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IFAC PapersOnLine 55-2 (2022) 487–492

Buildings energetic improvement: first elements about isolating panels layout design

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Abstract: The goal of this communication is to present the first ideas and proposition about the panels layout design problem in order to improve building energetic performances. First the origins and interest of the problem are presented. In two words, too many buildings with poor energetic performances and too low ratio of replacement lead to a very strong energetic retrofit need. Consequently, we describe the panels layout design problem, discuss some related works and propose the very first ideas in order to solve it with a heuristic approach. An example illustrates the problems and the propositions.

Keywords: Building energetic retrofit, isolating panels layout design, cutting and packing problem, configuration problem, layout optimization, constraint-based approaches

1. INTRODUCTION

The energy consumed by buildings for housing and economic activity represents an important part of the total energy consumption. It is constantly increasing and now reaches more than 40% in Europe and generates more than 35% of greenhouse gas emissions (Esser et-al 2019). This phenomenon, combined with the increasing scarcity of energy, which is becoming more and more expensive, encourages the construction of buildings with ever-improving thermal performance. However in Europe, the renewal rate of buildings is very low, in the order of 1 to 2%. If we were to rely on this renewal alone, it would take more than 50 years to bring the building stock up to the best energy level. It is therefore essential to support the development of energy renovation activities for existing buildings by industrialization and digitizing the energy renovation process.

Consequently, the proposed contribution belongs to a French national research project (ISOBIM) that proposes a set of computer aided tools dedicated to the assistance of energy renovation activities (Vareilles et-al 2015). The energy renovation is achieved with isolating panels fixed on the facades external of the buildings and the main assistance tools are : (i) building digitalization, (ii) panels layout design, (iii) panel manufacture planning (iv) on site project management. Our contribution deals with the second kind of tool that support panels layout design for building's façade. The considered buildings can have up to 6 or 7 floors.

As the work has just begun, our goal is to present the first ideas and some preliminary results. The contribution is consequently organized as follow: we first clarify and define the problem of panels layout design, then we discuss two solving approaches and propose at the end a potential combination of them.

2. THE PROBLEM OF PANELS LAYOUT DESIGN FOR BUILDING'S FAÇADE

We first introduce the considered panel solution, then describe how the façade should be modeled in order to allow panels layout design. This allows us to define our design problem and to introduce a key solution characteristic.

2.1 The isolating panels solution: two solutions

Two kind of panels solution exist.

The first one is a light solution, where the panels go around the facade singularities (window, door, balcony, various equipment's…), the panel are not heavy and are glued to the façade. Most of the panel measuring and cutting jobs are achieved on building site, the work is consequently most often artisanal and therefore not very industrialized.

The second one is a heavy solution where the panels integrate windows and doors in order to have a much higher building energy performance. These panels are heavier (up to some tons…) and are attached to supports deeply fixed into the resistant areas of the facade. Panels should be manufactured and assembled in a remote factory, they are delivered on site ready for mounting on the facade. The ISOBIM project relies on this solution and is the source of our panel's layout design problem.

Given this isolating solution, we can now define the facade model that fits our design problem.

2.2 The façade model for the panels layout design problem

Some assumptions are made for simplicity of the contribution, and we present here the key model features:
- A building is considered a set of vertical facades.
- A façade is modeled as a plane vertical rectangle, the panel design for potential triangle parts of the façade are considered

10.1016/j.ifacol.2022.04.241

to be done manually. A façade is defined with its width and height (w,h).
- Windows and doors are considered as industrial carpentry and are assumed to be rectangle. A window or door is defined by a position (x,y) with respect to the lower left corner of the facade and with a width and height (w,h).
- In order to attach panel, the support can be located on resistant areas that can correspond with : "floor-end" that are horizontal area between two floors, "cross-wall" that are vertical and separate rooms and “crossing” that are at the intersection of the two previous kinds of areas. These areas are defined by : a position (x,y) with respect to the lower left corner of the façade, a width and height (w,h) and a resistance in tons for supports (assuming a minimum on 1 meter between two supports).
- Two kinds of singularity areas can also exist in a façade. The first one is called “out-in” and require a full hole in a single isolating panel. This allows to consider for example: balconies, air-condition devices, light devices… The second one is called “out-out” and require that the panels go around this area as for example: garage door, non-horizontal ground. These areas are also defined by : a position (x,y) with respect to the lower left corner of the façade and a width and height (w,h).

An example of such a facade can be seen in figure 1 where dimensions are in cms. The panel design of the upper right triangle part is achieved manually. The considered façade is characterized by (w,h) = (2380,1240).Windows and doors are in white, resistant areas are in grey, out-in zone (balcony plus doors) are in horizontal dotted line, out-out zone (non-horizontal ground) are in vertical dotted line.

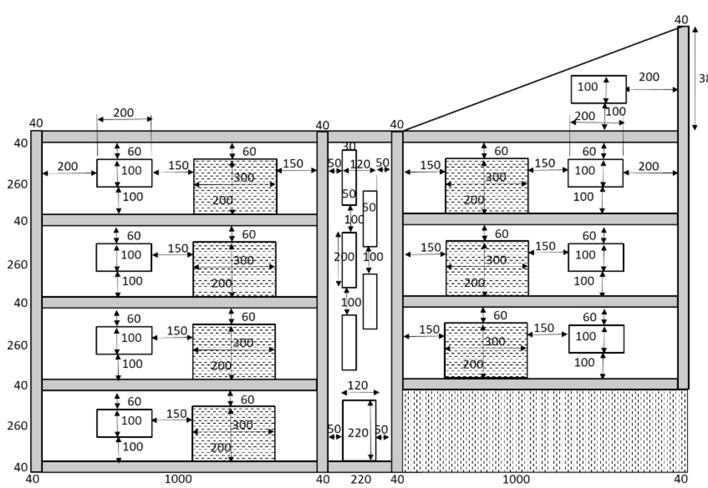

Figure 1 – A façade example

2.3 Problem constraints, solutions and key characteristic

The problem constraints relevant to the panel solution can be expressed as follows:
- The panel have minimum and maximum dimensions: width (Pwmin, Pwmax) and heights (Phmin, Phmax). For logistic and transportation constraints, all dimensions must be less than the truck load length (14 meters usually) and one dimension must be less than truck load height (3 meters usually). Consequently, maximum panel width and height are limited (usually (14 , 3) or (3 , 14)).
- The solution, as a set of panels, must cover the whole façade without any hole except “out-out” areas.
- Each panel much be larger than the integrated elements: window, door and out-in. A minimum distance (md) between the panel border and the integrated element must be respected.
- Each panel has a weight approximatively proportional with its area. This weight divided by the number of supports (given a minimum distance between two supports) should be less than the resistant area resistance.

Consequently, a solution is a set of panels, where each panel is characterized by:
- position (x,y),
- width and height (w,h),
- a list of supports characterized by their positions (x,y).
that respect all previous constraints.

It is clear that many solutions can exist, and some optimization criteria can helps to select a solution. As the goal is energy consumption of the building, a key criterion is to minimize the length of joins between panels where isolation coefficient are weak, closely related are the panel size to maximize and/or the number of panels to minimize. In some situations, in order to minimize production and mounting cost, solution with similar panels are preferred.

Given the previous problem and practitioner feedback, solutions are most of the time horizontal of vertical. This means that given a façade and a panel technique one panel “direction” is preferred and panels are either organized in layers or in columns. Of course, in some case it is not possible, and some mixes are necessary as very probably in the example of figure 1. This is this kind of problem which is interesting us.

3. FIRST SOLVING PROPOSITIONS

In a first section we consider related solving works. Then we propose a first heuristic approach and finally conclude about efficiency and optimality of the result.

3.1 Existing Solving approaches

Given previous definition, this problem can be associated with two families of problems: "cutting and packing" (Kendal et-al 2010) and knowledge based configuration (Felfering et al 20214).

Cutting and packing problems consider large and small objects and aim at placing the small ones in the large ones. Typical examples are: nesting of metal sheets, cutting of fabrics, arrangement of apartments or filling of containers. For two-dimensional problems, which our problem claims to be about, four parameters modulate the complexity of solution (Huang et-al 2013): (i) the existence of one or "n" large objects, (ii) the amount of small objects, fixed or to be determined, (iii) the size of all small objects, same or different, and (iv) the sizes of the small objects, fixed or to be determined.

Configuration problems consider that a product results from an assembly of predefined components (standard or configurable) respecting compatibility constraints and customer needs. The parameters modulating the complexity of this problem are: (i) the quantity of components of the product: fixed or to be determined, (ii) the nature of the components: standard (fixed dimensions or sizes) or parametrizable (dimensions or sizes to be determined but bounded) and (iii) the complexity of the constraints existing between the objects.

For these two problems in terms of solutions, when the quantity of small objects or components is fixed as well as their dimensions, it is possible to represent the solution space as a tree and to develop systematic search methods. When the problem is of reasonable size and the constraints allow to reduce the solution space, it is possible to consider the whole solution space and to find optimal solutions by mixing solving and constraint filtering methods. When we move away from these assumptions, it is more difficult to develop systematic search methods and the development of heuristics is then most often necessary.

It is clear that our panels layout design problem is at the top of the table in terms of complexity due to (i) quantities, sizes and positions of small objects to be determined and (ii) multiple geometric constraints. The most difficult feature to consider is undoubtedly the fact that the number of small objects is to be determined because it implies that the number of variables of the problem is not known when the solution search is launched. The work of (Vareilles et-al 2013 and Barco-Santa 2016) formalized this entire problem as a constraint satisfaction problem and showed that there are currently no generic and optimal approaches for all the diversity that can be encountered. Several greedy heuristics have been proposed and for a weakly constrained problem, an exact method exploiting the Choco solver has been proposed in (Barco-Santa et-al 2015) but its evaluation showed its limitations when the solution space becomes large.

3.2 Heuristic overview

Given previous results we therefore propose a solving heuristic relying on a layout processing that deals with either horizontal or vertical panels. Consequently, given a facade to process, the idea is to first determine if an horizontal or vertical layout is possible and if not to decompose the façade in sub-facades that could fit horizontal or vertical layout. Once this is achieved each façade or each sub-façade is processed with an horizontal or vertical layout.

The heuristic is shown in figure 2 and gives some priority to the horizontal layout. Globally, first a layout that is fully horizontal then fully vertical is searched. If no solution, an horizontal and then a vertical sub façade is searched with associated remaining sub-facades. The principle is to cut the entire facade or sub-facade into rows (horizontal layout) or columns (vertical layout) while respecting the constraints of: panel dimensioning, integrated elements (window, door and out-in), and panel lower edge in the resistant areas.

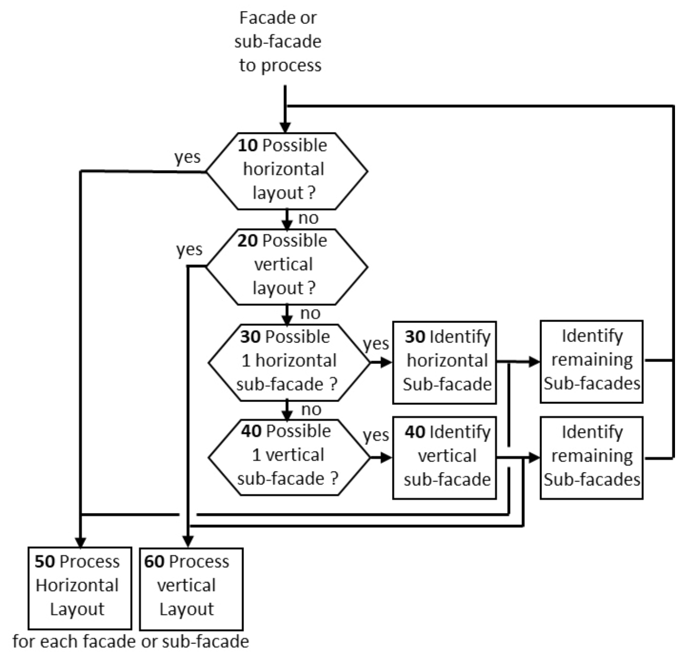

Figure 2 – Façade decomposition heuristic

3.3 Heuristic details

The heuristic of figure 2 works with a concept of "free zone". A free zone is a rectangle which is either horizontal or vertical. It crosses entirely the current façade or sub-façade without any intersection with elements: windows, doors, outin and outout.

For any current façade or sub-façade.

10 Check fully horizontal layout
11 - Identify all horizontal free zones
12 - For all couples of successive free zones, check if:
vertical distance between free zones
< panel max height – 2 * min distance between the panel border and elements
if no: no fully horizontal solution
check fully vertical layout (20)
if yes: possible fully horizontal solution
process horizontal layout (50)

20 Check fully vertical layout
21 - Identify all vertical free zones
22 - For all couples of successive free zones, check if:
horizontal distance between free zones
< panel max width – 2 * min distance between the panel border and elements
if no: no fully vertical solution
check sub-façade possible horizontal layout (30)
if yes: possible fully vertical solution
process vertical layout (60)

30 Check sub-façade possible horizontal layout
31 – If any, find the couple of successive horizontal free zones:
(i) that respects: vertical distance between free zones
< panel max height – 2 * min distance between the panel border and elements
(ii) with maximum length of horizontal overlapping elements (windows, doors, outin) between the horizontal free zones

if no couple: no sub-façade horizontal solution
check sub-façade possible vertical layout (40)
if yes:
Identify the rectangle between the free zone as an horizontal solution sub-façade with:
x = 0
z = middle of the lower floor-end
width = façade width
height = difference between lower/upper floor-end
Process horizontal layout (50) on this sub-facade
Identify one or two other remaining new sub-facades
Start the whole process (10) for each of them.

40 Check sub-façade possible vertical layout
41 – If any, find the couple of successive vertical free zones:
(i) that respects: horizontal distance between free zones < panel max width – 2 * min distance between the panel border and elements
(ii) with a maximum length of vertical overlapping elements (windows, doors, outin) between the vertical free zones
if no couple: exit problem solving
No layout solution for this façade or sub-facade
if yes:
Identify the rectangle between the free zone as a vertical sub-façade with:
if a cross-wall belongs to each vertical free zone,
x = middle of the left cross-wall
z = 0
width = difference between left/right cross wall middle
height = façade height
if no cross-wall belongs to each vertical free zone,
x = middle of the two free zone – panel max width/2
z = 0
width = panel max width
height = façade height
Process vertical layout (60) on this sub-facade
Identify one or two other remaining new sub-facades
Start the whole process (10) for each of them.

50 Process horizontal layout
60 Process vertical layout
For these two processes, we are either in a row or in a column that fits the panel size. Consequently, the layout solver just tries to maximize the width/height of each panel for horizontal/vertical layout. It is during this process that the panel final dimensions are decided. It is therefore at this step that the panel weight is taken into account as a constraint with respect to the resistance of the resisting area. And modulate panels dimensions.
It is also at this step that the use of a constraint solver could be of interest in order to maximize the panel size with respect to the resistance of the supporting areas.

3.4 Application to our example.

Running the heuristics on our example goes as follows.

Step 10 Check fully horizontal layout
Two horizontal free zones can be identified as shown in figure 3 with shaded rectangles. One between floor 1 and 2 and the other on the top of the façade.

The test 12 fails because the vertical distance between two free zones is much larger than the panel max height.
Consequently "check fully vertical layout" (20) is triggered.

Step 20 Check fully vertical layout
Four vertical free zones can be identified as shown in figure 4 with shaded rectangles. One (zf_1) on the left edge of the façade, a second one (zf_2) between windows and outin zone (balcony+window), a third one (zf_3) between the last outin and the stairway, the last one (zf_4) between the stairway and the outout zone.
The test 22 fails because the horizontal distance between (zf_2) and (zf_3) is much larger than the panel max width.
Consequently " check sub-façade possible horizontal layout" (30) is triggered.

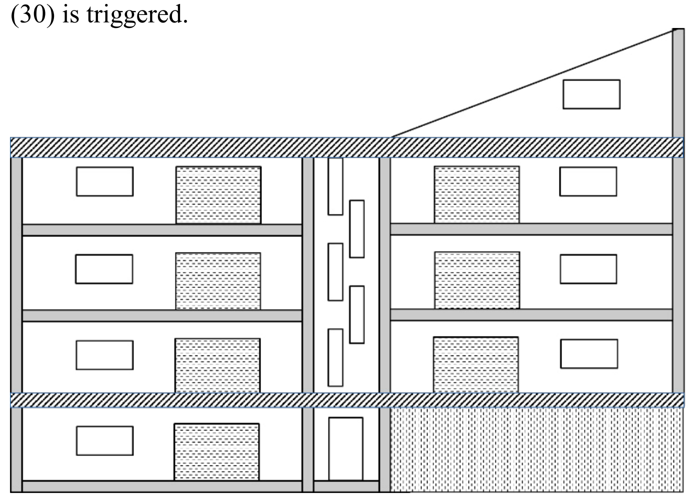

Figure 3 – Horizontal free zones

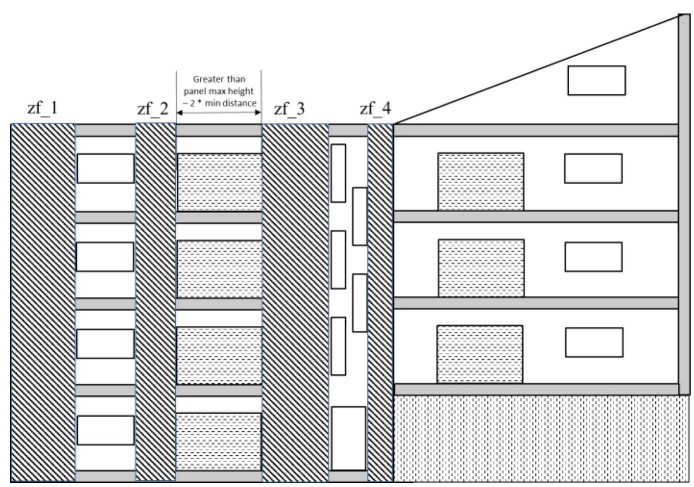

Figure 4 – Vertical free zones

Step 30 Check sub-façade possible horizontal layout
As the test 12 failed, the identification of 31 fails also.
Consequently " Check sub-façade possible vertical layout " (40) is triggered.

Step 40 Check sub-façade possible vertical layout
Two couples of vertical free zone are candidates: (zf_1, zf_2) and (zf_3, zf_4). The second couple (zf_3, zf_4) shows a larger length of vertical overlapping elements with five vertically overlapping windows.

Consequently, the rectangle between the two free zones (zf_3, zf_4) is considered as a vertical sub-façade (Vsf_1 on figure 5) . As a cross wall exist in each free zone:

x = middle of the left cross-wall = 1060
z = 0
width = difference between left/right cross wall middle = 260
height = façade height = 1240

Two other sub-facades, that will be identified (in a loop not detailed in this communication) as fully horizontal façades, (Hsf_2 and Hsf_3) on the left and right of the previous one (Vsf_1) are also as shown on figure 5.

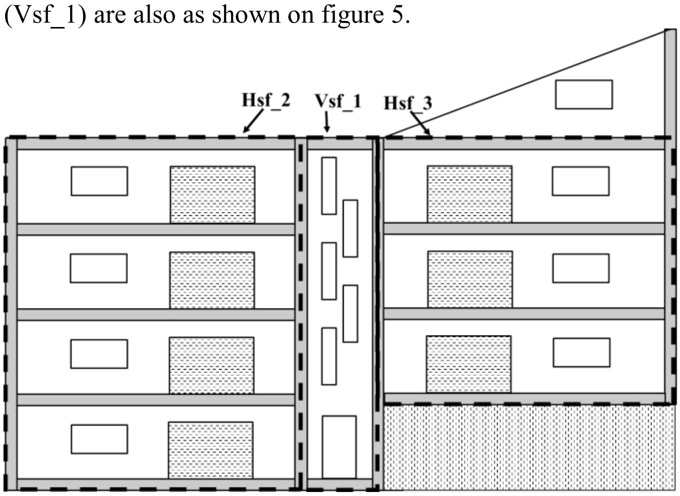

Figure 5 – Three sub-facades

Each sub-facades is then processed: Vsf_1 according to Process vertical layout (60) ; Hsf_2 and Hsf_3 according to Process horizontal layout (50). As the resistant areas are strong enough, large panels are enough: to cover vertically the vertical sub-facade (Vsf_1) and horizontally the two horizontal sub-facades (Hsf_2 and Hsf_3) as shown in the figure 6.

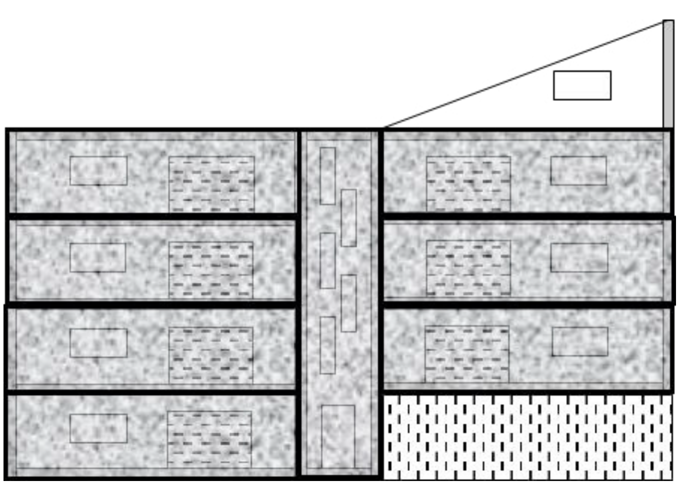

Figure 6 – Final layout

3.5 Discussion

This way to solve to the problem does not always lead to a solution. Very particular windows and doors distribution may forbid to find a suitable decomposition in horizontal and vertical sub-facades as the example shown in figure 7. However, this kind of situation is not very frequent mainly because of the building structure thar requires most of the time floor-ends and cross-walls that run all along the façade.

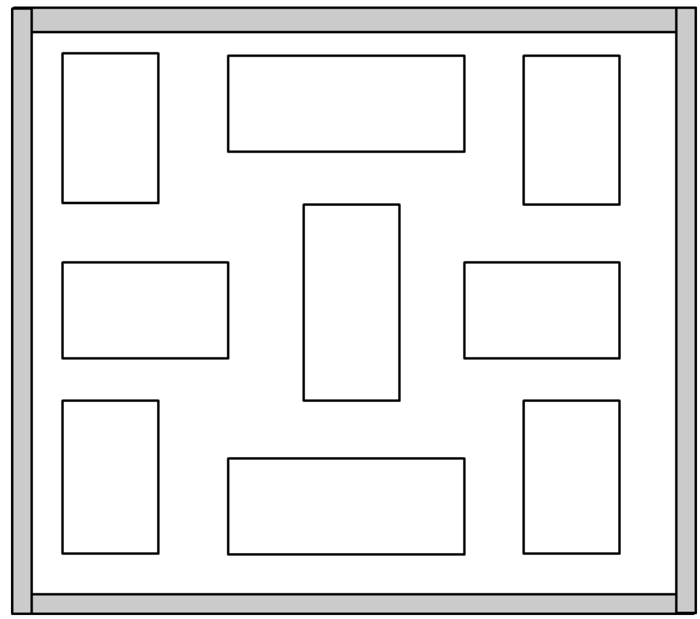

Figure 7 – Façade incompatible with our approach

The solution of figure 2 that sounds rather good is however not optimal with respect to the criterion length of joint between, panels. In fact, the solution shown in figure 8 is better because you replace a vertical join of 260 cms by an horizontal one of 220 cms. Our heuristic is not able to find this solution because our proposition to decompose the façade does not allow this layout. A pure constraint-based approach should be able to find this solution.

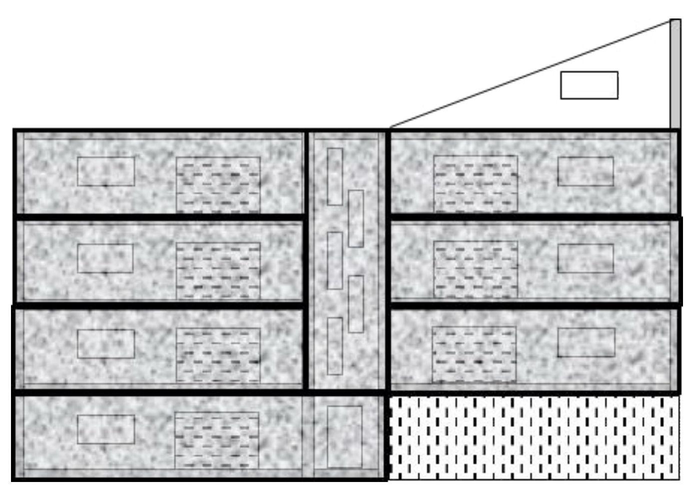

Figure 8 – A better layout solution for our example

As a partial conclusion, our proposition cannot deal with all the diversity of facades and cannot guarantee an optimal result. However, this first proposition is able to handle a rather large façade diversity and the results are not too far from an optimal one.

4. CONCLUSION

Our goal was to propose the very first ideas about the problem of panels layout design to improve buildings energetic performance. We have described the problem with almost all the constraints that exist in a real building energetic retrofit problem.

We have proposed a first heuristic-based solution that in fact
(i) decompose a whole façade problem in sub-facades problems
(ii) propose to solve each sub-façade independently.
The results sound rather robust but are not optimal and must be considered as a basis.

We are about to work now:
- on a detailed evaluation of this heuristics in terms of robustness with respect to façade diversity and distance to optimal solutions,
- on more fancy way to solve that would avoid the greedy and not optimal aspect of the proposition.

ACKNOWLEDGEMENTS

The authors want to thank the French national research agency that founded the project relevant to this communication.

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