Foundations for a Constraint-Based Floor Plan Layout Support in Participatory Planning

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We introduce the theoretical foundations to allow an accurate formal representation of the design problem on the inner spatial organization of low-cost dwellings. The ultimate goal is to support participatory planning processes through constraint-based design methods. We examine the space allocation problem on the basis of Graph Theory and Combinatorics, providing a concise mathematical background for an own implementation strategy called FLS (Floor plan Layout Support). FLS combines user-driven reasoning with automated search techniques. The user specifies a set of adjacency constraints between rooms whereas an automated search finds additional solution alternatives that match a problem goal state. Our testbed is the Chilean normative model for low-cost housing. This article presents for the very first time the complete set of possible floor plan layout alternatives for the Chilean low-cost housing, and a problem-solving procedure and decision support model to find topologically valid solutions to a set of user-specified constraints.

Introduction

Architectural planning is basically a two step problem solving process. The first step demands to determine those design conditions that describe the current state of the problem and those that a goal state of the problem must satisfy. Initial conditions concern the project insertion context mainly including applicable regulations and technical requirements. Goal conditions in turn, are concerned with the design intentions including needs and preferences of clients and planners. Strictly speaking, both types of conditions do nothing else than to constrain the set of allowed values that may satisfy certain configurartion variables of a goal state of the problem. Planning constraints specifically concerning the space allocation problem belong to the class of topological constraints. Topological constraints specify adjacency relationships between spaces and with their immediacy. So, solar access requirements (space orientation) may be specified by topological constraints on adjacency relationships between spaces and cardinal points of the compass.

The second step concerns the act of designing, which demands to create at least one instance of space configuration that may or not match a goal state of the problem, and then to evaluate it under diverse criteria. This instantiation of a possible goal state of the problem is only feasible by assigning specific values to a minimum number of parameters required to specify the eventual design solution in the three-dimensional space unambiguously. A valid design solution to a space allocation problem is then a state of the problem defined by an assignment of values that does not violate any topological constraints determined before. The creation of a design solution and its validation process may consume a lot of time and reasoning capacity. In low-cost housing planning, availability of time and resources to search for additional solution alternatives is rare. So planners usually repeat proven design patterns that may or not be the optimum alternative for the client requirements.

Current competitive project-based funding schemes applied in Chile – pioneer in reducing the housing shortage among Latin American countries – demand to develop new planning methodologies to exploit the advantages of modern ICTs. In the domain of space allocation problems, disciplines like Operations Research and Integrated Circuit Design are way ahead in developing suitable methods and supportive technologies. In regard to the participatory planning support, convetional planning methods and CAD-systems used in the practice of architecture do not meet the requirements in terms of a cost-effective project development.

Objectives

Our first goal is to develop an accurate formal representation of the space allocation problem concerning the domain of low-cost housing planning. Graph-based representations are known in the architecture domain as bubble diagrams, preceding the floor plan layout which is a scaleless two-dimensional representation of a state of the space allocation problem. Next, we will determine how many one-story floor plan layout alternatives can be achieved, according to the architectural program defined in the Chilean normative model for low-cost housing. Then, we will test a constraint-based solving procedure to find a set of topologically valid solution alternatives. Finally, we will test a standard procedure of Prescriptive Decision Theory to prove the degree of efficiency of the FLS strategy.

Perhaps the main advantage of using methods of Graph Theory to decompose diverse problems is the ability to provide a much better understanding of the intimate relation between the structure of the problem and the difficulty of solving it. The standard representation of the structure of a constraint satisfaction problem (CSP) is also a graph. In this case, the vertices of the graph correspond to variables of the problem and the edges correspond to constraints. Hence, the structure of the constraint graph may be used to simplify the solving process by giving an exponential reduction in complexity [Russell 02].

Regarding our purposes, we will use the type of simple connected planar graphs to represent adjacency relationships between dwelling rooms and with the outside. We will determine different classes of graphs on the basis of their morphological structure such that two nonisomorphic graphs are considered as two different classes of isomorphic graphs. Thus, a labeled graph (i.e. with distinctly identified vertices) is considered an instance of its class. The conversion of a labeled graph into a floor plan layout may be achieved through different computation procedures. Perhaps the oldest and simplest of them, is Grason's special type of dual graph representation [Grason 71]. Nowadays, a pre-programmed library of geometric objects simplifies the process towards a visualization of the design solution alternatives. The whole idea is to elaborate a concise map describing all possible floor plan layout alternatives to our specific problem. A graphic user interface, endowed with an adjacency matrix allowing the input of logical values {true, false}, may enable the user to specify a set of topological constraints and then interactively explore different valid alternatives of floor plan layouts.

According to Gross (1986) the constraint-based design process is an exploration of alternative sets of constraints and of the regions of alternative solutions they bound. Until now, the customary use of design constraints has been relegated to low-level product development phases, mainly concerning geometry modeling. Our research intentions aim at a computer aided constraint-based participatory planning procedure whereby high-level building development phases may be performed.

Development

First, we define our testbed, the Chilean normative model for low-cost housing. The Article 6.4.1., Chapter 4, Title 6 of the Chilean building code states, "All told, the low-cost housing shall have at least three enclosures: one bedroom to accommodate two beds, one room to accommodate living, dining and cooking activities, and one bathroom with toilet, washbasin and shower" [OGUC 04].

Second, we reduce variables of the problem. In order to reduce the production of trivial solution alternatives, we determined a minimum set of initial constraints to specify a generic definition of the very floor plan layout:

1. The floor plan of any architectural space is a plane surface.
2. All rooms are allocated on a plane surface.
3. The floor plan of any room is a rectangle.
4. Each room must be adjacent to at least one other room (compactness).
5. The complete floor plan is a rectangle.

Constraints 1 and 2, express the elementary geometric nature of the floor plan layout representation. By convention, any loss of useful space by room corners with acute angles should be avoided by using rectangles (3). Furthermore, the most compact surface is a convex surface (4). By simple deduction, the only convex plane surface that may result from the compact allocation of rectangles is a rectangle too (5). The compact two-dimensional allocation of n rooms on rectangles gives a total number of n – 1 party walls. This is actually the minimum possible amount of party walls; an effect that perfectly agrees with cost-saving criteria and thermal insulation optimization.

Third, we state the problem.

Given: **a.** A set i0 of three rooms, such that i0 = {A, B, C}
b. Four cardinal points represented by the name sequence {N, E, S, and W}.
Find the complete set of topologically valid solution alternatives for a three rooms single-story dwelling within the most compact surface.

Fourth, we decompose the problem. In order to explain the procedure, some elementary definitions must be given.

Def. 1.: An undirected graph *G* = *(V, E)* is a pair *(V, E)*, where *V* is the vertex set of *G*, and *E* is the edge set of *G* which consists of unordered pairs of vertices; i.e. e = *{u, v}* \in E, where u, v \in *V* and *u* ≠ *v*. Thus, *(u, v)* = *(v, u)*. If *(u, v)* \in *E in G* = *(V, E)*, a vertex v is adjacent to a vertex *u : u* □ *v*. When the graph is undirected, the adjacency relation is symmetric.

Def. 2.: A simple graph is an unweighted, undirected graph containing no self-loops.

Def. 3.: A graph is connected in the sense of a topological space if there is a path from any vertex to any other vertex in the graph.

Def. 4.: A planar graph is one which can be drawn in the plane without any two edges intersecting.

Fifth, we elaborate a graph-based representation of the problem structure. Let *Gi* = *(V, E)* be a *simple connected planar graph*, with a set of 4 vertices that represent the cardinal points, and a set of 3 vertices that represent the rooms. Both sets of vertices are distinguished by their permutability. Unlike rooms, cardinal points are fixed in space in such a way that the vertices are in every case allocated as upper (North), right (East), lower (South), and left vertex (West). Obviously, a permutation between these vertices is not possible. It turns out that the complete set of topologically valid solution alternatives for this particular problem is a union set of instances of two different classes of isomorphic planar connected graphs, *G1.1* and *G1.2*. (See Fig. 1).

In *G1.1* and in *G1.2*, edges connecting cardinal points preserve a cycle structure. So, we can consider the triad of vertices in the centre of each graph as a subgraph G'_3 for each class *G.1.1* and *G1.2* of graphs respectively. Since each room may be represented by any unlabeled vertex of G'_3, their permutation of degree 3 gives a total number of 3! = 6 different labeled subgraphs G'_3 representing floor plan layout alternatives for each class respectively.

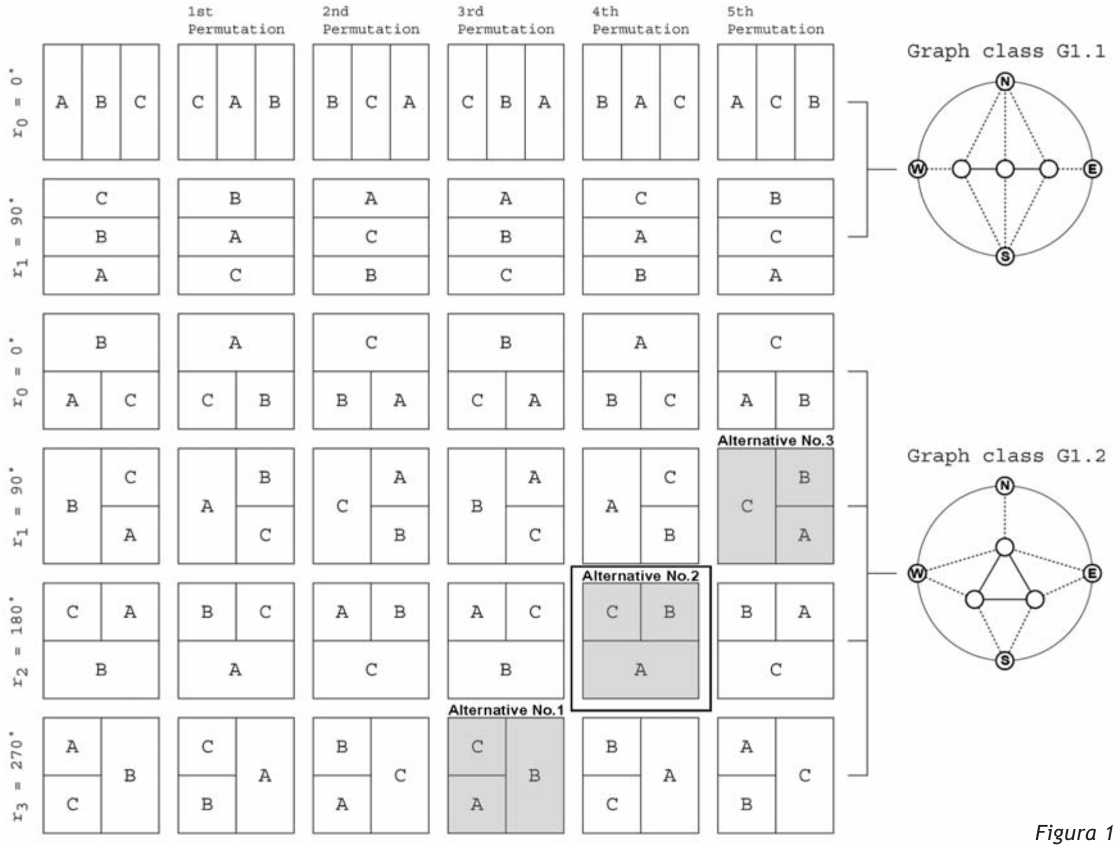

Figura 1

Furthermore, In order to find space orientation alternatives, we count 4 different rotations of G'_3 around its geometrical centre: r_1 = 90°, r_2 = 180°, r_3 = 270°, and r_0 = 0° (also called the null rotation). This procedure gives us a total number of 6 * 4 = 24 labeled graphs for each class *G1.1* and *G1.2* of graphs respectively. Nevertheless, for the class *G1.1* of graphs, two automorphism sets appear in the rotations r_2 = 180° and r_3 = 270°of G'_3. Each automorphism set contains 6 identical instances of the class *G1.1* of graphs that have to be discounted. Finally, there are only 12 different instances of the class *G1.1* of graphs, and 24 possible instances of the class *G1.2* of graphs.

Sixth, we solve the problem. The complete set of topologically valid solution alternatives for a three rooms single-story dwelling within the most compact surface contains 2 * 3! + 4 * 3! = 36 different floor plan layout alternatives. Considering the three areas for living, dining and cooking activities inside a single room, its formal representation shall be a *clustered graph*, whereby the complexity of the problem increases exponentially. Further analyses prove that a total number of 36 classes of *clustered graphs* are required to achieve the aforementioned map representing the complete set of floor plan layout alternatives for the Chilean normative model of low-cost housing (See Fig. 2).

Using the same procedure, but taking an extra subgraph into account, the complete set of solutions contains then 3! * 2 * 2 * 2 + 3! * 4 * 2 * 34 = 1.680 different floor plan layout alternatives.

Seventh, we introduce some constraints to the problem on three rooms {A, B, C} stated above:
1. *Rooms A and C cannot serve as circulation space.*
2. *Room B must be oriented to the north-east.*
3. *Room C must be oriented to the north.*

This minimum amount of constraints leaves us only 3 valid floor plan layout alternatives (marked on Fig. 1)

Eighth, we test a standard decision model. Every decision model consists of four basic elements [Laux 03]: (i) alternatives, (ii) outcomes, (iii) state of nature, and (iv) objective function (if needed). The possible outcomes of a decision are defined as the combined effect of a chosen alternative and the state of nature that obtains. Let be C and B the most private rooms of

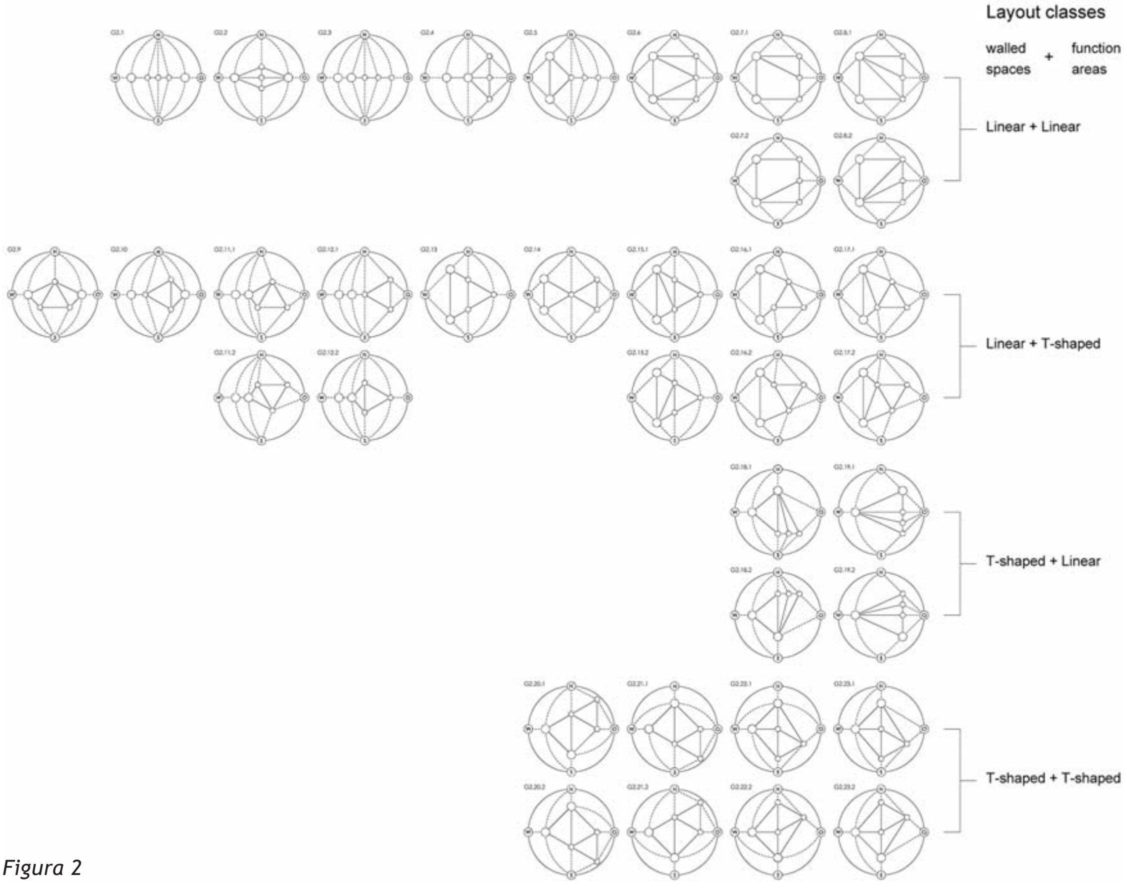

Figura 2

the dwelling (e g. bedroom and bathroom). A relevant variable to the state of nature is the space orientation with respect to the street:

Let be,

Sate of Nature 1:
The street at the north side of the site.

Sate of Nature 2:
The street at the south side of the site.

In this very simple case, our decision criterion promotes the alternative that has the largest number of rooms (of total two, C and B) separated from the street. Thus, the very best alternative to choose is Alternative No. 2 (marked on Fig. 1) in the *State of Nature 2*. The constraint-based design procedure in conjunction with a simple decision support model allow dwellers and planners to explore and to choose the optimum alternative from a wider variety of design solutions.

Conclusions

The maximum degree of each vertex representing a room, disregarding edges connecting it to the cardinal points, is equal to n - 1, where n is the total number of permutable vertices, i.e. the rooms.
In regard to the permutation problem, each permutable vertex appears (n-1)! times at the same location inside the graph structure, by each rotation (orientation). Regarding the clustered graphs required to represent the three areas inside a single room, this number is ($n!$ / n)* 2.

Graph-based representation methods prove accuracy in formalizing complex problems and likewise in solving them. Constraint-based geometric reasoning proves special efficiency in supporting collaborative design activities with non-designers. A computer aided constraint-based participatory planning may let dwellers and planners to explore a wider variety of housing alternatives, satisfying their own requirements with much more precision than currently.

References

Grason, J. 1971. An Approach to Computerized Space Planning using Graph Theory. Proceedings of the 8th workshop on Design automation, ACM Press, New York, pp. 170-178
Gross, M. 1986. Design as Exploring Constraints. Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge.

Laux, H. 2003. Entscheidungstheorie. Springer-Verlag, (5th ed.), ISBN 3540438777, Berlin.

OGUC. 2004. Reglamento Especial de Viviendas Económicas. Ordenanza General de Urbanismo y Construcciones. Ministerio de Vivienda y Urbanismo de Chile.

Russell, S., and Norvig, P. 2002. Artificial Intelligence: A Modern Approach. Prentice Hall, (2nd ed.). Englewood Cliffs, ISBN 0137903952, New Jersey.

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