraints

Interactive renovation configuration is provided by constraint propagation that prunes bad solutions and progressively guides the way to good ones. In apartment buildings renovation, the range of knowledge to exploit and to model leads us to integrate into a single configurator different constraints types as well as their filtering methods. In this section, we outline the kind of variables and constraints that are necessary to formalize apartment building renovation model.

5.1 Classical CSP Approaches

In building renovation configuration, we have to formalize different kinds of knowledge relevant to:

- civil engineering regulations that must be followed absolutely to the letter. For instance, fire barriers have to be installed between two consecutive stories in order to stop the spread of fire,
- civil engineering know-how that is the core knowledge of the companies involved in the *CRIBA* project,
- working site assembly process that allows us to define the suitable way of assembling the new frame and envelope all around the building.

For instance, we have seen in Section 4, that the working site local atmosphere has an impact on the panels dimensions: if the working site area is very windy, wind speed peaks ≥ 80 $km.h^{-1}$ several times a year, the panels have to be smaller in order to be fixed onto the faades without stopping the renovation with nonworking periods.

As the range of knowledge to model is wide, we need to use different CSP approaches and their filtering algorithms, such as discrete CSP ([Montanari, 1974], [Mackworth, 1977], [Bessire and Cordier, 1993], [Faltings, 1994]), continuous CSP ([Lhomme, 1993] or [Benhamou *et al.*, 1994]) and mixed CSP ([Gelle, 1998]) depending on the type of the variables (discrete, continuous, symbolic or numeric) and the type of constraints (compatibility constraints or mathematical formulae).

5.2 Groups and Multi-instances of Constraints

In the renovation configuration, we have to cope with several instances of the same configurable components. For instance, in order to cover a facade with its new envelope, we need to configure x times a panel (such as described in Subsection 3.1). We do not know in advance how many panels will be necessary, as it depends on a lot of data (working site description, block description, etc.). Therefore, we need to group variables and constraints into sets or classes, which can be instantiated as much as needed.

5.3 Dynamic Constraints

We have seen in the building renovation configuration process, Section 4, that we can decide to fix the panels on a metal envelope, or to create new openings on a facade. These decisions imply firstly the consideration of new components in the BOM and secondly, the insert of their assembly tasks in the assembly process. Therefore, we need to take into account the activation of configurable components as defined by [Mittal and Falkenhainer, 1990], [Sabin and Freuder, 1996] and [Faltings *et al.*, 1992].

5.4 Geometric Constraints

In order to prefabricate the panels, we need to determine precisely the dimensions and the position of each component on the panels. The accuracy of the topographic measures and the precision of the components dimensions and position are the crucial factors for the industrialization of the building renovation and the goals of the *CRIBA* project. Therefore, in order to do so, we need to integrate to the configurator geometric constraints (for a complete survey, see, [Dohmen, 1995] or [Fudos and Hoffmann, 1997], and for more recent work see [Jermann *et al.*, 2000], [Zawidzki *et al.*, 2011] or [Regateiro *et al.*, 2012]).

5.5 Global Constraints

As we cannot know in advance how many panels are needed to cover a facade, we have to cope with constraints that depend on the number of instances of the same class. For instance, if the height of the facade is covered with more than one panel, the sum of all the panels heights has to be equal to the facade one. Therefore, we need to integrate and filter different kinds of global constraints [van Hoeve and Katriel, 2006].

6 Conclusion

The aim of this paper has been to present a prospective study on the development of the interactive configuration system for the renovation of apartment buildings.

Firstly, we have presented the apartment buildings renovation problem and what the main objectives of the *CRIBA* configurator are: the interactive definition of the renovation thanks to the associated bill of material and the building site assembly process as well as a first cost estimation. Then we have focused on two configurable components that are the panels and the angles and highlighted their main characteristics. In the fourth section, we have outlined the top-down and multi-step building renovation configuration process. In the final section we have put forward some ideas on the different kinds of CSP approaches we have to integrate in the configurator in order to support and guide the configuration of buildings renovation.

The apartment buildings renovation configuration is a challenge however you look at it. First of all, we want to industrialize a process that is nowadays traditionally made by craftsmen. This point is quite a revolution for the civil engineering field where only few industrial engineering methods are applied, and in particular in SMEs. Secondly, in order to be able to use a configurator, we need to extract, validate and formalize relevant knowledge. In our application field, the nature and the origin of knowledge are quite various. We have therefore to use different types of variables and constraints. The filtering engine has therefore to integrate different kinds of propagation methods. Thirdly, we need to cope with different variables priorities. For instance, all the variables which describe the whole working site have a strong impact on the dimensions of the panels and cannot be changed: we cannot decide to use a special convoy if the working site is not accessible with such a convoy. If an inconsistent solution is found, we will propose to the user to change her/his choices firstly on the panels and then to progressively zoom out to the whole working site.

As we are still in the very earliest stage of the *CRIBA* project and as apartment building renovation configuration is quite a complex process, we need to model in details the BOM components and their constraints. When this is done, we have to select, analyse, adapt and integrate constraints approaches and filtering algorithms in our propagation engine *CoFiADe*. *CoFiADe* has already been used for supporting heat treatments configuration [Aldanondo *et al.*, 2006], simultaneously product and planning configurations [Vareilles *et al.*, 2008] and helicopters maintenance configuration [Vareilles *et al.*, 2009]. The development of the graphical user interface in order to allow the user to see the result of her/his configuration is also a challenge. It is not the core of the configuration problem but it is clearly a need for the companies involved in the project.

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