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Research

A Transformation Grammar for Housing Rehabilitation

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Abstract. Existing housing stock must be rehabilitated to meet the new needs of dwellers in the current information society. Consequently, Information and Communications and Automation Technologies (ICAT) must be integrated in living areas. Both shape grammar and space syntax can be used as tools to identify and encode the principles and rules behind the adaptation of existing houses to new requirements. The research proceeds by first identifying the dwellers' demands and determine how the use of technology influences them. The second step is to identify the functional, spatial, and constructive transformations performed manually by human designers in order to infer the corresponding transformation rules and encode them into a grammar. The third step aims to test the grammar in other dwellings that are part of the corpus of the study.

1 Introduction

This paper describes ongoing Ph.D. research that starts from the premise that the future of the real estate market in Portugal will require the rehabilitation of existing residential areas in order to respond to new dwelling requirements, including the incorporation of Information, Communications and Automation Technologies (ICAT).

In an era in which information has a structural role in society, this study proposes to reflect on the transformation of lifestyles that has occurred in recent decades and its impact on the demand for new housing functions and types. The incorporation of new housing functions calls for a new approach to the design of domestic spaces in which conventional spaces need to be complemented with new areas to accommodate activities such as telework and telehealth, in response to the growing demand for access to information and for comfort in homes.

The study focuses on a specific building type, called *rabo-de-bacalhau* (literally, "cod tail") built in Lisbon between 1945 and 1965. This typology was chosen mainly because it is very representative of the period and follows specific generative principles common to all of the buildings within the corpus. Considering that Lisbon has a high percentage of vacant homes and that the existing housing infrastructures are sufficient to respond to the current housing demand in the city, the problem becomes one of how to rehabilitate existing buildings and supply them with features that meet contemporary needs for comfort and access to information, amongst other aspects.

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The ongoing research has three objectives:

1. To identify how the use of technology influences lifestyles and creates new dwelling requirements, and how this affects the spatial and functional organization of dwellings. This work complements Pedro's [2000] and Duarte's [2001] frameworks for incorporating new dwelling modes, new domestic groups, and ICAT-related demands. This step has been completed, resulting in the definition of functional programmes suitable for each family profile;
2. To define appropriate ICAT sets to incorporate into the dwelling spaces so as to guarantee environmental sustainability and the social integration of citizens, adapting them to each household according to present and future needs. These ICAT sets are applicable to the individual dwelling as well as the building as a whole, including rehabilitated existing residential stock as well as new buildings. This step has been completed, resulting in the definition of a set of ICAT packages suitable for different family profiles;
3. To define design guidelines and a methodology to support architects involved in the process of adapting existing dwellings and incorporating ICAT technologies, allowing them to balance new dwelling trends with sustainable requirements and economic feasibility.

This paper focuses on the methodology for housing rehabilitation, which is the ultimate goal of the study.

2 A methodology for housing rehabilitation

The ongoing research intends to define a rehabilitation methodology for Lisbon's existing housing stock to enable it to respond to new technology requirements and new lifestyles. The fundamental goal of rehabilitation is to upgrade houses by incorporating and updating ICT and domotics infrastructures, resolving emerging conflicts affecting the use of space prompted by the introduction of new functions associated with such technologies.

To tackle the problem of developing a general methodology for housing rehabilitation we used the *rabo-de-bacalhau* type of building. This allowed us to apply the methodology to actual buildings so that transformation principles could be inferred and then tested. Only with a specific morphology would it be possible to test different hypotheses for functional rehabilitation.

Our work started with the analysis of contemporary demands for dwelling and the development of a knowledge base for the existing ICAT sets for homes, to be taken into account in the application of the rehabilitation methodology. We then proposed a hypothesis for such a methodology, based on the conceptual schema for the design process proposed by Duarte [2001] for the mass customization of housing, following March and Stiny's "Design Machines" [1981]. According to this conceptual schema, the design process consists of two sub-processes: a formulation process that takes user and site data and generates a description of an appropriate house, and a design process that takes such a description and generates a matching solution within a given design language. Accordingly, it was hypothesized that a rehabilitation methodology should encompass four steps, as shown in fig. 1.

The first step consists of gathering the data needed for the rehabilitation process: the household profile and a description of the existing dwelling.

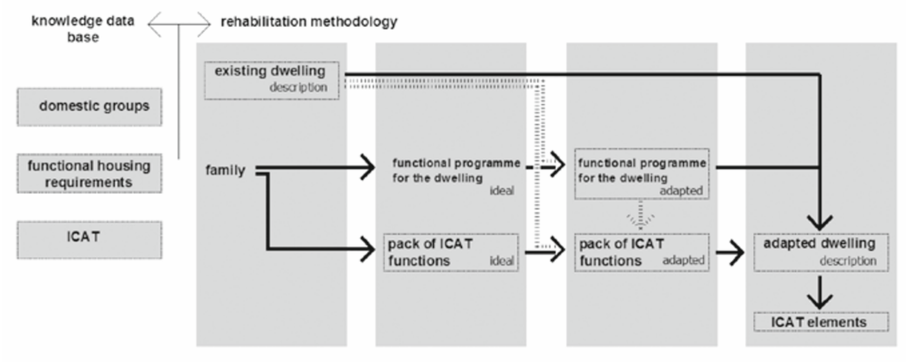


Fig. 1. Basic steps in the planned rehabilitation methodology

In the second step, the household profile is used to determine the ideal functional programme for the dwelling – following Pedro's and Duarte's work on the housing programme mentioned above – as well as the ideal pack of ICAT functions. The functional programme in this case is a description of an ideal housing solution for the family that is not bound by any existing morphological structure or design language.

In the third step, the existing dwelling, the ideal functional programme, and the ideal ICAT pack are used to derive a description of a compromise or adapted solution based on the existing dwelling. Since the solution is influenced by the existing morphological structure, it is necessary to transform the description of the ideal solution obtained in step 2 into the description of an adapted solution.

Finally, the layout of a design solution for the particular family in the particular dwelling is obtained from the description of the adapted dwelling, including the ICAT components needed in the dwelling. In order to incorporate ICAT into the dwellings, two complementary methods were established. Firstly, the introduction of ICAT in dwellings changes some aspects of living (e.g., home cinema, telework, etc.) which were taken into account in defining the functions of contemporary houses. Secondly, the introduction of ICAT in dwellings leads to physical changes in the house due to the need to accommodate cabling infrastructures and terminal elements.

Following the work described above, the methodological hypothesis was to use description grammars, shape grammars, and space syntax as tools for identify and encoding the principles and rules underlying the adaptation of existing houses to meet new requirements. The idea was to use such rules as part of the methodology for the rehabilitation of existing dwellings, as mapped out in fig. 1.

2.1 Shape grammar and space syntax

Shape grammars were invented by Stiny and Gips [1972] more than thirty years ago. They are "algorithmic systems for creating and understanding designs directly through computations with shapes, rather than indirectly through computations with text or symbols" [Knight 2000]. A shape grammar is a set of rules that are applied step-by-step to shapes to generate a language of designs.

Shape grammars are generative because they can be used to synthesize new designs in the language, descriptive because they provide for ways of explaining the formal structure of the designs that are generated, and analytical because they can be used to tell whether a new design is in the same language.

In 1976 Stiny distinguished between original and analytical grammars. Original grammars enable new design languages to be created, whereas analytical grammars make it possible to understand existing languages.

A parametric shape grammar is an extension of the basic shape grammar formalism and is used to encode neatly a wider range of formal variations for the same rule. In a parametric shape grammar, each rule consists of a set of several rules. By using parametric rules we can encode varying features of shapes so that a greater variety of shapes can be matched to the left-hand side of the rule and then be transformed by the right-hand side.

In this current research, a new type of grammar, called transformation grammar, has been developed to adapt existing dwellings to new requirements. A transformation grammar needs to be parametric because of the variety in the shapes and dimensions of the rooms found in existing dwellings. To transform "rabo-de-bacalhau" dwellings using shape grammars, we needed a grammar that could identify rooms, walls, and spaces whilst taking several features into account, namely area, length, width, function, and material properties. For instance, a bedroom is represented by a quadrilateral shape that satisfies certain requirements such as minimum area, a certain proportional range between length and width, the need for natural light and ventilation, and the need for a door connecting to a circulation area. In this context, a bedroom could be a 4 x 3 m or 3.5 x 4 m rectangle or a 3.5 x 3.5 m square or even a quadrilateral shape with walls that are not perpendicular to each other.

In order to verify the functional adequacy of the original dwellings and the rehabilitation proposals, it was first necessary to determine the fundamental performance criteria by which housing spaces fulfil functional requirements, and then to find a formalism that could be used to analyze spatial configurations from this perspective. The first task was based on Pedro's work [2000], whereas space syntax was used for the functional analysis of spatial configurations.

Space syntax was conceived by Bill Hillier and Julienne Hanson in the late 1970s as a tool to help architects understand the role of spatial configurations in shaping patterns of human behaviour and to estimate the social effects of their designs. In their theory, space is represented by its parts, which form a network of related components. In our research, space is a dwelling in which rooms and circulation areas are connected components with different permeability characteristics. Using space syntax methodology, space is represented first by maps of convex spaces to describe contiguity, adjacency, and proximity and then by graphs in which spaces become nodes and connections become arcs to describe accessibility and permeability.

Research has been developed that combines shape grammar and space syntax in order to formulate, generate, and evaluate designs [Heitor et al. 2004]. In this present research, we used space syntax to provide an accurate means of describing and evaluating spatial properties and therefore, to "increase the likelihood of generating solutions that closely correspond to the user's requirements" [Heitor et al. 2004: 494].

In this research we use shape grammar as a tool to define the methodology for rehabilitating existing types and space syntax as a tool to evaluate the spatial properties of the existing and proposed dwelling designs.

To analyze both the original dwellings and the rehabilitation proposals we considered integration, relative asymmetry, and depth. Integration expresses the degree of space centrality and measures the complexity of reaching this space within a given spatial system. The integration core is obtained by measuring the relative distance of this space from all others in the system. Relative asymmetry (RA) measures the integration of a space by assigning a value between (or equal to) 0 and 1, in which a low value describes high integration. For instance, the degree of integration is usually higher in rehabilitated dwellings than in original ones (see Table 1 below). Depth is a configuration property of a spatial layout. A space is at depth 1 from another if it is directly accessible from it, at depth 2 if it is necessary to go through an intermediate space, and so on [Bellal 2004].

Depending on the strategy followed in the rehabilitation process (see strategies in §3.1), the integration of different functional areas in the dwelling may change. This analysis can be used to choose an adequate rehabilitation strategy, taking family needs and demands into account.

In the current stage of our research, space syntax is not being used to its full potential. We are using graphs to analyze integration, relative asymmetry, depth and control value. In the future, we intend to use the values of these features to evaluate each final rehabilitated design.

2.1.1 Transformable elements: points, lines, surfaces or volumes? A building, a dwelling, or any other kind of construction is defined by its solid mass (e.g., walls, floors, ceilings) and spatial voids (e.g., spaces and rooms). Conventional representations of architecture use lines to represent the boundaries between solid masses and spatial voids, in 2D drawings (figs. 2a, b) or 3D models (fig. 3a). These representations are abstractions of the real objects.

Another, more abstract way of representing architectural space when the exact shape is not of ultimate importance is by means of a graph (fig. 2d,e and fig. 3c). In a graph, the spatial void is represented by a node that connects to other nodes by vectors that are called arcs and represent spatial connections (doors and windows.) In a graph, a spatial void can be represented as a convex spatial void which means that if a room has *n* different convex spaces, it will be represented with *n* different nodes.

Different ways of representing dwellings and the transformation rules of the proposed rehabilitation methodology were considered for the current research. The decision regarding which ones to use depended on the architectural elements manipulated in the transformations. The essential elements are walls, doors, and ceilings. Space use (function) was a fundamental attribute of void shapes. In other words, regardless of the architectural representation chosen for the material elements, they had an underlying functional meaning, shown in fig. 2c, d and e, which also had to be included in the representation.

In this context, there were three possibilities:

a. To define rules with justified graphs in which nodes have a functional meaning. This is the most abstract way of representing reality and it limits the possibility of understanding adjacencies, which is extremely relevant in rehabilitation processes. However, at this level of abstraction it is possible to clearly identify the position of a space in the house and characterize its presence, for instance in terms of integration and accessibility (fig. 2e);

b. To define rules with lines and surfaces that represent spatial voids and their functional meaning. This is an abstract way of representing reality and forces us to use the entire spatial void as an element (fig. 2c);

c. To define rules with lines representing the boundaries between solid masses and spatial voids (walls and openings, i.e., doors and windows) in 2D drawings. Using this representation allowed us to: i) assign functional meanings to elements; ii) focus on particular elements (walls and openings) abstracted from the shape of the spaces; and iii) focus on adjacency relationships between different spaces (fig. 2a).

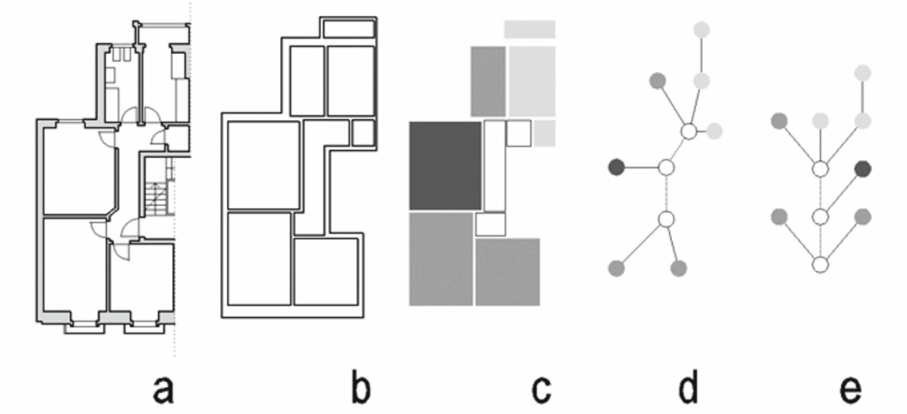


Fig. 2. Different ways of representing a dwelling in 2D: a) traditional floor plan; b) set of solid masses; c) set of spatial voids; d) graph or convex map; and e) justified graph. These representation use points, lines, and surfaces

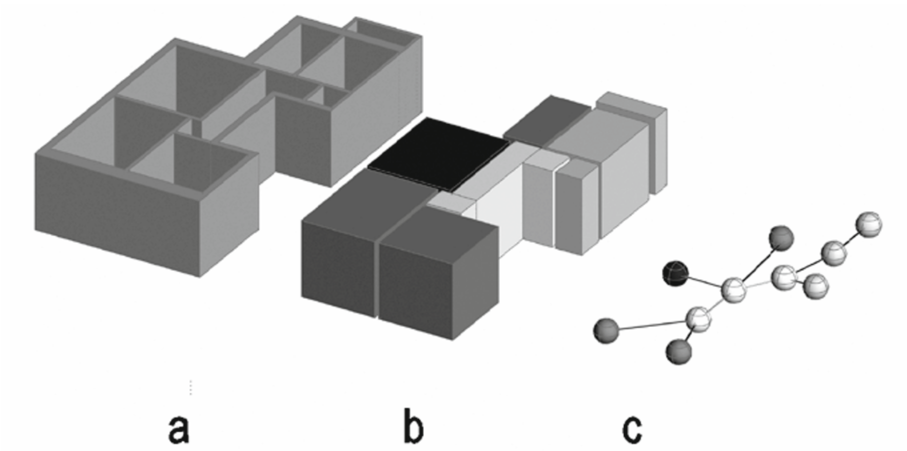


Fig. 3. Different ways of representing a dwelling in 3D: a) set of spatial voids; b) set of solid masses; c) graph

As its advantages suited the goals of the intended transformation grammar better, c) was the representation chosen. It was used to represent the twenty-five designs that constitute the case study and to develop the transformation grammar. In addition, justified graphs were used to complement the description and evaluation of spatial properties.

2.2 Methodology for inferring the transformation grammar: experiments

The methodology used to infer the transformation grammar was divided into three steps, each corresponding to a particular type of experiment:

Step 1: testing the feasibility of the experimental setup by the first author of this present paper and defining a set of preliminary rehabilitation rules that could be transmitted to the experimental subjects in step 2. This step has already been completed (§2.2.1);

Step 2: finding rehabilitation solutions that could satisfy the functional and constructional requirements of each family in a given dwelling. These solutions, designed manually, were used to infer transformation rules. This step has already been completed (§2.2.2);

Step 3: testing the transformation rules inferred in the previous step to confirm whether the solutions generated following these rules were satisfactory. This step has not yet been completed (§2.2.3).

This paper concentrates on the findings of the second step.

The goal was to relate domestic groups (families) to dwellings (existing houses). Prior to applying the methodology, data concerning the domestic groups, case study dwellings, new housing functions, and the pack of ICAT functions was gathered and organized as follows:

1. Families/future inhabitants: five families, differently composed in term of numbers, age, and family relationships, were used in the experiments, namely couples with children, young couples without children, old couples, and couples with children from previous marriages. Initially, people living alone were not considered because the sample dwellings were too big for this family type. Following this, the study focused on how couples with no children or one-person households could be accommodated by dividing each dwelling into two autonomous smaller dwellings, since this accounts for one of the most sought-after types of accommodation in the rehabilitation market in Lisbon [Caria 2004: 163].
2. Existing houses: the housing sample is composed of twenty-five dwellings, some of which were chosen for use in the experiments in the first and second steps. The selection criterion was to choose ten dwellings of varying types (see types, fig. 7) and areas that could potentially satisfy the requirements in the functional programmes for the selected families. To verify this criterion, the area of each dwelling was compared with the area requirements of each family. Two different dwellings that satisfied the criterion were then assigned to each family to obtain ten different dwelling proposals at the end of the experiment (five families x two dwellings.)
3. Functional programme: the minimum functional programme for each family was determined in accordance with Pedro's guidelines and then combined with the requirements expressed by each family in an interview especially designed for this purpose. In the interviews, the families were asked to describe the dwelling they thought they needed, i.e., not an ideal dwelling but one that could fulfil their real needs. They also were told that the dwelling would be in a rehabilitated building with small rooms (the average area of the habitable rooms is 13 m^2) and that they would have to consider economic constraints. The description had to include the

required housing functions or rooms, as well as the topological relations between them. Finally, they were asked to rank their requirements in order of priority.

4. Pack of ICAT functions: in the experiments that were carried out the ICAT pack was reduced to technologies that had an impact on spatial organization (e.g., home cinema, telework, definition of night and day areas for sector alarms). The resulting requirements were then added to the functional programme.

These elements were then given to the experimental subjects in steps 1, 2 and 3.

2.2.1 Step 1. The first and second steps aim to identify the fundamental functional, spatial, and constructional transformations to be carried out on the dwellings studied. The first step consisted of an experiment in adapting the dwellings performed by the first author of this present paper in order to infer some basic transformation rules and to test the feasibility of the exercise, before assigning it to other subjects in steps 2 and 3.

This step included two tasks. The first task consisted of proposing transformations to the dwellings taking the future dwellers' requirements and constructive constraints into account. This resulted in twenty different layout proposals, two for each family/dwelling pair, in order to explore the various possible solutions. The second task consisted of inferring transformation rules from the transformations proposed in the first task. Only higher level transformation rules were inferred, meaning that detailing rules were not considered.

2.2.2 Step 2. The experimental subjects in step 2 were architects with experience in designing houses. The goal of this experiment was to enlarge the set of rehabilitation solutions in order to understand how different approaches may be used to solve the same problem and, therefore, to obtain a larger basis for inferring rules.

This experiment aimed to identify the functional, spatial, and constructive transformations performed manually by human designers, in order to infer the corresponding transformation rules and encode them into a transformation grammar.

In this experiment, the same data from experiment 1 was used, namely, ten existing dwellings and five different families. Two of the architects participating in the experiment were asked to design a solution for all ten family/dwelling pairs (two dwellings for each family,) which yielded twenty different drawn proposals at the end. Three architects designed for five family/dwelling pairs (one dwelling only per family), producing fifteen different drawn proposals.

The experimental tasks were explained to each of the experimental subjects separately and they then completed the work in their offices.

The experimental subjects were asked to perform two tasks: first, using paper or CAD software, to draw a design solution for each family/dwelling pair, taking the functional programme into account as well as the construction constraints; second, to explain the strategy they used to obtain each design proposal.

The data that resulted from these experiments included sketches (two of the architects designed by computer and so did not produce sketches), final drawings of the proposed layouts, and texts explaining the process followed in each case (two of the architects explained the process verbally and so did not write texts.)

The data was analysed and transformation rules are now being inferred. So far, it has been possible to identify two types of design proposals: only one architect proposed transformations like the ones shown in fig. 5b, and four architects proposed transformations like the ones shown in fig. 5c. All the architects respected the given constraints and the priorities expressed by the families. One architect did not comply with the constraint of not demolishing more than 2 meters of wall. In general, they all said that it was difficult to respond to functional requirements because of the original morphology of the dwellings and the demolition constraints.

This step is still in progress and the expected result is a transformation grammar for use in adapting existing dwellings to specific families. §3 describes the present stage of the transformation grammar.

2.2.3 Step 3. The third experiment will be undertaken in a few months' time and will be carried out by two or three architecture students. They will work with dwellings that are part of the corpus but were not used in the previous experiments. The goal is to test the proposed grammar on dwellings that were not used to infer its rules. This will enable us to check whether the inferred rules provide the compositional means for making new transformations in other existing dwellings for other families.

3 Transformation grammar

The definition of a housing rehabilitation methodology is one of the goals of this research. To achieve this goal it is necessary to determine the functional programmes and ICAT packs for specific family profiles. This task can be performed as a standalone process without using the transformation grammar.

However, the use of a specific case study allows us to extend the methodology further. The use of a shape grammar makes it possible to transform existing houses in a very exact and systematic way. Instead of just generating new shapes, as in a traditional shape grammar, a transformation grammar will allow an existing design to be transformed into a new one that matches given requirements, using knowledge that relates family profiles to functional programmes and ICAT packs.

To understand the morphology of the existing building types we carried out a functional, constructional, and social characterization of the buildings, which were constructed between the 1940s and the 1960s. The social characterization was crucial in order to understand the principles that had shaped the existing layouts. Characterization of the construction was necessary in order to define the demolition constraints during the rehabilitation process. Our aim was to make rehabilitation as unintrusive as possible, without compromising comfort and access to ICAT.

The proposed methodology seeks to produce rehabilitated designs that are "legal" because they are in the transformation language and "adequate" because they satisfy the *a priori* set of user requirements [Duarte 2007: 330]. According to Duarte, a grammar applied to an architectural problem must satisfy two functions: it must create or transform an object within a specific language and it must create objects that satisfy the requirements given at the outset. As such, the grammar is structured as a discursive grammar, which includes a shape aspect and a descriptive aspect that evolve in parallel to guarantee that an appropriate dwelling design can be obtained from the description in the functional housing programme. However, unlike Duarte's case, our goal in developing and applying the transformation grammar is not to generate new dwellings using the same language as the existing ones. Our goal is to understand the existing dwellings and the new user requirements prompted by the use of technologies in order to devise transformation principles for adapting existing dwellings to these new requirements.

This grammar clarifies the principles behind the adaptation of the dwellings, such as making circulation more fluid by removing doors in hallways, enlarging social areas by connecting adjacent rooms, and so on. The grammar also encodes principles related to construction constraints, such as avoiding the removal of concrete columns or other structural elements.

The proposed shape grammar is defined in the algebra *U12,* in which lines are combined on a plane. This algebra is augmented by labels in the algebra *V02,* where label points are used to define dwelling functions, and by weights in the algebra *W22,* where shaded surfaces are used to distinguish between the different constructional elements (structural elements, infill brick walls, and light partition walls). The use of shading allows existing infill brick walls that can be taken down to be identified, as illustrated by the rule in fig. 4.

Fig. 4 shows a shape rule that includes a shape part (with shape, labels, and weights – *S, L, W*), a conditional part referring to functional and dimensional aspects, and a descriptive part. Some rules, such as the one shown in fig. 4, have a generic shape that is shared with other rules, whose conditions or descriptions may change.

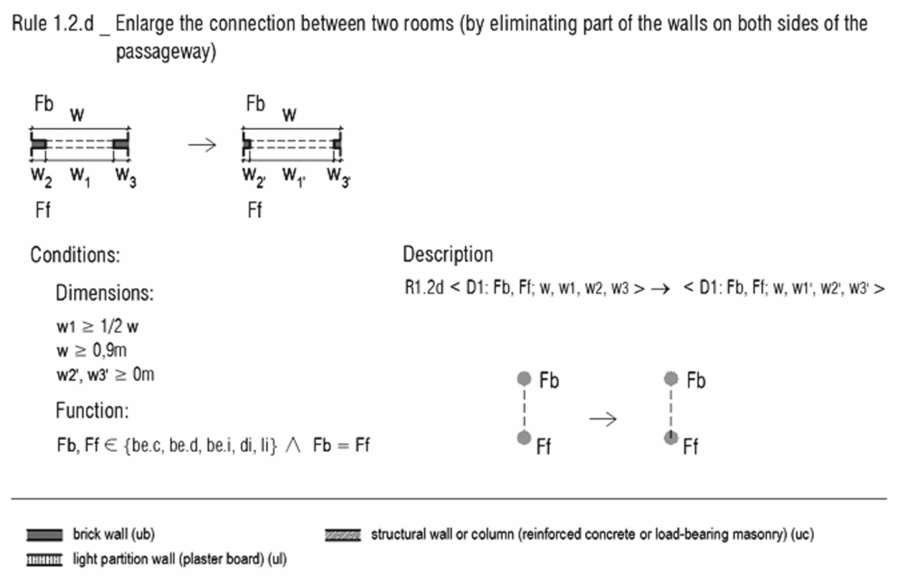


Fig. 4. Example of a rule for enlarging a passageway between two adjacent rooms by partial or total demolition of walls. The shape part is shown at the top and the conditional and descriptive parts are shown at the bottom, on the left and right, respectively

3.1 Three rehabilitation strategies

The process of inferring transformation rules allowed us to identify two possible ways of transforming the dwellings. In addition, a third way of transforming the dwellings was explored in order to create smaller dwellings for households consisting of only one or two people.

Each of these three rehabilitation strategies has advantages and disadvantages in terms of functional and constructional aspects, which can be combined in the same building to generate a wider market offer.

Fig. 5. Rehabilitation strategies: a) original dwelling; b) first strategy; c) second strategy; and d) third strategy. The top row shows the plans and the bottom row the corresponding justified graphs

The buildings in the case study have six to nine floors with a left-right symmetrical layout and two dwellings on each floor. This arrangement is repeated on all floors. The layout of an original dwelling used in the experiments in step 2 is shown in fig. 5a. The results of applying the three rehabilitation strategies to this layout are shown in figs. 5b to d. The differences in the resulting transformations lie in the number of dwellings on each floor and the position of the kitchen in each dwelling.

The three strategies are as follows:

1. Maintain two dwellings on each floor and move the kitchen from its original position in the rear wing of the building (fig. 5b).
   The aim is to strengthen the relationship between social and service areas and to segregate the private area from the rest of the dwelling. The strategy proceeds by:

a) converting the smallest room in the front of the dwelling into the new kitchen, and assigning social spaces (living and dining rooms) to adjacent rooms;

b) occupying the rear wing with private areas (bedrooms and private bathrooms).

2. Maintain two dwellings on each floor and the position of the kitchen (fig. 5c).
The aim is to keep construction transformations to a minimum without compromising the user requirements established in the functional programme. This strategy can be used to rehabilitate just one dwelling in the entire building and is described in more detail in §3.2.2.

3. Divide one dwelling into two smaller ones and create a kitchen in one of the new dwellings (fig. 5d).
The aim is to obtain smaller dwellings and a variety of dwelling types within the building.

a) In the rear dwelling, the social area will preferably be adjacent to the existing kitchen;

b) In the front dwelling, the new kitchen will be located in the smallest room at the front of the building (as in the first strategy) and the social area will preferably be adjacent to the kitchen.

It is possible to combine all three strategies in the same building. Strategies 1 and 3 have a greater constructional impact and require a new vertical drain pipe, as well as a chimney for the new kitchen. The combination of strategies 1 and 2 would have a major constructional impact and would not generate new dwelling types within the building, thereby leading to a narrower market offer. The combination of strategies 1 and 3 would also have a major construction impact but would generate new dwelling types.

The integration (I), relative asymmetry (RA) and depth (TDN) values of the layouts in fig. 5 are shown in Table 1. By comparing the original dwelling with the rehabilitated ones the following may be concluded:

– the first strategy leads to layouts in which the service area is better integrated and has less depth. The circulation and private areas will also be better integrated and have less depth with this strategy;

– the second strategy leads to layouts in which all the areas are better integrated and have less depth.

As the third strategy generates considerably smaller dwellings, the comparison between their syntactic properties and those of the dwellings produced by strategies 1 and 2 was not considered.

In the case presented in this article, the syntactic properties differ according to the rehabilitation strategy chosen. In addition, other cases studied show that such properties also differ according to the initial dwelling types. Such results suggest that the *rabo-de-bacalhau* dwelling types A to D (fig. 7) have particular characteristics which enable specific rehabilitation strategies to be carried out. This observation leads us to believe that the combination of rehabilitation strategies and dwelling types allows us to design for various lifestyles and thus meet current market demands.

	Original dwelling			First strategy			Second strategy			Third strategy (T1/T2)		
	i	RA	TDN	I	RA	TDN	i	RA	TDN	i	RA	TDN
Min	1.6	0.2	50	1.9	0.2	46	2	0.2	40	1.2/1.9	0.2/0.2	5/17
Mean	2.8	0.4	70	3.2	0.3	68.6	3.1	0.3	57.2	2.6/3.3	0.5/0.4	7.2/25.8
Max	4.1	0.6	104	5.5	0.5	97	5	0.5	76	6/6.4	0.8/0.5	9/34
Private area	2.26	0.44	77.5	2.86	0.36	73.2	2.57	0.39	63.2	1.5/2.67	0.66/0.39	8/27.6
Social area	3.17	0.32	61	2.59	0.38	77	3.46	0.29	51.5	3/4.22	0.33/0.26	6/22
Service area	2.07	0.49	84.8	2.73	0.37	75	2.22	0.46	71	1.2/2.5	0.83/0.41	9/29.5
Circulation area	3.43	0.29	57.7	4.58	0.22	52	4	0.26	47.4	6/4.62	0.16/0.25	5/21.5

Table 1. Integration (i), relative asymmetry values (RA) and total depth for current node (TDN) of original dwelling and the three rehabilitation strategies (all calculations performed using AGRAPH software)

Fig. 6 shows the simplified derivation and decision tree for the three rehabilitation strategies described above, which is reflected in the structure of the grammar described in the following section.

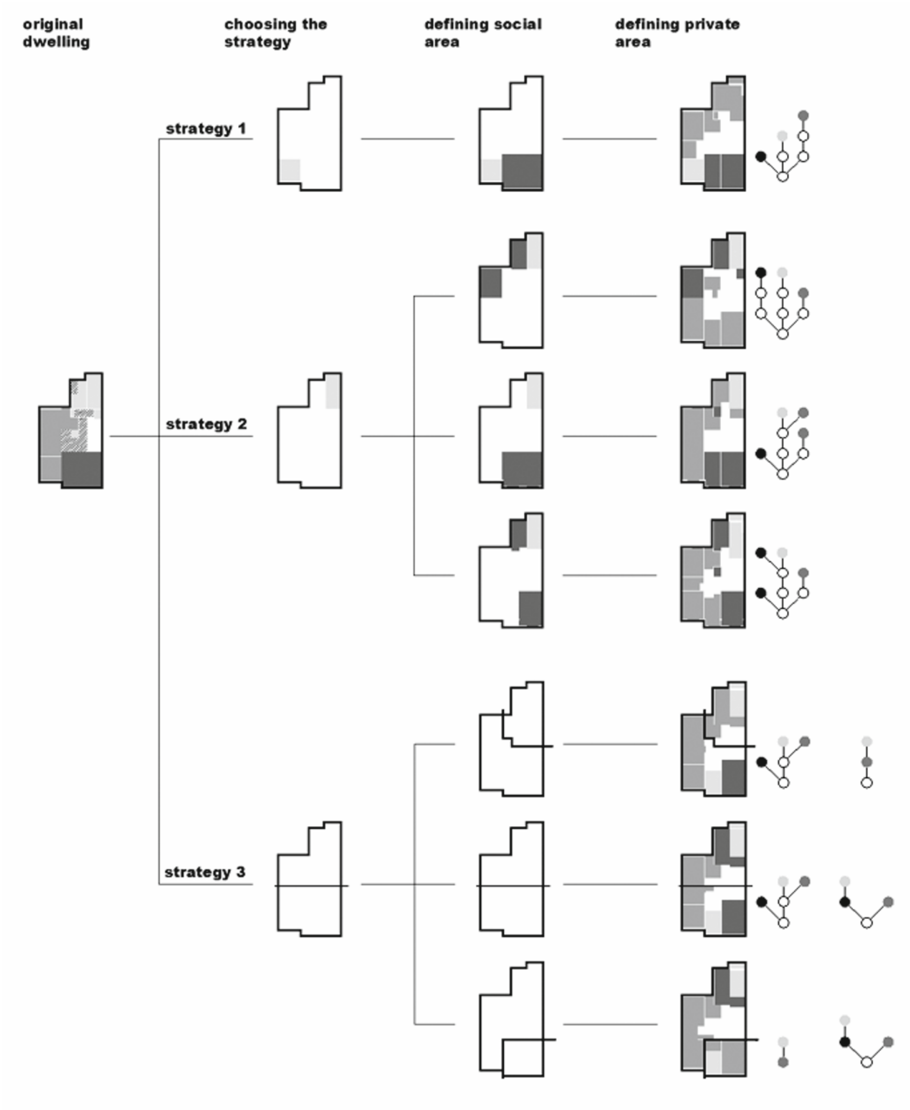


Fig. 6. Simplified derivation tree for the different rehabilitations strategies

3.2 Rules of the Transformation Grammar

The different experiments undertaken during the process of inferring the rules of the transformation grammar revealed certain rehabilitation patterns. The decision-making processes used by the experimental subjects tended to be similar and to follow the same sequence for major decisions, for instance, the location of private and social areas.

As described in the previous section, there are three different rehabilitation strategies for the buildings in the case study, but in developing the grammar we decided to consider the one with the least constructive impact first, namely the second strategy, shown in fig. 5c. The three rehabilitation strategies are briefly described in the next section. The rules corresponding to the second strategy are described in §3.3.3 and were inferred from experiments in which the solutions generated followed this strategy.

3.2.1 Choosing an appropriate dwelling. The first major decision in the rehabilitation process is to choose an adequate dwelling for a given family. There are three possible market scenarios in which such a decision will have to be made: a family looking for a dwelling to rehabilitate, a family intending to rehabilitate its current dwelling, and a property developer intending to rehabilitate an existing dwelling for sale or for rent, in which case the future dwellers are unknown.

In any of these cases:

– if a family is seeking to buy a dwelling to rehabilitate, it would be necessary to identify a set of dwellings of the type that could accommodate the family's functional programme;
– if a family intends to rehabilitate its current dwelling, it would be necessary to assess whether this dwelling would respond to the family's functional programme and, if not, to propose another dwelling (fig. 8);
– if a property developer intends to rehabilitate an existing dwelling for sale or for rent, it would be necessary to carry out market analysis to estimate the potential buyer or tenant family type. In this case, the future dwellers are anonymous.

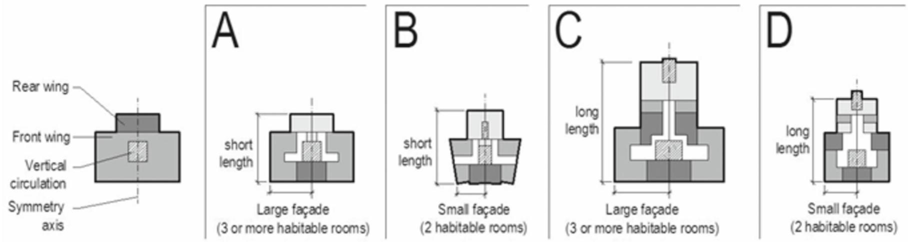


Fig. 7. Types of *rabo-de-bacalhau* dwellings

The selection of an appropriate dwelling or the assessment of the appropriateness of an existing one is based on two criteria: i) the correspondence between the type of dwelling (fig. 7) and the family structure, and ii) the correspondence between the area needed to accommodate the functional programme and the area of the dwelling. These data are summarized in data tables not shown in this paper. The area needed to accommodate the functional programme is an essential parameter that allows us to select a dwelling type from among the ones included in the case study, labelled A to D. The data tables show that types A and C have larger areas and that types B and D are more appropriate for smaller families. Despite this, all the types except type B can be subdivided using the third strategy (fig. 5d).

When looking for an appropriate dwelling the following two scenarios are possible:

a. looking for an original dwelling;
b. looking for a dwelling that has been divided into two smaller ones, in which case the proposed dwelling has no, one, or two bedrooms, i.e., it is T0, T1 or T2 accommodation, respectively.

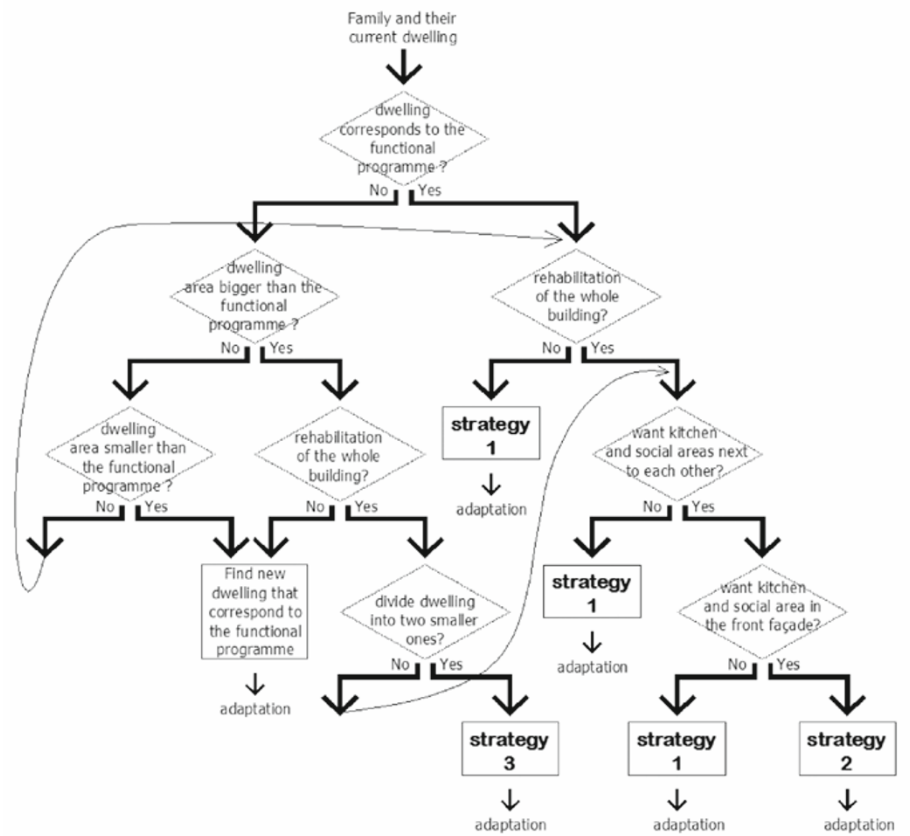


Fig. 8. Decision algorithm for the choice of a rehabilitation strategy when a family intends to rehabilitate their dwelling

3.2.2 Adaptation of the dwelling. The next decision concerns the adaptation of the family's dwelling to the new functional programme and the required ICAT pack. As mentioned above, we will show how adaptation proceeds according to the second rehabilitation strategy. This strategy aims to have the least construction impact without compromising the requirements established by the functional programme and the ICAT pack. It can be applied to just one dwelling or to an entire building. Following the experiment results, the list of steps in this strategy has been systematized as shown in Table 2 and is explained below. Steps 0 to 6 are currently being developed. Step 7 will be developed in the coming months. Due to space limitations, in this paper we only show a sample of the transformation rules in order to illustrate how the grammar works and can be applied.

All the transformations proposed in the grammar involve the construction or demolition of walls, as well as the assignment of functions to rooms. Therefore, the proposed rules include the following types of actions: i) adding walls, which enables rooms to be divided and wall openings to be removed or reduced; ii) eliminating walls, which enables adjacent rooms to be joined or rooms to be connected together; iii) the assignment of functions to spaces; and iv) changing functions between spaces.

0	Assignment of kitchen / according to the chosen strategy		
1	If functional programme has 2 or more bedrooms → defining private area	1.1	***Assignment of bedrooms***
		1.2	***Adapting bedroom shapes***
		1.3	Assignment of private bathroom(s)
		1.4	Adapting private bathroom shape(s)
2	If functional programme has 2 or more bedrooms → defining social area	2.1	Assignment of living room, dining room, home office, media room
		2.2	Adapting living room, dining room, home office, media room
		2.3	Assignment of social bathroom
		2.4	Adapting social bathroom shape
3	Defining circulation (social and private area)	3.1	Assignment of circulation
		3.2	Adapting circulation
4	Defining service area	4.1	Adapting kitchen shape
		4.2	Assignment of laundry room
		4.3	Adapting laundry room shape
		4.4	Solving circulation in the service area
5	Defining storage spaces	5.1	Assignment of clothes storage
		5.2	Assignment of general storage
		5.3	Solving circulation involving storage spaces
6	Solving circulation between different circulation spaces		
7	Incorporation of ICT elements (This part of the shape grammar will be developed in the coming months; only some examples of steps are presented here)	7.1	Introduction of water detectors
		7.2	Introduction of presence detectors
		7.3	Introduction of temperature sensors
		7.4	Introduction of smoke detectors
		7.5	Introduction of control panels
		7.6	…

Table 2. Steps to follow in adapting a dwelling. Steps 1.1 and 1.2 (in bold) are described in greater detail in the text

Step 0: Assignment of kitchen

The grammar starts by locating the kitchen. In accordance with the chosen strategy, the kitchen can be assigned to one of the following locations:

- First strategy: move the kitchen from its original position to the front of the building. Call rule 0.1c or rule 0.1d;
- Second strategy: maintain the kitchen position. Call rule 0.1a or rule 0.1b;
- Third strategy: maintain the kitchen position at the rear of the dwelling and assign a new kitchen to the front of the dwelling.

Step 1: Defining private area

The grammar continues by locating the private and social areas, proceeding as follows:

a. If a private area requires two or more bedrooms, this area should be located first (step number 1), either at the front or rear of the building. Call rule 1.1;
b. If a private area requires fewer than two bedrooms, the social area should be located first (step number 2), at the front or rear of the building. Call rule 2.1.

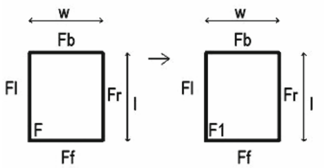
Rule 1.1: Assignment of bedrooms

With this rule we can assign a bedroom function to an existing space (fig. 9). The left-hand side of the rule verifies whether an existing space has the features required for it to become a bedroom. Specifically, considering the required number of bedrooms *n* defined in the functional programme, it determines *n* rooms that satisfy the following requirements:

– Bedrooms are rooms with natural light and ventilation;
– Bedrooms have an area equal or superior to 7 m^2 (single bedroom), 9 m^2 (twin bedroom) or 10.5 m^2 (double bedroom);
– Bedrooms must have direct access to a circulation area;
– Connections between two bedrooms must be via a private circulation area or, in exceptional cases, through a service circulation area;
– In dwelling types A or B, bedrooms will be located at the front of the dwelling (second strategy);
– In dwelling types C or D, bedrooms may be located at the front or rear of the dwelling.

Some of these requirements can be overridden by specific family requirements. For instance, a family might want a bedroom that can be accessed directly from the living-room.

Regra 1.1.a assignment of bedrooms (minimum level)



Conditions:

Dimensions:

$7m^2 \leq F < 9m^2 \wedge w, l \geq 2{,}1m \Rightarrow F1 \in \{be.s\}$

$F < 10{,}5m^2 \wedge w, l \geq 2{,}1m \Rightarrow F1 \in \{be.t, be.s\}$

$F \geq 10{,}5m^2 \wedge w, l \geq 2{,}7m \Rightarrow F1 \in \{be.d, be.t, be.s\}$

Functions:

$Fb \vee Ff \vee Fr \vee Fl \in \{ext\} \wedge Fb \vee Ff \vee Fr \vee Fl \in \{ci, cl, dr\}$

Description:

Assignment of single bedroom

$R1.1a < D1: ext, \{ci, cl, dr\}, Ff, Fl; F; Z > \rightarrow$
$< D1: ext, \{ci, cl, dr\}, Ff, Fl; be.s ; Z - \{be.s\} >$

Assignment of twin bedroom

$R1.1a < D1: ext, \{ci, cl, dr\}, Ff, Fl; F; Z > \rightarrow$
$< D1: ext, \{ci, cl, dr\}, Ff, Fl; be.t ; Z - \{be.t\} >$

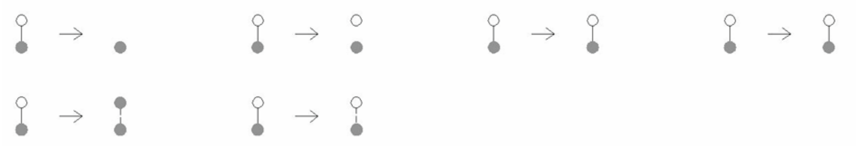
Assignment of double bedroom

$R1.1a < D1: ext, \{ci, cl, dr\}, Ff, Fl; F; Z > \rightarrow$
$< D1: ext, \{ci, cl, dr\}, Ff, Fl; be.d ; Z - \{be.d\} >$

Fig. 9. Rule 1.1 Assignment of bedrooms (minimum level). The shape part is shown at the top and the conditional and descriptive parts are shown at the bottom, on the left and right, respectively

Rules 1.2: Adapting bedroom shapes

To clarify and reduce the number of rules presented here we classify the rules for adapting bedroom shapes in the following four spatial configurations, represented by means of a graph (fig. 10).



Adding or appending an adjacent space	Closing or widening the connection with an adjacent space	Changing door position	Reducing bedroom area

Fig. 10. Possible topological transformations involved in the adaptation of bedroom shapes. Dark gray nodes represent bedrooms and white nodes represent other spaces. Lines between nodes represent connections between spaces. Dashed lines represent widened connections.

The use of graphs helped us to group rules according to the topological transformations involved, without considering specific shapes. For instance, several rules may be used to add an adjacent space, but in all cases two nodes are merged into one. Therefore, graphs are used in a parallel grammar where nodes and arcs are descriptions of space configurations. From among these transformations of space configurations, we will only exemplify the ones that manipulate a connection between two adjacent spaces (fig. 11).

In fig. 12 we show a possible derivation of the rehabilitation proposed in Figure 5c following the second strategy. The final layout of this rehabilitation is a result of the experiments carried out to infer the grammar (see §2.2.2, Step 2) and was designed for a specific family with a specific functional programme.

4 Conclusions

Information plays an increasingly important role in our lives and, as a consequence, ICAT is changing the ways in which we inhabit spaces. Recent intelligent technologies aim to maximise the use of information with the dual goal of providing houses with increased access to information and comfort through the use of automated control systems.

In addition, the rehabilitation of Lisbon's existing housing stock in order to meet the new space-use requirements demanded by new information age lifestyles is a priority in the political agenda.

Our ongoing research aims to identify strategies that allow an adequate balance to be achieved between these goals. This paper explores the use of shape grammar formalism in a rehabilitation context.

In this context, formalism is used to encode the rules for transforming existing dwellings into new ones adapted to contemporary lifestyles. In addition, space syntax is used to form a parallel description grammar to guarantee that designs with adequate functional organization are generated. The resulting compound grammar is proposed as a way of developing and encoding a methodology for housing rehabilitation that can easily be explained to, and applied by, architects.

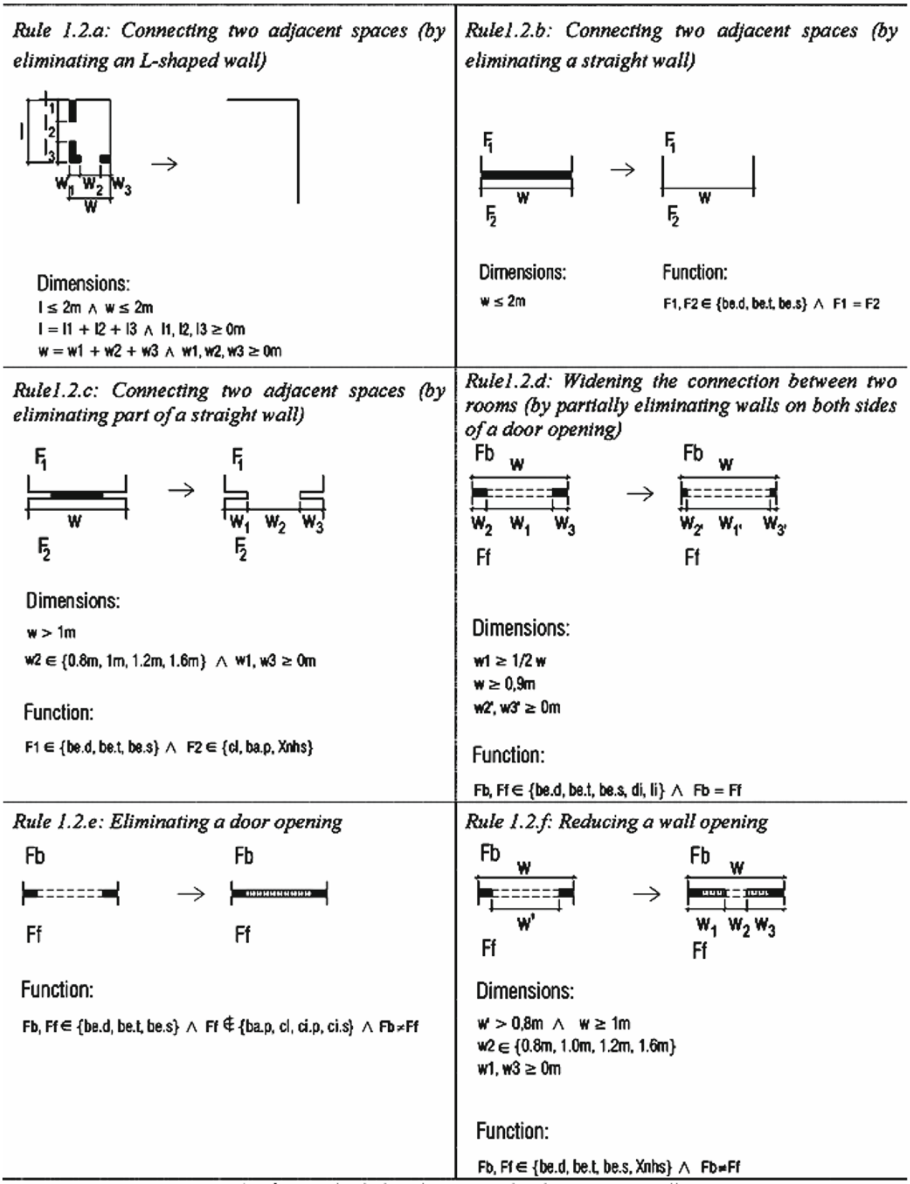


Fig. 11. Rules for manipulating the connection between two adjacent spaces

Fig. 12. Partial derivation of one rehabilitation transformation

The transformation rules of the grammar were inferred following a set of experiments in which several architects were asked to rehabilitate specific dwellings for specific families. The rehabilitated dwellings belong to a building type used as a case study because it accounts for a significant number of buildings in Lisbon. The experiments revealed patterns of design decisions and transformations which made the development of the grammar feasible.

Future work will be concerned with completing the compound grammar and fine-tuning the relationship between the shape grammar rules and the space syntax graph descriptions.

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