A SYSTEM FOR PROVIDING CUSTOMIZED HOUSING

Integrating design and construction using a computer tool

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Abstract. This paper describes a system for generating customized mass housing. The aim is to provide dwellings at an affordable cost with recourse to mass production and yet guarantee that they are tailored to their users. It combines two systems, a rule-based design system and a prefabricated building system. The integration of both systems is achieved through the development of a computer tool to assist designers in the various stages of the housing design process. This tool produces three kinds of outputs: three dimensional models, construction drawings, and a list of construction elements, including their cost and information for manufacturing.

1. Introduction

A considerable amount of studies was developed over the last decades to improve housing conditions, diminish final costs, and customize dwellings. Professionals from different fields presented different approaches. While architects are interested in functionality, aesthetics and ergonomics, engineers are more concerned with structural systems, ease of construction, and overall costs. The role of the client in the housing provision process is increasingly smaller. The great majority buy ready-to-use dwellings, hoping for a greater level of versatility that could allow them to personalize their homes.

In the recent past, efforts have been made to integrate all these different, and sometimes conflicting, interests and still provide for a doable, affordable and customized dwelling. During the second quarter of the twentieth century architects like Le Corbusier, Walter Gropius, and other modernist architects proposed housing designs that employed prefabricated elements in an effort to accelerate construction and diminish costs in large scale mass housing.

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These approaches were put in practice in the devastated post second world war Europe.

In the 1960's, Habraken developed the theory of supports (2000). This theory proposed a matrix system that included a tartan grid based on which modular elements were created and combined to generate dwellings. Functional spaces were considered as design elements and manipulated like building elements. Designers were supposed to developed specific rule systems that they could manipulate to design different housing solutions, thereby promoting diversity and customization. The theory also foresaw the recourse to prefabrication, using standard elements, to permit greater efficiency in the construction process and controlled final costs. However, the system implementation depended on the rigorous establishment of design rules and on the correct and efficient manipulation of such rules.

In the 1990's, Duarte proposed a framework to overcome limitations in the implementation of design and building systems (1995), which foresaw the use of computers systems to assist in the design and construction processes. He illustrated this framework with the development of a computer program for exploring housing solutions within Siza's Malagueira style, whose compositional rules were inferred after careful analysis (2001; 2005). This program first helped the user to establish a housing program based on user and site data, and then generated a solution that matched the program, which took the form of a three-dimensional model.

The subsequent logical step was to facilitate the construction process. A great amount of the designer's effort and time is invested in drawing, detailing, and organizing construction data. Another share of time is spent in expensive and long on-site construction tasks. The goal of the present work is to contribute for diminishing the time and labour spent in such tasks. This is achieved by automatically generating construction drawings, once the design is settled, and by producing files that compile the data required for automated production, including bills of construction elements.

The motivation for developing the current work was the difficulty faced by designers in the use of a sophisticated light-weight prefabricated system produced by the British firm Kingspan. The richness of this system permits to construct a great variety of buildings, but its complexity jeopardizes its use in practice, thereby diminishing its commercial potential. The strategy to overcome this limitation was twofold. First, it was to develop a housing design system that permitted to design mass customized housing based on the Kingspan building system. And second, it consisted in creating a computer system that allowed the easy exploration of the universe of solutions and the automatic generation of information for fabrication. From the commercial viewpoint, the idea was to provide the firm with a new business model that enabled it to sell its product and gain market share.

Due to time constraints, however, it was not feasible to develop a new design system. Therefore, the solution was to look for an existing system that fulfilled the intended goals—the generation various dwellings—and was compatible with the Kingspan building system, thereby enabling to demonstrate the proposed model to the client. This system was the ABC system conceived by the Spanish architect Manuel Gausa.

2. Methodology

The development of this project can be divided into three stages: first, the establishment of the rule system; second, the coding of such a system into a computer program; and, third the assessment of the program.

The first work stage combined the selection, study, and adjustment of the design system to the construction system. The design system was adapted from the conceptual idea of the ABC design system conceived by the Manuel Gausa, the leader of Actar. This design was never materialized since it was created for the Ceuta competition in 1994, but it was object of analysis by leading architectural publications. It stands out due to its innovative approach that applies prefabricated systems to mass housing while giving the final user the opportunity to customize the dwelling with serial elements without the risk of overpricing the final result. The system borrows its name from the acronym of the functional units used in the design of dwellings: *Armario*, *Baño* and *Coziña* (storage, bathroom, and kitchen.)

The design of dwellings is not imposed by the architect, but suggested according to a set of conceptual rules. These rules predefine possible relations between functional spaces and control geometrical proportions. In addition, they define the external building envelope by reflecting the design of the interior layout. The original system yielded apartments with one or two bedrooms, whose spectrum of possible configurations was demonstrated in the form of a combination grid (Figure 1).

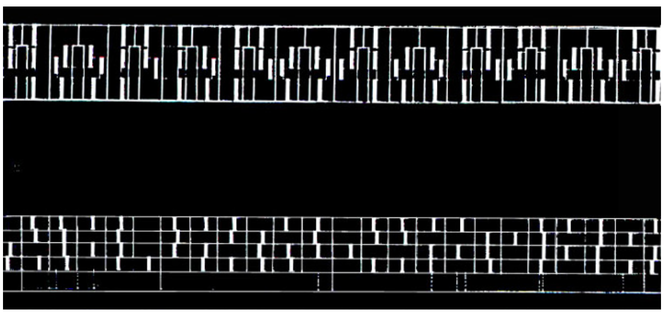


Figure 1. Compositional grid designed by Manuel Gausa to illustrate how layouts can result from the different placement of functional units; the top row shows layouts in plan and the one bellow shows the corresponding section (Gausa 1998)

The construction system is based on the Kingspan building system developed by the British firm Kingspan. It is a prefabricated building solution that presents two features, a steel cold formed structure and an envelope constructed with standard finishing elements. It is a complete system that can become too complex, hence the difficulties of penetration in the architectural market. Nevertheless, it is a versatile building scheme with high dimensional tolerances. It can be adapted to different geometries and its modular characteristics also permit the use of other standard finishing materials and envelope solutions. It presents some conditionings in terms of number of floors, maximum length, height, and thickness. For instance, the maximum number of floors is 6, and the pillar and beam grid cannot overtake 12 x 4.5 x 3.5 m.

The rules of both the design and the construction systems were identified and systematized, and then encoded into the computer program. This was developed in AutoLISP, a dialect of common LISP, using VisualLISP, an editor that runs within Autodesk's AutoCAD since the 2000 version. The computer program is composed of a number of functions, each being responsible for a specific task (for instance, the layout of a certain functional unit) or for the representation and geometrical construction of a particular building element (like a window frame, for example.) The program operates in three stages. The first is targeted at the development the three dimensional model of the housing units and the building; the second stage aims at creating bi-dimensional representations; and the third stage consists in the quantification and listing of all the construction elements required to erect the building.

3. Design and Constructive system:

The final design system is an upgrade from the one proposed by Gausa (1998, 1999), since it was necessary to increase the flexibility of the system concerning the number of rooms, the total area of each housing unit, and the number of floors. After these alterations, the universe of solutions was enlarged to encompass the design of studio flats up to four-bedroom apartments, with areas ranging from 50 to 150 m^2, and the design of buildings with one up to six floors (the maximum number allowed by the structural system.) Despite the alterations, the basic compositional and spatial relationships remained untouched, thereby preserving the underlying architectural concept. Namely, the altered system retained major conceptual ideas from the original one, such as the spatial distribution principles, the functional units placement scheme, and the façade design rules.

The adaptation of the construction system did not require the need to perform any major changes and it was directly applied and coded into the computer program. This could be explained by the already mentioned versatile features of the system, which possesses a modular and orthogonal geometry with high dimensional tolerances that makes a wide variety designs feasible. The structural layout follows simple rules that rely on major spatial vertexes to free the interior from structural constrains and keep it fluid as required by the design system. The secondary framing occupies the inner spaces of external walls and partitions, thereby diminishing their visual impact on the internal space.

The functioning of the design system can be illustrated by a set of rules that determine the internal layout of the dwelling, depicted in Figure 2, and a set of spatial confinement and wall placement rules, shown in Figure 3.

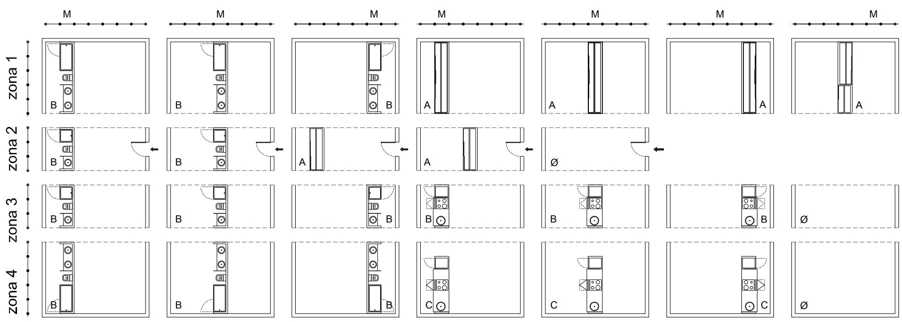


Figure 2. Spatial system: matrix after Gausa's original drawings illustrating several possibilities for placing functional units and used to infer their placement rules. Legend: A-storage, B-bathroom, C-kitchen, Ø-open-space

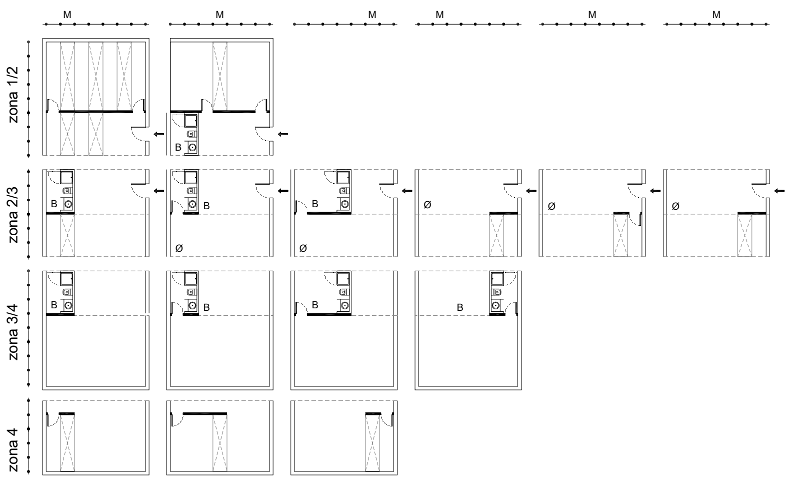


Figure 3. Spatial system: matrix after Gausa's original drawings illustrating several possibilities for creating spaces by placing partitions and doors and used to infer the delimitation rules.

The spatial distribution is defined by the designer according to the following premises: every dwelling has to include at least one functional unit of each kind (storage, bathroom, or kitchen); living or sleeping spaces are adjacent to the façade to ensure natural lighting and ventilation, while circulation and services are located in the inner core of the dwelling. With this in mind, the designer can create different dwellings by placing the three functional units on different locations. Spaces are defined by the position of such units. The spectrum of possible placements are described in the scheme and coded into the program, which does not allow any other combination.

The internal layout is established based on two aspects: first, the predefined housing program or design brief and second, the preferences of the designer in terms of spatial distribution. The design brief is input during the initial steps of operating the computer program. The program assists the designer and enquiries about the number of bedrooms and overall area of the dwelling. Based on this information, the internal distribution is defined step by step from the so called zone 1 or sleeping area, to zones 2 and 3, corresponding to access, circulation and services, and finally, to zone 4 or the living area. The same sequence is followed during the generation of the dwelling when the computer program asks the user to place different units on different locations and assists him in this task to guarantee an acceptable final result.

Success is guaranteed by a well established set of rules that define all the acceptable relationships among adjacent spaces. For instance, in zone 1 or the sleeping area, three types of spaces may be placed: a bathroom, a storage unit, or a simple sleeping space. In addition, there are three different locations for the chosen unit, each resulting on a different spatial arrangement. In a similar fashion, zone 2 can host a bathroom, a storage unit, or an open space. However, the placement options are constrained by the presence of the entrance, which does not allow the creation of a small space close to the entrance door. Other rules can be extracted from the table in Figure 2; some address aesthetical aspects and others functional matters, such as circulation, environmental aspects, or hygiene.

Once the basic spatial layout is defined by the user, the computer program completes the interior design with the placement of walls and doors as shown in Figure 3. In this task, the program takes into account the use of a particular space, but also those of adjacent spaces. Sleeping spaces are always confined by walls, except in studio apartments where space is completely fluid. Similarly, services like washing spaces are limited and enclosed by walls to guarantee water proofing and privacy. Kitchens are delimited by walls and doors according to the house typology and the corresponding required area. Other rules can be inferred from the table in Figure 3, like those for placing a door to a given space when the most immediate location is occluded by an adjacent space. All these rules are encoded into the program and illustrated in the table.

The design of the façade is a reflection of the layout of inner spaces. This means that the placement of the functional units predetermine the placement of opaque façade panels and a colour code associated with the unit type is used to colour the panel. The remaining façade panels consist of transparent glass windows to provide for natural lighting and ventilation.

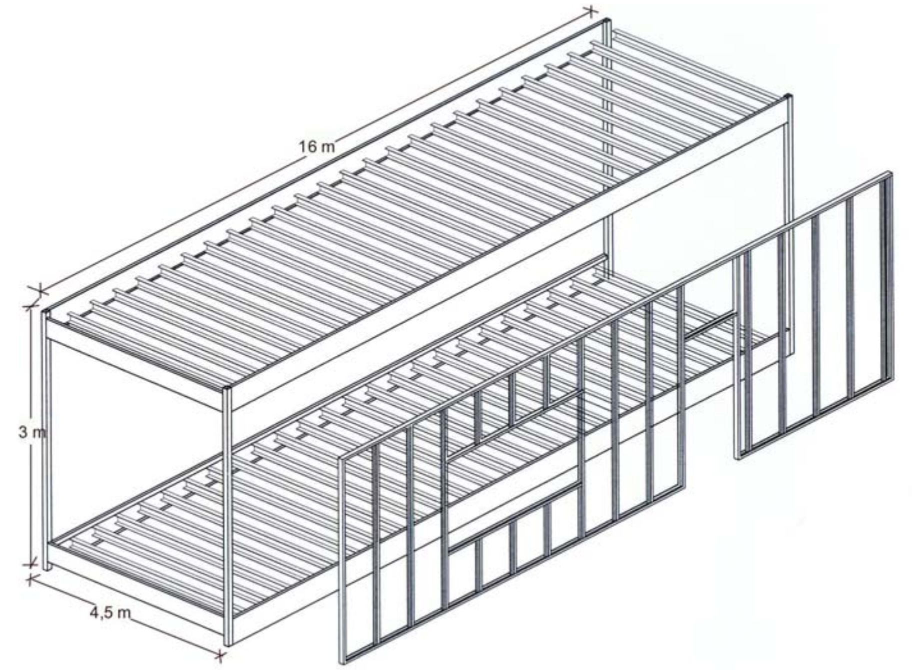


Figure 4. Structural and framing system from the Kingspan building system. Typical prefabricated grid with maximum dimensions.

The Kingspan building system is a complete construction system composed by three subsystems: a structural system, a framing system, and a lining system.

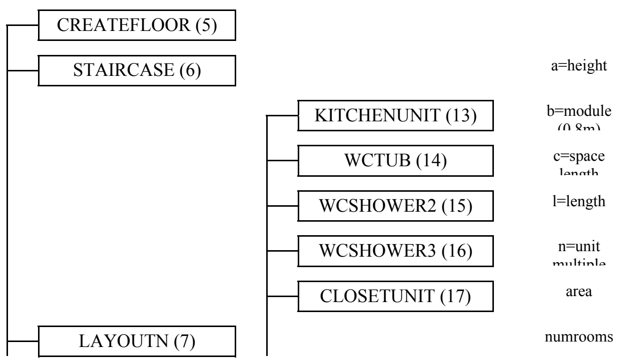
The structural system is composed of galvanized steel elements that form a pillar and beam orthogonal supporting frame. These elements are manufactured by cold forming or simply by hot rollers and transformed into linear elements with diverse standard sections. These vertical and horizontal elements form a three-dimensional grid that frames each portion of interior space called a zone in the design system. The maximum grid dimensions are 4,5 m x 16 m x 3,5 m for the width, length, and height, respectively, as shown in Figure 4. The structural system can support up to six storeys, but structural reinforcement is recommended for more than three levels.

The framing system acts as a secondary reinforcement to the structural system and occupies the gaps between main structural elements, both in external walls and slabs. Cold-rolled galvanized C and I sections are used repeatedly to conceive the framing. I sections are used as main support, in beams and pillars, while C sections are used as wall and façade studs and slab supporting elements.

The lining system depends on the choices of the designer and the materiality of a specific housing design. The internal lining and ceiling systems are prepared to adapt to various layouts and introduce most of the standard manufactured finishing products available on the market. However, for this particular project it was chosen coloured glass-fibre reinforced concrete panels and aluminium window frames for the façade, and concrete prefabricated panels for the side walls. The interior walls and ceilings are finished with plaster boards, and the floor is levelled with a light concrete layer finished with wooden boards in living and circulation spaces and with tiles in wet spaces.

4. Computer program

The integration of the design and the construction systems into a single platform is possible thanks to a computer program that assists the designer in the conception of dwellings. As mentioned in Section 1, some of the major shortcomings and drawbacks of past design systems stemmed from difficulties in applying their rule sets, often extensive and complex, in an accurate and efficient manner. In the current case, many of the design aspects valued by designers, such as harmony of spatial proportions, functionality, salubriousness, structural stability, or even building codes[1] are encoded into the computer program, which assists in and evaluates each design move.



1 The current design system encodes the principles defined in the Portuguese building regulations, called REGEU – "Regulamento de Edificações Urbanas".

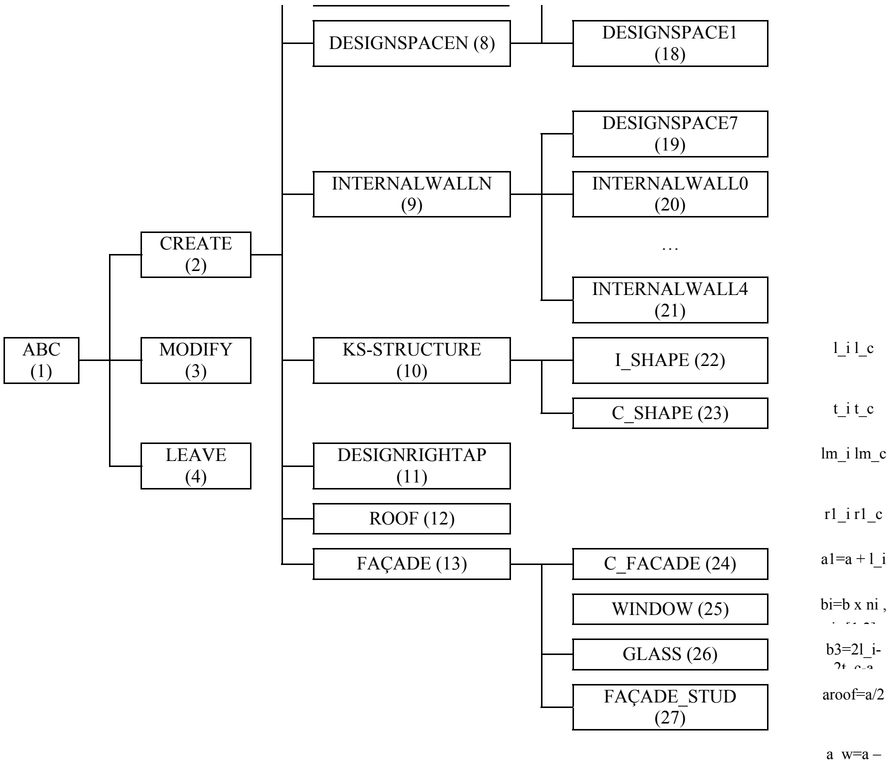


Figure 5. Computer program structure – functional diagram

The structure of the computer program is diagrammed in Figure 5. The main function, called ABC, is responsible for activating the program and initiating the Create, Modify and Leave cycle. The Create function generates the housing building design. This function starts by enquiring about basic building features such as the number of floors and floor height. This is followed by the activation of the function Createfloor, which will repeatedly run until the specified number of floors is designed. This function is responsible for the design of common spaces, including stairs, lifts, and circulations, as well as for the design of each housing unit, starting with left side one. For each dwelling, the interior design will evolve from zone 1, the sleeping area, to zone 2, the access area, to zone 3, the service area, and finally, to zone 4, the living area.

Design at this stage is assisted by the functions LayoutN and DesignspaceN (with N < 7). The former is responsible for the placement of the perimeter wall, and the latter for the assignment of functions to spaces. DesignspaceN depends directly on the functions Kitchenunit, WCunit, and Closetunit, which generate different types of functional units to equip each dwelling with the basic services, namely, kitchen, bathroom, and closet. It also prompts the user to select functional units and to specify their correct location within zones.

Once the available dwelling area is packed with the selected spaces, the computer completes the design by assessing the resulting spatial distribution and then by placing appropriate boundaries among spaces – doors, walls, or partitions – according to the rule system illustrated in Figure 3. The function Designrightap performs a cycle where the functions just described are recalled and mirrored in order to design the right side dwelling.

Once the floor is completed, the KStructure is responsible for the erection of the Kingspan building system dimensionally adapted to the generated design. This function will call sub-functions like I-beam, C-stud, and other sub-functions that are responsible for modelling particular elements. I and C sections are placed both horizontally and vertically to form frames that are parametrically defined in the function and then adjusted to specific spans.

The façade is designed according to the inner placement of functional units. Opaque panels are aligned with the units and placed by the function Façade. Façade is also responsible for designing and modelling window frames, glass panels, and structural studs calling upon the sub-functions C-stud, Window and Glass. The process is repeated for each floor until it ends with the placement of the roof above the top floor by the function Roof.

The design process can be monitored by the designer and client in real time with great precision since a three-dimensional model of the design is created in parallel to the decision making process (Figure 6). This allows the modification of undesired solutions or the comparison among different ones, which are enabled by activating the Modify function or the Create function, respectively. Once the user and the client are satisfied with the design, they can exit the program by activating the Leave function. Previously saved solutions can be later retrieved and modified as well.

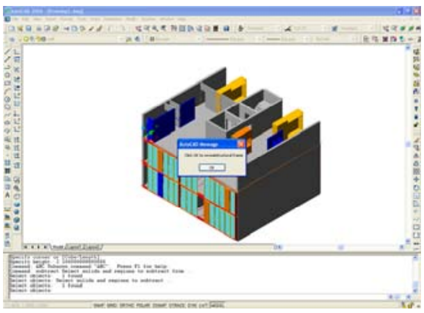
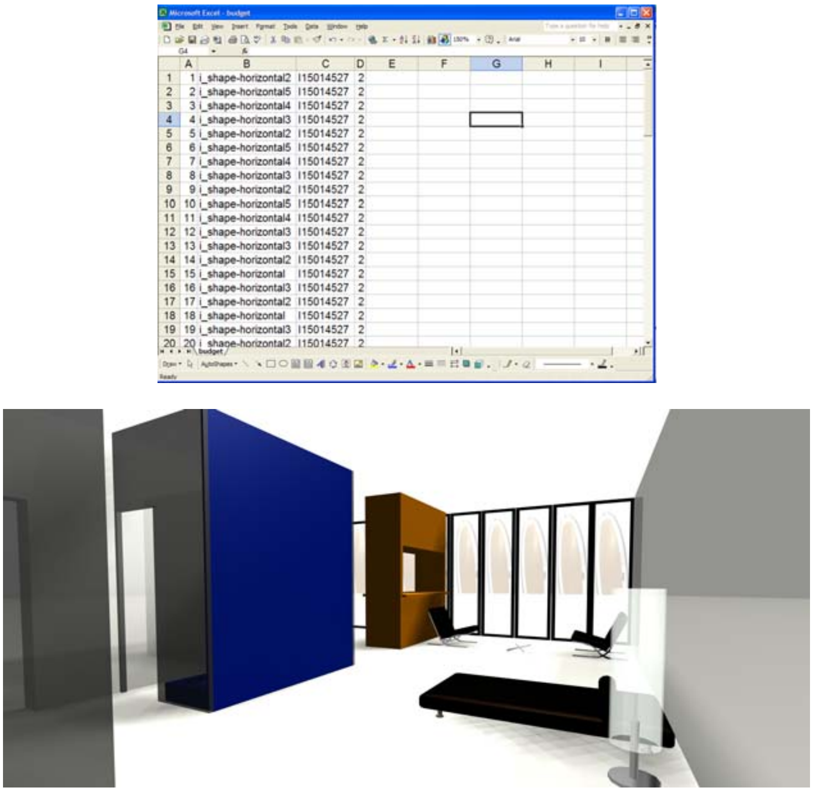


Figure 6. A 3-dimensional model of the evolving design is displayed to facilitate assessment and decision-making.

There are three different outputs of the computer program: the three-dimensional model just mentioned, but also bi-dimensional drawings and bills of quantities (Figure 7, top). The main purpose of the three-dimensional model is to facilitate visualization and assessment of the design by the designer and the client, which can take several forms with increasing levels of sophistication. It can be used for immediate visualization within AutoCAD, it can be exported into rendering software to obtain photo-realistic views (Figure 7, bottom), or into a virtual reality system for virtual walks-through. It also can be utilized to generate a physical model using a rapid prototyping machine. The bi-dimensional drawings can be used as licensing drawings for approval of the design by the town hall, or as construction drawings to guide the construction of the building, following standard procedures.



	A	B	C	D	E	F	G	H	I
1	1	i_shape-horizontal2	I15014527	2					
2	2	i_shape-horizontal5	I15014527	2					
3	3	i_shape-horizontal4	I15014527	2					
4	4	i_shape-horizontal3	I15014527	2					
5	5	i_shape-horizontal2	I15014527	2					
6	6	i_shape-horizontal5	I15014527	2					
7	7	i_shape-horizontal4	I15014527	2					
8	8	i_shape-horizontal3	I15014527	2					
9	9	i_shape-horizontal2	I15014527	2					
10	10	i_shape-horizontal5	I15014527	2					
11	11	i_shape-horizontal4	I15014527	2					
12	12	i_shape-horizontal3	I15014527	2					
13	13	i_shape-horizontal3	I15014527	2					
14	14	i_shape-horizontal2	I15014527	2					
15	15	i_shape-horizontal	I15014527	2					
16	16	i_shape-horizontal3	I15014527	2					
17	17	i_shape-horizontal2	I15014527	2					
18	18	i_shape-horizontal	I15014527	2					
19	19	i_shape-horizontal3	I15014527	2					
20	20	i_shape-horizontal2	I15014527	2					

Figure 7. The output of the program includes a bill of construction elements (top), and a 3D model that can be exported to rendering software to create photorealistic views (bottom).

The bill of construction elements is used to facilitate budgeting and manufacturing. For each element modelled by the computer, a record is inserted in a list that compiles every element, its numerical reference, and its dimensional features. This list is converted by the function Record and saved as an .xls extension file, the standard EXCEL file format, which can be opened with MS Office to assess and control the overall budget. The same list can be used for automated production of prefabricated elements with the specified dimensions in the right quantity.

5. Conclusion

The aim of this study was the creation of a system to explore tailored housing solutions and to produce documentation for mass-producing them using prefabrication as a way of rationalizing construction and controlling costs. The way chosen to guarantee the efficient application of the underlying design and construction systems was the development of a computer program that encodes both systems. This program can assist the designer and help to minimize the time and effort spent in conceiving, drawing, detailing, and budgeting solutions. The program also facilitates the participation of the client in the design of his or her own dwelling as a decision maker. Customization and diversity in mass-housing become goals that can be achieved without overpricing the final result since design and fabrication are partially automated.

The proposed system is in line with previous approaches, but it goes one step further. In a paper called Design Machines, George Stiny and Lionel March (1981) proposed a theoretical model for the automated production of artefacts. The model foresaw the automation of both design and fabrication. This model was implemented by Wang and Duarte (2002) who developed a program that permitted the generation of 3-dimensional abstract objects using shape grammars (Stiny 1980) and the fabrication of the corresponding physical models using rapid prototyping. Later on, Duarte (2001; 2005) proposed a theoretical model for the automated production of dwellings called discursive grammar. This model foresaw the automated generation of housing designs that matched given criteria within a given design language. The model's validity was illustrated with an implementation developed for the case of houses designed by the architect Alvaro Siza at Malagueira. The model also foresaw the use of computer aided-manufacturing to produce houses, but the link between design generation and fabrication was yet to be implemented. The current system establishes such a connection.

In addition, there are three important differences between the two implementations. First, in the previous implementation, the rules of the design system were codified using a shape grammar, whereas the current one relies on parametric design. Shape grammars constitute a well-defined formalism that facilitates the process of devising, structuring, and applying rules systems that define languages of designs. A grammar permits to explain the features of designs in a language, to say whether an unknown design in that language, and how to generate new designs in the same language. However, shape grammars are difficult to implement in the computer because they require one to solve difficult technical problems, linked to shape recognition and rule application. On the other hand, there is no clear formalism to develop parametric systems of designs and one has to rely on his or her intuition to do it. Moreover, parametric design does not offer a rational explanation of how designs are categorized and generated. Nevertheless, once a parametric model is devised, it is much easier to implement and apply in the computer. Because the design system was purposefully devised by the architect and thus its rules were very clear, and because the current research had very practical goals, it was decided to develop a parametric model, instead of a shape grammar.

The second difference is that in the previous implementation there was a clear separation between the generation of the housing program and the generation of the corresponding solution, whereas is the current one there is not. Such a separation permitted greater flexibility and interaction in the definition of housing specifications, but implied that the user only visualized the impact of his choices at the end of the specification process, after making all the decisions and the program generating the solution. By evolving the 3D model while the user made choices, it was possible to visualize the result and correct it immediately, thereby making it easier and faster to tailor the design to the family needs

The third difference is that in the previous implementation the generation of designs was fully automated and the user could be the architect or the client, whereas the current one was targeted at the architect right from the beginning. As a result, it was developed as a design support tool and the degree of automation is considerably lower. This avoided complex technical problems such as shape recognition and optimization and made programming easier. Because the role of the architect is more apparent, the use of the tool is likely to be more accepted by the architectural community.

Acknowledgements

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References

Duarte, JP: 1995, *Tipo e módulo. Abordagem ao processo de produção de habitação*, LNEC, Lisboa.

Duarte JP: 2001, *Customizing Mass Housing: A Discursive Grammar for Siza´s Malagueira Houses*, Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Duarte, JP: 2005, A discursive grammar for customizing mass housing; the case of Siza's houses at Malagueira, *Automation in Construction* **14**: 265-275.

Gausa; M: 1998, *Housing new alternatives, new systems*, ACTAR and Birkhäuser, Barcelona.

Gausa; M. and Salazar, J: 1999, *Singular housing, the private domain*, ACTAR and Birkhäuser, Barcelona.

Habraken; N.J: 2000, *El Diseño de soportes*, Editorial Gustavo Gili, Barcelona.

Stiny G: 1980, Introduction to shape and shape grammars, *Environment and Planning B: Planning and Design* **7**: 343-351.

Stiny, G; March, L: 1981, Design machines, *Environment and Planning B: Planning and Design* **8**: 245-255.

Wang, Y; Duarte, JP: 2002, Automatic Generation and Fabrication of Designs, *Automation in Construction* **11**(3): 291-302.