Manifold Façades

A grammar-based approach for the adaptation of office buildings into housing

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This article focuses on the use of shape grammars in rehabilitation processes to transform existing, obsolete building stocks into required building types. It is described how a grammar-based transformation methodology can lead to the development of a design tool that enables the exploration of preliminary design solutions and the evaluation of their impact in terms of massing, functional programme and, eventually, cost and energetic behaviour. The goal is to assess the capacity of an existing building to be adapted to a different use. The article is focused on the transformation grammar. In particular, it is investigated the transformation of "office building types" into "residential building types", aiming at defining a quicker and more informed decision-making process. Future work will be concerned with evaluating the performance of the solutions generated by the grammar.

Keywords: Rehabilitation, office buildings, adaptive reuse, addition strategy, shape grammars

INTRODUCTION

The overall goal of this research is to support rehabilitation processes based on adaptation, that is, on the transformation of existing, obsolete building stocks, into required building types.

According to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (2007), "Over the whole building stock, the largest portion of carbon savings by 2030 is in retrofitting existing buildings and replacing energy using equipment due to the slow turnover of the stock." Such rehabilitation processes represent, in fact, a viable alternative to strategies that rely on demolition followed by construction, which have high energetic and environmental impacts. Within the built environment, commercial buildings are quite important in this regard, given the number of obsolete buildings of this kind that exist on the market and the possibility of rehabilitating them using an "across-use adaptation strategy" (Wilkinson et al. 2014), which consists in the re-use of existing buildings that still have a potential lifespan, by adapting them to a new function, thereby extending their lifecycle.

Moreover, transforming obsolete vacant office buildings into housing, will respond simultaneously to the crescent structural vacancy rate of offices,
which will be unlikely reabsorbed in the market due to multiple factors, as well as to the high demand for new affordable dwellings, a situation that resulted from the economic crisis of the past years. The rehabilitation process of an existing building to suit the new conditions and requirements takes into consideration functional, behavioural and structural characteristics. It is therefore needed the development of a redesign strategy, defined as the “process of modifying an existing built design based on additional criteria from another domain” (Chase and Liew 2001). Shape grammars are the formalism explored in this paper to systematize the desired rehabilitation strategy, by identifying and encoding in the grammar the design principles and rules for such an adaptation.

ADAPTING BUILDINGS THROUGH A GRAMMAR-BASED METHODOLOGY

Shape grammars (Stiny 1980) are considered one of the earliest methodologies of visual computation using "algorithmic systems for creating and understanding designs directly through computations with shapes, rather than indirectly through computations with text or symbols" (Knight 2000). In the approach proposed in this paper, the shape grammar formalism is not used to create new designs, but it is adopted as an instrument to encode the principles of a methodology for the rehabilitation of existing buildings. In this sense, it follows the footsteps of previous works on design grammars for the customization of mass housing (Duarte 2005) and on transformation grammars for housing rehabilitation (Eloy 2012), which stem from Knight's transformations in design concept (Knight 1994).

The aim is to encode in a rigorous way the rules to adapt an existing building type to a new use, taking into consideration specific contextual features. The goal is twofold: (i) exploring different scenarios of conversion for a certain building type, whether given or not a preliminary functional programme; and (ii) supporting the decision-making process by providing information for the evaluation of the different adaptation scenarios.

The rehabilitation methodology is organised in two main parts: the first includes the definition of a grammar for transforming buildings to a new function and the second outlines a framework for assessing the performance of the generated solutions. This paper is focused on the former, while the elaboration of the latter will be developed in a subsequent phase of the research.

The grammar for adapting offices into housing can be defined simultaneously as transformative, because it is applied in the transformation of existing parametric building types and generic, because it aspires to develop an "ontological classification of context-and-style independent design moves" (Beirão et al. 2011) for the adaptation of a "generic office building type" into housing, regardless the functional programme or the future developer or user.

However, at this stage of the research, it is still not clear whether it is possible to identify a "generic office building type," even within a certain cultural and temporal context, and to represent the overall office stock by a single generic grammar. To overcome these difficulties, first we chose a particular building as a case study, which we know to be archetypic of a well-known office type widespread in the region that requires the urgent development of specific rehabilitation strategies, and then we used the selected building to devise a transformation grammar that can be applied to all instances of the type.

CONTEXT OF THE RESEARCH

Field of application: from a specific case to a broader application

The urban region of Milan has been taken as the focus of this research due to the massive presence of obsolete office buildings whose use needs to be redefined. A survey on vacant and abandoned offices in this region has been developed (different sources have been taken into account for the survey on vacant and abandoned offices in the Milanese region, between them: Municipality of Milan, Map of unused private buildings available at [1] on May 31 2016) with the
Figure 1
From the original case building to a parameterized schema of its building type: left – original floorplan; middle – floorplan after demolition of unnecessary elements; right – parametric schema encoding the building type.

purpose of identifying the localization and the typological, morphological, constructive, and performative behaviour of these buildings. The data collected in this survey suggested the coherent grouping of the analysed sample into building types, characterized by substantial common features. Nevertheless, within the same building type, there is considerable variation in terms of dimensions and spatial relations between the constitutive elements of buildings, including external perimeter, structural elements, and the position and configuration of the circulation core, which enriches the corpus under consideration. Each type has been described through parametric models as abstract representations of entire categories. In this way, it is possible to work with families of shapes, characterized by similar topologies but different parameters, and it is feasible to propose refurbishment actions applicable to all the buildings with the same features, that is, of the same type. As mentioned above, to develop and test the proposed shape grammar methodology a specific building that was considered an archetypical instance of the selected type was chosen as case study (Figure 1).

Rehabilitation strategy: incremental addition
The main intervention strategy considered for the rehabilitation is "incremental addition", that is, the introduction of a new multidimensional envelope, which can be 60 to 250 cm deep. By adding this envelope, the floor plan can be expanded both with new interior spaces (e.g. new service areas or extensions of the already existing spaces) and new exterior areas, usually missing in a traditional office building (e.g. loggias or balconies). The addition of this envelope also facilitates the upgrading of technical installations.

In short, the advantage of this strategy is threefold. First, it maximizes the expected benefits of refurbishment, namely "additional floor area, additional equipment, implemented technical installation, improved envelope performance" (Gaspari et al. 2013), by concentrating in the volumetric additions the majority of the interventions. Secondly, it minimizes the operations inside buildings, which tend to be more complex and expensive. And thirdly, it permits a complete renewal of obsolete buildings from several viewpoints: qualitative, by requalifying neglected buildings and activating urban regeneration processes of the surrounding context; spatial/functional, by adapting and equipping buildings with adequate spaces for a comfortable living standard; structural, by intervening in buildings that are near to the end of their life cycle (about 50 years) and need seismic improvements; and energetic, by improving the envelope, reducing energy consumption and enabling energy production through renewable sources.

A FRAMEWORK FOR THE GRAMMAR-BASED REHABILITATION METHODOLOGY
The proposed methodology dwells on the idea that an algorithmic design tool for generating and testing new design configurations from given contextual data, could be useful for the preliminary evaluation of the efficacy and repercussions of different refurbishment scenarios. The methodology takes into ac-
count: (1) boundary conditions; (2) urbanistic constraints; (3) construction constraints, according to national and local regulations; and (4) information describing the specific building type, including structural, spatial, and functional characteristics.

The main steps of the proposed methodology are organised in four phases and rely on "user inputs" and "generated outputs" as described in following. The fourth phase, the Evaluation, is here mentioned only for the sake of completeness, but it will be developed in future work.

-Diagnosis (Input): it concerns the analysis of the existing building and its context to determine admissible incremental additions scenarios. In this analysis are considered aspects related to (i) dimensions; (ii) constructability; and (iii) constraints.

-Problem setting (divided into Brief Finding and Design Strategy): it deals with the definition of the preferred functional programme (percentage of dwelling types and mix of incremental additions) and the identification of the main design strategies, both for the division into dwellings and for the allocation of incremental additions, to use in the generation of scenarios within the grammar. The result of this phase is the definition of the "ideal rehabilitation pattern" for the adaptation of the building type.

-Design process (Formulation and Generation): it consists in the application of the ideal rehabilitation pattern to the real building. Starting from the outlined brief, the final functional programme will be formulated as a combination of the "ideal programme" and the building capacity identified in the Diagnosis phase. As a result, it will be generated a system of solutions for adapting the building, able to merge the set of constraints, given by the original building and its context, and the admissible incremental additions.

-Evaluation: it aims to establish the "transformability" of a specific building by obtaining transformation indicators that express its aptitude to reuse.

THE OFFICE INTO HOUSING ADAPTATION GRAMMAR

Methodology
The development of the grammar rules evolved iteratively taking into account normative constraints, features of the dwelling types, and characteristics of incremental additions. In each iteration, rules were tested by applying them manually to a specific case and then refined to get a more satisfying result. The resulting grammar uses different representation devices, including: 1) lines representing walls combined on a plane to generate the floor plan; 2) planar surfaces representing dwelling at the building level and rooms at the dwelling level 3) labels to express attributes of shapes and sub-shapes, to represent contextual conditions, and to indicate where subsequent shapes can be placed; 4) graphs, made by points and lines, to represent required and de facto topological relations between the different components of floor plans; 5) weights, to indicate properties of the shapes (for example constructive features) and to identify appropriate areas for the allocation of specific functions.

In order to have a process of generating solutions amenable to use by designers, it was necessary to define compositional principles. These principles are encoded into a "design matrix" that represents both the features of the given building type and admissible boundaries of final design solutions. The generation of solutions by the grammar works by "populating" the grid with 2D shapes that represent the dwellings and their respective incremental additions.

Structuring the grammar: the levels
The structure of the adaptation grammar is organised in different levels, each subdivided in stages and steps that correspond to the various and often independent phases of the design process (Figure 2):

-Level 0_Preparation of the Floor Plan: it deals with the definition of a representational system that identifies the building elements and the characteristics of its context. The main properties that have been defined and play a specific role in the application of
the grammar rules comprise: (1) contextual features; (2) building functions; (3) constructive features. This level will be extended with rules for making demolitions. In fact, before design can proceed it is necessary to remove from the floor plan all the elements that are not required for conversion into housing, such as internal partitions, specific office appliances, and additional stairs and elevators.

**Level 1: Design Matrix Definition**: it consists in the definition of a system of axes (structural grid, central core and circulation loop) and a system of boundaries (admissible perimeters for the allocation of additions) related to the initial building features and to the range of transformation possibilities, constraining the alignment of walls and the assignment of functions on the design matrix. This derives from the superimposition of axes and boundaries and it provides the metrics for the composition of new interior and exterior spaces, defining modules and sub-modules to use in the organization of space.

**Level 2: Division into Dwellings**: it is meant to explore the ability of the floor plan to accommodate a specific or variable functional programme and it will be described in detail in the following sections. It has to be considered together with level 3, which deals with the assignment of incremental additions, because they are strongly interdependent.

**Level 3: Volumetric Additions**: it regulates the spatial configurations deriving from the allocation of incremental additions. Together with level 2, it permits one to explore the range of possible solutions within the framework defined by the grammar rules, thereby permitting to find a solution that suits the purpose of the refurbishment, both in terms of functional and performative behaviour.

**Level 4: Internal Organization**: it will be used only to verify if the division into dwellings deriving from the previous phases is able to generate interior spaces in an adequate manner. The minimum dimension required for each room has been established according to existing regulations and three main internal zones have been identified: day area, night area and service area. Once allocated the main zones, the subsequent subdivision into rooms will generate detailed organization of the dwelling.

**Level 5: Facade Grammar**: from the combination of the previous levels, it is possible to generate the corresponding elevations and a 3D model, thereby allowing one to understand the formal consequences of the different refurbishment strategies.

**Level 6: Allocating Technical Installations**: this level will be added in future work.
A LEVEL IN DETAIL: LEVEL 2 "DIVISION INTO DWELLINGS"

A detailed description of the level "Division into Dwellings" is provided below. The main design actions that are performed during the execution of the stages and steps of this level are: (1) the customization of the design matrix, (2) the choice of a circulation scheme, and (3) the allocation of dwelling types in the programme, which runs in parallel with the allocation of the Volumetric Additions (Level 3). The main purpose of this level is to allocate dwellings that match given conditions. A dwelling is defined in the grammar as a 2D rectangular shape characterized by width (w), length (l) and area (a) which can vary within a pre-determined range of square meters. The different dwelling types considered in the functional programme were established based on the analysis of the competitions for the design of new social housing in the municipality of Milan in the last ten years (Living in Milan 1 (2002-2005), Living in Milan 2 (2005-2009), Milano Housing Sociale “Bando 8 aree” (2008), International Design Competition of Social Housing "Una comunità per crescere" (2009-2010), Housing Contest, (2010)). These include t0: studio flat, t1: 1-bedroom apartment, t2: 2-bedroom apartment, t3: 3-bedroom apartment and they can be allocated in different positions within the building boundaries, depending on their dimensions. The two main positions are: the corner position, that is, a location where the new dwelling has two sides adjacent to external walls, and the adjacent position, meaning a location where the new dwelling has one side adjacent to an allocated dwelling and one side adjacent to an external wall.

In order to be an acceptable solution, the generated shape has to comply with four main conditions: (1) the minimum area is within the predefined range; (2) the width and length are within certain predefined proportions; (3) lighting and ventilation are guaranteed; and (4) a connection to the circulation loop is guaranteed. The grammar rules include specific instructions that limit the ways in which they can be applied so that a dwelling matching the above conditions is generated. In addition to conditions intrinsically related to the dwelling shape, conditions related to the context need also to be taken into account and these are expressed in the shape part of the rule using labels and in the conditional part using if/then relations. Figure 3 shows the schematic partial generation of a floorplan matching a specific program following the grammar rules.

**Stages and steps**

The derivation of designs consists of five stages. Each stage is divided into steps that are accomplished through the application of the shape grammar rules (Table 1). The consecution of stages in each level is sequential as each stage has to be fully finished before the following can be initiated. Nevertheless, more than one rule can be applied at a given stage in a non-deterministic order and the execution of the various levels of the grammar often takes place in parallel. Level 2 concerns the allocation of dwellings in the housing programme. In Stage 1, it is customised the Design Matrix taking into account the context of dwelling and one side adjacent to an external wall.

<table>
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<tr>
<th>Stage</th>
<th>Action</th>
<th>Step</th>
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| 1     | Customizing the design matrix (DM) | 1.1 Customizing the DM to the contextual conditions  
1.2 Customizing the DM to the chosen design strategies |
| 2     | Circulation definition (C) | 2.1 Defining the circulation loop  
2.2 Defining the entrance area (direct doors or through corridor) |
| 3     | Allocation of the dwellings in the programme (D) | 3.1 Allocating corner dwellings  
3.2 Allocating adjacent dwellings  
3.3 Adapting dwellings (after the allocation of additions L3) |
| 4     | Adjusting the layout to the circulation (AJ) | 4.1 Connecting the dwelling to the entrance area  
4.2 Re-adapting dwellings (after the definition of the corridor) |
| 5     | Terminates |   |
Figure 3
Simplified shape rules (a) and partial derivation of a design for formulated functional programme (b). There are rules for allocating rectangles (A, B and L), for dissecting (N), connecting (M), extending (H) and reducing (I) rectangles; rules for assigning (C) and modifying (D) functions and rules for allocating shades (E). Legend: T4 – 3-bedroom apartment, T3 – 2-bedroom apartments, T1 – studio flat.

the building under consideration (Step 1.1) and applied the design strategies defined in the previous phases (Step 1.2). In Stage 2, it is selected the circulation strategy that is more adequate, considering the functional programme and the features of the specific building (Steps 2.1 and 2.2). The circulation schema is the starting schemata for the subsequent application of rules. Stage 3 includes the allocation of dwelling types and it starts with the allocation of the bigger dwellings in the corner position (Step 3.1) and proceeds with the positioning of the remaining dwellings in the functional programme following the chosen compositional principles (Step 3.2). In parallel with the execution of the Step 3, takes place the allocation of the incremental additions of the dwellings being allocated (Level 3 Volumetric Additions). In Step 3.3 it is verified the compliance of the dwellings generated in Step 3.2, after allocating incremental additions, with area requirements for each dwelling type, readapting their dimensions if necessary to satisfy them. In Stage 4, the access to dwellings is guaranteed (Steps 4.1 and 4.2) by connecting them to
the central core, either directly or through a corridor. Rule application terminates once all the dwellings in the programme are allocated (Stage 5).

**Rules**

The definition of the set of rules comprises: design moves, requirements, conditions, and constraints. The rules encode the design strategies and principles used in the adaptation methodology, so that it can be applied to a wide range of situations and adjusted or modified according to the necessities that emerge from their application to a concrete case in practice. A detailed rule is shown in Figure 4 to facilitate the understanding of the logic behind the development and structuring of the grammar rules. It defines the allocation of a dwelling in the corner position and it aims at embedding the instructions for the definition of any type of dwelling in the programme. Each rule is organised in five parts: a shape part; a label part; a conditional part, which imposes restrictions on functional, dimensional and regulatory aspects; a description part, and an additional part that specifies the initial general conditions of the rule applications process. These parts are described in further detail below.

**General conditions.** They include: the set of dwellings included in the design brief (D); the set of dwellings allocated so far in the derivation (D'); the set of functions in the floor plan when rules begun to be applied, namely, from inside out, core area, circulation loop area, habitable area, and incremental additions area; (E), the possible different dwelling types (t(dn)) and their dimensional requirements. Moreover, it also includes the main contextual features that affect the allocation of dwellings: (i) solar orientation; (ii) contextual location of the different elevations of the original building; (iii) position of the building with respect to the lot boundaries; and (iv) views types and quality.

**Shape part.** In the shape part, the rule is visually explained, indicating, on the left side, the shape before the application of the rule and, on the right side, the result of the transformation. It also includes the design matrix, which constrains rule application. Finally, in articulation with the description part, it includes a graph, depicting the spaces and functions involved in the transformation and the topological relations between them.

**Conditional part.** The conditional part of the rule comprises a section describing the dimensional requirements and a section describing the functions. The dimensional section specifies the range of possible areas for the different dwelling types. Allocation takes place only if the area available for the allocation of the dwelling permits the introduction of a shape within the specified dimensional range. In the functional part, "F" represents the general function of "habitable area". "Ft" and "Fl" are exterior walls (Wexn), and "Fb" and "Fr" are other generic habitable areas. The conditional part also indicates that any dwelling type can be allocated in the corner position, starting from the bigger one and then considering others in descendant order.

**Description part.** The abbreviated general description of an allocation rule has the following format:

\[
R_i <D_n: Wex_n, (hba); D'; E> \rightarrow <D_n: Wex_n, (hba); d(t_n); D' + \{d(t_n)\}; E - \{hba\}, E + \{d(t_n)\}>
\]

The left part of the description indicates: the stage in the derivation to which the rule can be applied (Dn); the functions of the surrounding shapes, namely, exterior walls (Wexn) and the inhabitable area (hba); the function of the shape to which the rule can be applied (F); the set of dwelling types in the programme already allocated in the floorplan (D'); and the set of current functions in the floorplan (E). The right part of the description includes: the functions of the surrounding shapes (Wexn, hba); the function to allocate, that is, the generic dwelling type d(tn), which is added to the set of dwelling types in the programme already allocated in the floorplan (D'); the inhabitable area (hba) is deleted from the set of current functions in the floorplan (E); and the allocated function d(tn) is added to the set E. Each time the rules is applied and a dwelling is allocated, it is deleted from the set D of
Figure 4
Example of detailed rule for the allocation of a dwelling type in the corner position, with general conditions, shape part, condition part and abbreviated description.

The dwellings in the programme to allocate, to prevent further allocation of the same dwelling in subsequent steps of generation, and it is added to the set D’ of the dwelling types in the programme already allocated in the floorplan.

A TOOL FOR FACILITATING THE DECISION MAKING PROCESS
The main goal of the ongoing research is the creation of a "scenario-making" tool that encompasses all the principles behind the adaptation of obsolete office buildings into housing. This tool could have a significant role in implementing transformation policies for existing building stocks as it could be used in finding the most suitable strategy for adapting specific buildings in accordance with such policies. For this purpose, it is rather important to complement software implementing the grammar with software for evaluating solutions from various viewpoints, which could provide performance indicators and inform the generation of solutions matching desired criteria. The final objective of the proposed tool is not to generate optimized solutions but to provide a universe of adequate solutions with known performances thereby making it possible to understand the trade-offs among different design alternatives and the relation between geometry and performance or, in other words, between form and function. In this way, designers and developers could gain an adequate understanding regarding the effects of their
design decisions, since early stages of the design process, while they still have the possibility of modifying the solutions to attain specific design goals.

DISCUSSION AND CONCLUSIONS
The initial motivation for this research was the necessity to satisfy sustainable requirements for the built environment, while responding to the growing demand for new affordable dwellings. This paper presents a grammar-based methodology for this purpose. The proposed grammar enables the adaptation of existing building types with a specific function, "office building," into a new converted function, "residential building," through the application of a sequence of predefined and systematic operations, defined as steps to be performed by rules in the grammar.

An appropriate testing of this general framework is still to be done. So far, the rule set was developed for the Level 2, Division into Dwellings, and Level 3, Volumetric Additions. Nevertheless, it already takes into account functional, technical, and construction requirements, thereby giving an indication of the feasibility and appropriateness of the proposed methodology.

In the current stage of the work, the grammar addresses the generation of floor plans in two dimensions. However, to fully evaluate design scenarios, it will be necessary to develop the façade grammar, foreseen in Level 5, which should articulate the floor plan with the elevations, thereby encompassing three dimensions.

Future work will be concerned with the completion, refinement, and computer implementation of the grammar. This objective is crucial to achieve some of the most important promises of the proposed grammar-based approach, namely the fast generation of design alternatives that are adequate to particular design contexts.

The complete methodology for the rehabilitation of existing building stocks also includes the evaluation framework for assessing the performance of the generated solutions, which is yet to be developed.

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REFERENCES


Knight, TW 1994, Transformations in design. A formal approach to stylistic change and innovation in the visual arts, Cambridge University Press


Stiny, G 1980, 'Introduction to shape and shape grammars', Environment and Planning B, 7, pp. 343-351


