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Domestic Prototypes Co-Designed Through Experimental 1 m^3 Topological Cubes

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Abstract This paper shows a prototyping project carried out with first-year architecture students at the University of Alcalá. The project starts with the development of a 1 m^3 prototype associated to a micro-domestic space for each student, generating forty-five microarchitectures. The main objective for all students is domesticity. Students interpret their domestic intimate space developed in a 1 m^3 cube. The aim of this paper is to test the learning process on domestic layout through a prototyping approach. The approach is based on twenty-five previously selected architectural references, and proceeds through a process of co-design learning and design thinking to the translation and experimental approach of ten prototypes constructed at a scale of 1:1. This paper focuses on the learning process carried out with the DPM (diagram, plan, model) methodology and patterns generated by the students' architectural projects through the development of prototypes.

Keywords Architectural education · Co-design · Domestic prototypes · DPM (diagram, plan, model) methodology · Project-based learning (PBL)

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Introduction

The interaction of multiple agents in the architectural design process, the scale of projects and issues related to domesticity and flexibility, among other factors, increase complexity in the design stages. Authors such as Kiatake and Petreche (2012) mention that this complexity, which increases to the extent that a design process is in more advanced states and any change in the initial parameters or alteration of possible solutions requires a greater effort, is related to a greater displacement of the research that occurs in the initial phases of the design process (concept of design, capacity of interpretation or planning), where the levels of abstraction, interpretation and generation of ideas are high compared to the final stages of the process.

The programme to be developed is based on a domestic space established in a reference in the Netherlands from the seventeenth century (Rybczynski 1986). Different approaches to the *domestic cube* have been carried out before, from the square grid-based design Roman villas in the first to fourth centuries (Pinho and Xavier 2013) to the primitive hut of Marc-Antoine Laugier in the eighteenth century. According to Rudolf Laban (1966) and his theory of the icosahedral ergonomic and choreographic space, this primitive hut with six two-dimensional faces creating a three-dimensional space responds to human necessities: a floor to isolate from the ground, walls to protect from the air and a roof to protect from the rain. Another reference is the topological cube, which can be framed from analysing Sol LeWitt's incomplete open cubes (LeWitt 2001; Rozhkovskaya and Reb 2015) to Giorgio Scarpa's rotational geometry and John Hedjuk's (1971) "Nine Square" problem at the Cooper Union.

In our project, taking into account three starting points—the primitive hut, the topological cube and twenty-five pre-established architectural references—students are said to create a domestic space based on a 1 m^3 prototype, at a scale of 1:1. Andy Milligan and Ron Rogers (2006) describe the concept of "experience prototyping" as an attitude, an interdisciplinary interaction between design, economy and experiences. Pieter Jan Stappers (2007) has written about prototypes as the designing act of creating prototypes being in itself a potential generator of knowledge.

To achieve the objectives of the course, the teaching process is based on experimental learning (Dym et al. 2005), that means, a hybrid learning process based on three points. Blended learning (De Jorge-Moreno 2012), social constructivist learning theory (Minneman 1991; Cialdini 2005) and an *atelier* based on workshop classes such as cooperative learning and group work, analogous terms that describe "students working together in a group small enough that everyone can participation a collective task" (Cohen 1994) mixed with some specific master class.

The concepts "design thinking" and "co-design", along with the applied methodologies DPM (Diagram, Plan, Models) and PBL (project-based learning) make it possible to understand the development of the project encompassed in an experimental learning process. The concept of design thinking is characterised as a

process of thought that is compensated between the qualitative focus, linked to creativity and intuitive thinking, and the quantitative focus, linked to standardisation and objectivity. It encompasses a set of skills such as decision-making, thinking as part of a team, the ability to handle uncertainty or reason and communicating in different design languages (Dym et al. 2005).

Authors such as Elizabeth Sanders and Pieter Jan Stappers (2008) used the term co-design as the "collective creativity as it is applied across the whole span of a design process". In co-design, different experts, such as researchers, architects, engineers, designers or developers, and potential customers and users—who are also experts, that is, "experts of their experiences" (Sleeswijk et al. 2005)—come together to collaborate creatively.

The objective of this paper is both related to the co-design of guided prototypes and an analysis of the degree of comprehension and creative thinking development of architecture's students, through strategies of collaborative and proactive learning based on problem-solving. The development from the initial concept to the final prototype by means of experimental learning processes and mixed methods of research can contribute to an increase in the acquisition of skills of compression, abstraction, interpretation and conceptualisation of the architectural principles in projects.

The paper is organized as follows. First we show how references are assign to the students and introduce the methodology. New we show the main results followed by the final exposition. Finally, we arrive at the conclusions.

Methodology

Description of References for Projects Students' Domestic Spaces

In order to develop the prototypes, twenty-five pre-established architectural references (Fig. 1) were provided to guide students. The choice of these references was initially based on different concepts analyzed from a database of 110 projects elaborated by the authors of this work. Included in the references are the architect, with the year or the country as descriptive factors. From the qualitative point of view, special attention was paid to: whether the project was constructed or not; whether it was a single experimental prototype; whether it was an ergonomic changeable space; whether it was modulated dwelling or a cube; if it allows grouping. At the quantitative level and by means of a Likert scale, factors such as the scale (XS, S, M, L or XL) of the assigned reference are analysed. The degree of mutability was evaluated. The references were grouped according to the hybrid program or use of the reference. Finally, the degree of possibility of change and mutation of the given reference was evaluated.

From the creation of the mentioned variables and by means of a cluster analysis, an exploratory analysis was carried out to determine the process of association of the references. Different combinations of variables and techniques were used. Although there were no significant changes in the results, the choice of six variables were the following ones: module or cube, allowance for change, use, prototype or

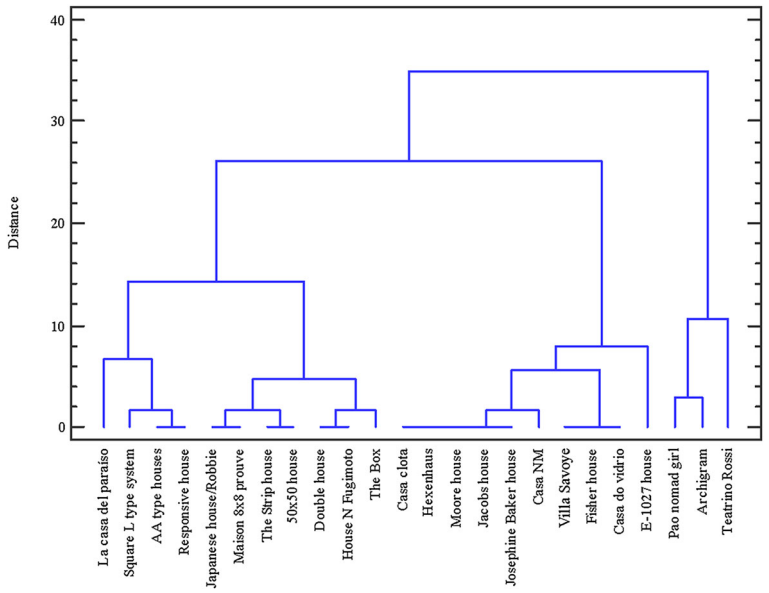


Fig. 1 Dendrogram of the twenty-five references

not, clustering and scale, the most remote neighbour method and squared Euclidean distance were chosen. These guidelines are in order to obtain a complete chain of the twenty-five projects. Figure 1 shows the dendrogram of the references, that is, a graphical representation of the result of the tree-grouping process. It is constructed as follows: (1) in the lower part of the graph the twenty-five projects are arranged; (2) the joints between projects are indicated by three straight lines. Two are directed at the projects that are joined and are perpendicular to the axis of the projects, the other is parallel to this axis, situated at the level in which they meet; (3) the process is repeated until all the projects are connected by straight lines. If we cut the dendrogram into a given distance level, we obtain a classification of the number of groups existing at that level and the projects that form it. As can be seen in Fig. 1, there are three groups, where the Pao of the nomad girl of Toyo Ito with Kazuyo Sejima, next to the Teatrino of Aldo Rossi and the references of the group Archigram, are the references that form the group that is nested in the end and therefore has less of a relation to other projects or constructed works.

Research Participants

The participants, as already mentioned, were first-year students of the first design course of the 2017 architecture program at the University of Alcalá. The students could choose between two versions, workshop and non-workshop. Surveys were carried out at the beginning and end of the project in order to determine the degree of understanding of the activities to be carried out to materialise the prototype, with special interest in the conception, interpretation and abstraction phase from the

assigned references. The surveys allowed for analysis of the degree of satisfaction of the students during the project and also allowed us to identify some of their characteristics. Table 1 shows the technical characteristics of the surveys.

Regarding the demographic characteristics of the students, 26 are female, 39 of the total number of students chose architecture as the first study option, 9 have an architect in their family and 14 have previous knowledge of the profession (professional training or architectural studies).

In order to supervise the students' performance level, whose results will be shown below, the development of their activities was controlled according to their degree of satisfaction and understanding of the project. Some authors, such as Melvin Blumberg and Charles Pringle (1982), mention that a person's performance level is a function of their ability (intelligence and individual abilities), motivation (intrinsic and extrinsic) and the opportunity to perform (constraints on their performance).

In these surveys, we also obtained evaluation of students' degree of comprehension of domestic space, as well as other information regarding whether the students' knowledge or attitude to architecture arose before enrolment in university, as be discussed below.

Instruments and Procedure

The learning carried out in the project was experimental and holistic; this is the ideal generating a connection between learning and the creative process. Authors such as Heron (2008) argue that this learning is a sum of four concepts. Two of them come from Aristotelian learning: thought, related to intellectual statements, and action, related to aspects of resolution. The other two concepts are the ability to imagine, related to ludic dreams and visions, and feeling as an active method. These last two concepts include *feelings* in learning to understand the creative process (Welford 2004).

Table 1 Characteristics of the sample. Source: Own elaboration

	Technical characteristics of the study
Analysis unit	Students of 1st year of the School of Architecture of the University of Alcala, atelier group ("Grupo Taller UAH")
Geographical scope	University of Alcala-Madrid
Population	54 Students enrolled in the 2017 course
Sampling type	For convenience
Sample size	45 (83.3%) Students
Sampling error/confidence interval	5.9% (95%); p = q = 50
Measuring instrument	Individual survey
Date embodiment	February–April 2017

In order to understand the development in which this study was conducted, Fig. 2 presents the process of creating projects carried out at a sequential, temporal and repetitive level through the DPM methodology. The students' work process is based on experimental learning, defined as an interaction between empirical works and works related to the constant revision of the literature (Dym et al. 2005). This learning took place during the four months that the project lasted (from February to May 2017).

The process was carried out in three phases, #1, #2, #3, the beginnings and ends of which are shown in Fig. 2.

Development of the Phases

Phase #1 and Global Perspective

In the month-long phase #1, students worked in pairs. At this time, they were asked to create an individual online blog (https://grupotallerblog.wordpress.com/proyectos-1/) along with the collective work. Figure 3 shows different phases and activities with sequential time criteria.

In phase #2, which lasted for a month and a half, work occurred individually, allowing us to get to know the progress of each student with his or her project and translation of references.

In phase #3, the duration of which was a month, the work was in teams. This process of collaborative work brings with it the interrelation of ideas and work processes to achieve the objectives, improving the organisation of the process, putting ideas in common and improving communication when working in teams (Steen et al. 2011).

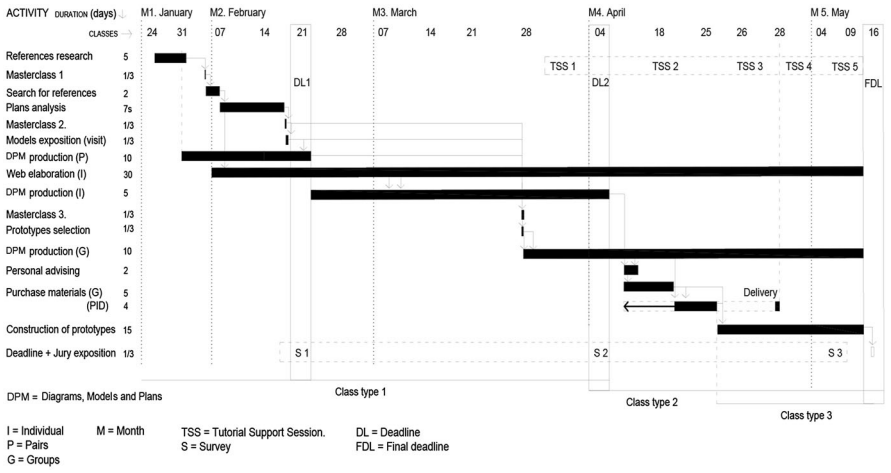


Fig. 2 Gantt diagram and project

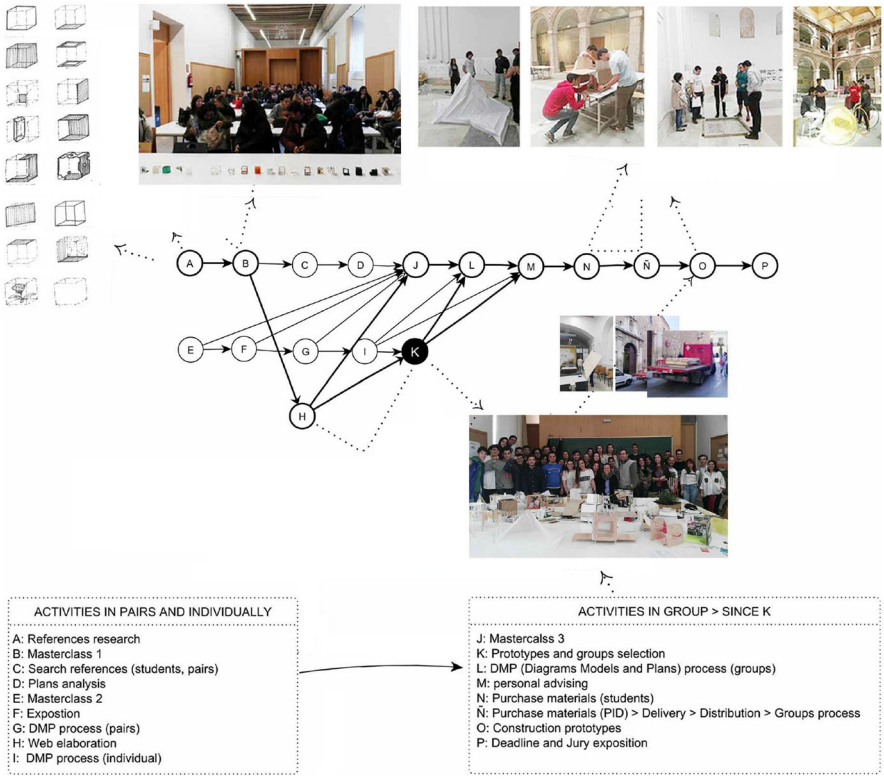


Fig. 3 Phases and activities of network project

As for the strategies carried out in the mixed work in the workshop, the following stand out. On the one hand, the workshop was based on lessons supported by classroom work, attendance at exhibitions and discussion. In addition, specific master classes were held each time a new phase or concept was established. In addition, individualised tutoring was given to classes as additional time.

One of the most relevant strategies was the practical work requested from the students for the final construction of the prototypes. In this part, there are three key points. First they were asked to carry out the DPM process throughout the project, in all its phases, in a repetitive way. This was done and internalised by working with the DPM three consecutive times. Figure 4 shows that the result through the models after the development of diagrams and the development of plans, was parallel to the basic structure of the project to deepen it during the 4 months of work. The DPM process was repeated by increasing the metric scale and therefore the level of development, with both of the plans and diagrams as the models. This work was published each week on their blogs. This online space allows for control by the teacher when the number of students is large (De Jorge-Moreno 2012).

Fig. 4 Class 11. Photography of the second competition, 4 April 2017

Phase #2 References in the Process of Developing Prototypes

In this phase, a series of questions were asked to extract strategies from the references and to export them to the translation of prototypes. The questions led to the 1:1 scale development of domestic prototypes. The references and their developments in the projects will be approached in the following section in relation to the prototypes. Subsequently the ten prototypes built will be analysed. Finally, four patterns (Alexander et al. 1977) will be presented in the process of the final domestic topological cube.

On the one hand, this phase provides a theoretical base of references for the students (Fig. 1). This has the aim of facilitating the implementation and development of spatial capacities in variable and experimental domestic environments, which in turn with strategic associative capabilities improves their learning through the final construction of prototypes at a scale of 1:1.

The translation of the initial reference is transferred to the plans, models and prototypes through some guidelines previously given to the students. Asking questions is fundamental in the design process (Dym et al. 2005).

The prototype *Filters* started from the reference to the Villa Savoye of Le Corbusier. The prototype was based on the distribution and maximum optimisation of the space to create a comfortable place for the users, related to their ergonomics. In turn they evaluated the versatility of the space, obtaining a cyclical space and one of continuous change like a chessboard. The basic programme was a village and the programme introduced in the prototype is based on the domesticity transferred to the public space.

The prototype *Sand and Perceptions* obtained from its reference perceptual factors like the filters through which it passes to a series of movable panels, arranged in racks. The student personal perception was of "a filter of the existing reality linked to psychiatric centres".

From the prototypes *Mr. Gym, Blue Garden* and *Wormhole*, based on the reference to the Pao (portable tent-house) of the nomad girl of Toyo Ito (Ito 2000), different translations are extracted. One of them, *Wormhole*, extracts the versatility of the Pao both for its shape and its weightlessness. The students also analyse the envelope that takes the prototype as a space "that protects you in specific moments". They define their space as an envelope where the user can introduce himself and create new experiences inside. The organic form allows it to acquire the versatility of change and adaptation to the body as a second skin. This project is abstracted from the 1 m^3 geometric form, meaning the volume together with the topological and non-formal relationship of the base statement.

The prototype *Blue Garden* obtains its light, transportable and ephemeral architecture from the previous analysis of Pao of Toyo Ito. It is also inspired by Japanese architecture and culture in terms of values such as the care of and importance of nature and lightness of their interior modulations of traditional constructions. It proposes a project based on the combinatorics of a portable garden-lounge, whose grouping with other prototypes generates an experimental domestic space.

The prototype *Knotted*, whose project of reference is the Casa NM (gaSSz Architects, 2007), obtains from its reference the introduction of counting in a minimum space with the necessary possibilities and functions. Its project is limited to the 1 m^3 cube, fixing some knots as shown in Fig. 5 with three openings that allow for the creation of various configurations with the same slats. This prototype allows for a configuration based on the combinatorics of the incomplete open cubes of Sol LeWitt (2001).

The *Set-mesh* prototype is part of Jaap Bakema's Square L-type system reference, a module system of 6.3 × 6.3 allowing for diverse groupings of space. The reference of Bakema is a project of houses for the reconstruction of damaged areas after the second world war. This project allowed associations that were both horizontal and vertical.

Fig. 5 Students working on the *Knotted* prototype

Among the associations from the reference to the prototype, in groups of 4–5 students, a total of ten groups and forty-five students concluded that the most determining factors are the distribution of spaces and perception and the user's perception of the projects when interacting with them. However, the parameters that most influenced the students when it came to conceiving the space are those of flexibility, and lightness in the portability and versatility of the space, as will be analysed below.

Phase #3 Co-design of Topological Cube Prototypes

During phase #3 of the project, the prototyping was explained. Jan Pieter Stappers has described prototypes as:

> …the core means by which the designer builds the connection between fields of knowledge and progresses toward a product. Prototypes serve to instantiate hypotheses from contributing disciplines, and to communicate principles, facts and considerations between disciplines. They speak the language of experience, which unites us in the world. Moreover, by training (and selection), designers can develop ideas and concepts by realizing prototypes and evaluating them… The designing act of creating prototypes is in itself a potential generator of knowledge (if only its insights do not disappear into the prototype, but are fed back into the disciplinary and cross-disciplinary platforms that can fit these insights into the growth of theory) (2007: 87).

The process of co-design was realised taking into account the topological concept of the space of the prototypes. That is, the study of qualitative properties developed with transformations of space (Tepavčević and Stojaković 2014). In the second phase, about forty-five initial variants of the 1 m^3 cube were created, as shown in Fig. 6, based, on the one hand, on the previous references given and, on the other, on the evolution of the students' creative thinking, together with the guidelines from teachers. From this point, the final phase of the design of the prototypes on the 1:1 scale was made.

Finally, ten of forty-five prototypes built were selected in a competition for their level of development and didactic possibilities.

In Fig. 7 we can observe the influence of the twenty-five references given; as can be seen, two references have a significant nodal density, thus indicating the important predominance in the development of students' work. The first of these is the Clota House by Benedetta Tagliabue and Enric Miralles, a work built in 1991 in Spain. The main influence of this project on students was the central skylight. Through its geometry and arrangement of angles, this element allows the entrance of light into the interior space. In addition, the use of the masonry without coverings in Clota House inspired them in their final prototypes, leaving the material seen without any coverings, architectural finishes or paintings.

The second reference is the Pao of the nomad girl, a project realised in 1985 by Toyo Ito and Kazujo Sejima. It is based on a circular base envelope and a possible development based on triangular structures. This project had a final influence on twelve students (Fig. 7). It also encouraged the final development of three of the ten

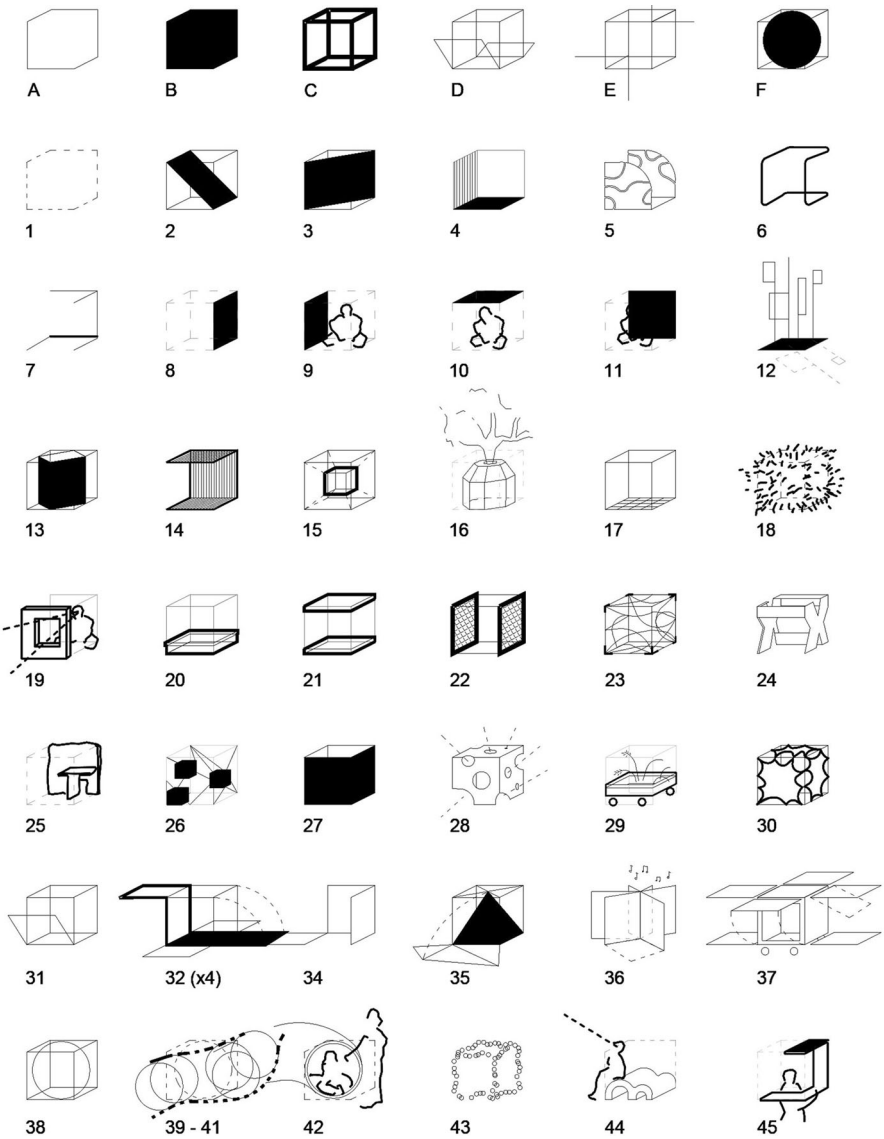


Fig. 6 Forty-five raised options of the cube linked to a micro domestic space. From the twenty-five initial references given previously and in the combinatorics between work teams, the final design phase was reached. **a** Perimeter exterior. **b** Structure. **c** Volume interior. **d** Folding. **e** Axis. **f** Topology

selected prototypes of the same reference. This leads to the conclusion about the possibility of the factors mentioned above. In the case of the Pao, it is an experimental prototype: it has an XS scale, and is a visionary project whose objective is to give visibility to a factor that today is still present—domesticity and its evolution or experimental progress. In addition, the Pao has the possibility of generating changes or combinatorics.

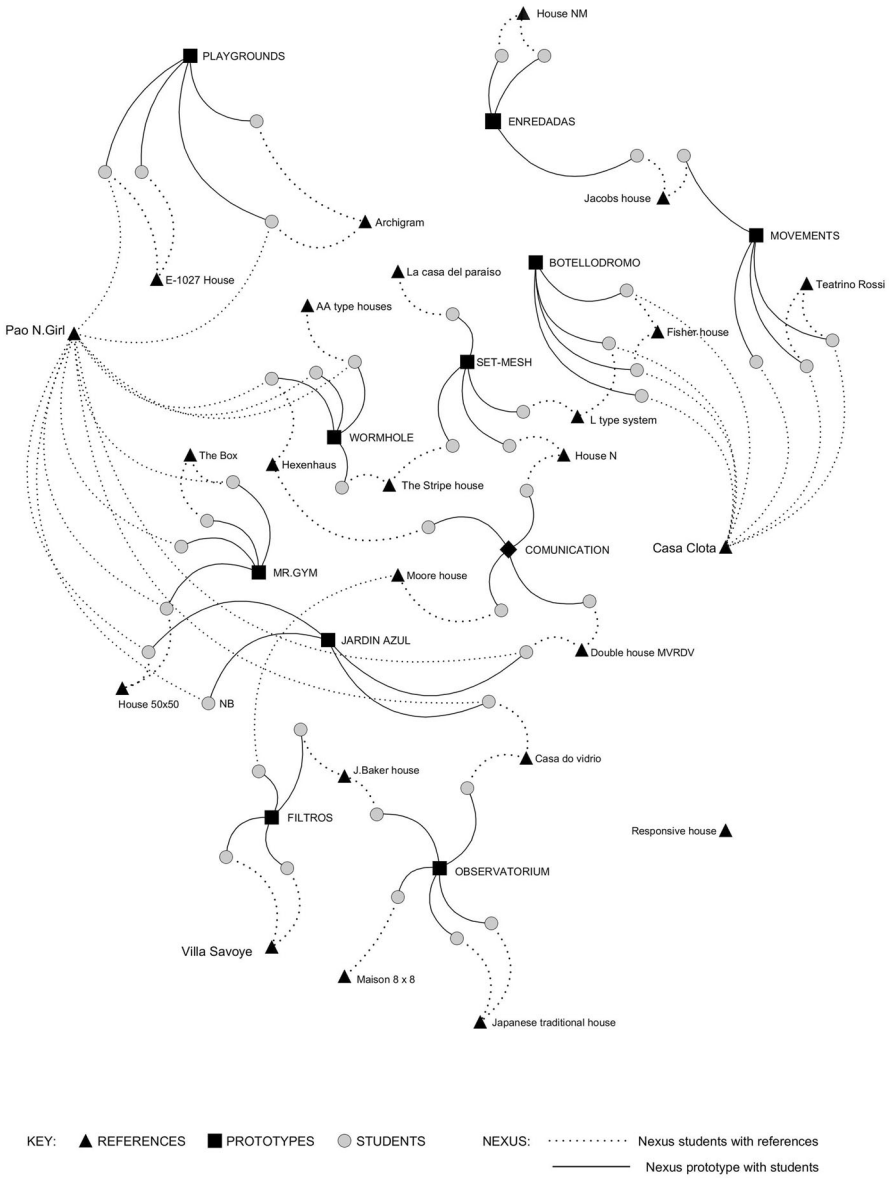


Fig. 7 Network of references, students and prototypes

In Fig. 7 we can see how the references (marked with a triangle), the students (marked with a circle), and the prototypes (marked with a square) generate a new work-network. The fusion of references by each of the students creates an atmosphere of interconnected work for the construction of the prototypes, and illustrates that they are enriched by the contribution of the references that come together when members of other references are grouped together to form the

prototype team (see prototype *Blue Garden*). The grouping of students belonging to different initial references promotes the acquisition and natural hybridisation of concepts carried out in the final prototype. This is the case of the prototypes *Observatorium* and *Set-mesh*, whose students come from four different references, and which reflects this interaction in the final prototype, both in its form and in its base concept.

Data Collection and Analysis

In this section we present the results obtained from the pre- and post-project surveys completed by the students. The pre-survey included a set of architectural subjects (domestic spaces comprehension, experience, previous knowledge, relations with familiar architect). For the degree of comprehension and satisfaction we used a Likert scale ranging from Low (1) to High (5). A typical question asked to assess comprehension/satisfaction was: What is the degree of comprehension or satisfaction of the work you are doing? Questions to assess architectural subjects included: What space of your house is dispensable or essential? What space does not currently exist in a house? Would you invent it?

The descriptive analysis of Table 2 shows the degree of compression and satisfaction. The values of understanding and satisfaction are high and show how both evolved between surveys.

In order to better understand the relationship between the degree of comprehension and satisfaction in the different surveys carried out, given the relationship of these factors to the performance already discussed above, an analysis was carried out in greater depth than the one shown in the Table 2, where only the value of the mean is taken into account. Figure 8 shows a graph illustrating the complete distribution of the four variables by means of a box plot and graph in the form of a violin according to the surveys. In the central part of each graph is the detailed box plot, indicative of the range and extreme values of the distributions. In the external form, you can see the kernel distributions. Clearly, a shift of the values of comprehension and satisfaction of the second survey (light grey violins) can be seen in the higher levels in relation to the first.

Regarding the features reflected by students' characteristics, 32% have previous knowledge of architecture, due to relationships with a relative, friend or previous study and 90% of them chose an architecture degree as their first option. Regarding evaluations related to domestic space, 90.84% define this as *domus-casa*. Dispensable spaces were identified as living room, dining room, hallway; essential or more frequently used spaces were bedroom, bathroom and kitchen.

Concerning the development of outdoor spaces and whether or not they should be included inside the house, the responses are very divided. 80% of them show around twenty different choices, where the highest percentages focus on swimming pools, sports areas, gardens and co-working areas.

Table 2 Degree of understanding and satisfaction. Source: Own elaboration

Ítem	Survey #1	Survey #2
Degree of understanding (average DE)	3.82 (1.11)	4.21 (0.61)
Degree of satisfaction (average/DE)	3.91 (1.27)	4.23 (0.65)

Results and Exposition

The ten prototypes developed in Fig. 9 are grouped into four patterns (Alexander et al. 1977). On one side are the prototypes that maintain the cubic configuration from the beginning to the end of the process. In this section three prototypes are entered: *Knotted* (1), *Mr. Gym* (2) and *Set-mesh* (3). On the other hand are those that occupy the volume initially given in a 1 m^3 cube but are expanded by organic forms, complex geometries, or topological relationships of the space to be explored, that is, a non-metric concept of space (Tepavčević and Stojaković 2014). These are the prototypes *Wormhole* (7) and *Movements* (8). A third group is identified in those prototypes that maintain the perimeter base of 1 × 1 in some of their "faces" and develop an open form based on the use assigned by the students. In this group are the *Botellódromo* (9), *Filters* (6), *Blue Garden* (5) and *Observatorium* (4). A fourth group is formed by the *Playgrounds* project (10). This prototype creates four spaces by intersecting two planes.

Out of the ten prototypes, four were chosen. The first prototype, *Set-mesh*, is associated with pattern #1 cubic Euclidean geometric space, maintaining the cubic

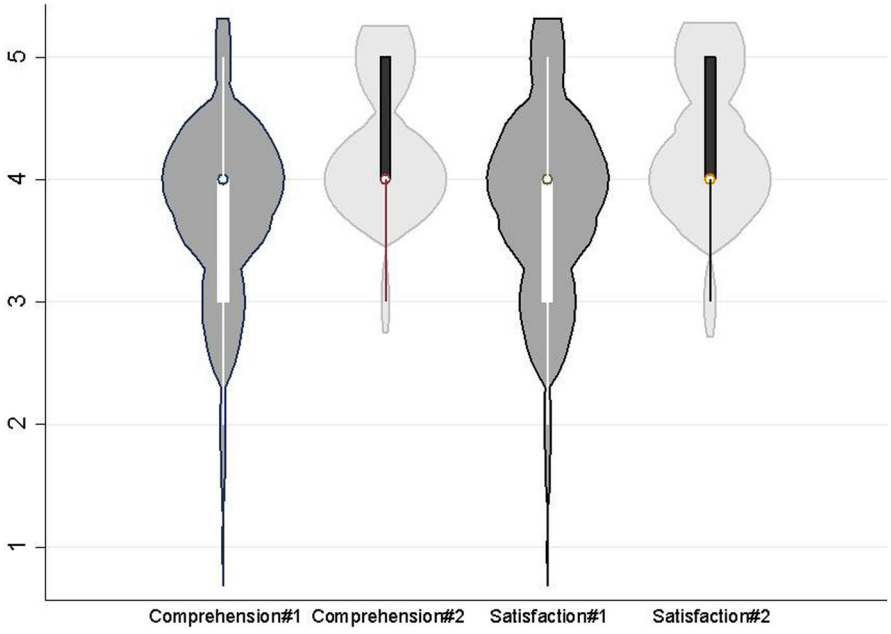
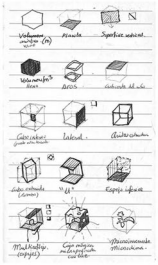
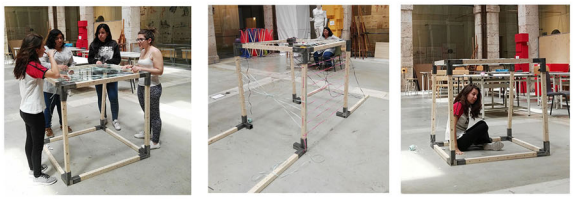


Fig. 8 Violin graphs of the degree of understanding and satisfaction of the surveys




Starting point.



1 Knotted



2 Mr.Gym

3 Set-Mesh

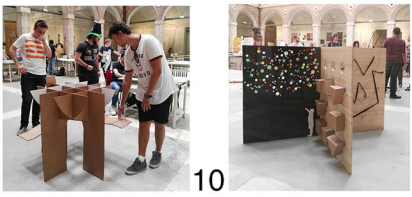
4 Observatorium



5 Blue garden.

6 Filters.





7 Wormhole

8 Movements

9 Botellódromo

10 Playgrounds

Fig. 9 Development of ten prototypes

form from the initial phases of the process to the final execution on a 1:1 scale. It proposes a prototype based on a mesh, influenced by its reference to Jaap Bakema, and two framed quadrants of 1 × 1 wood allowing the *z*-axis to vary according to the needs of the user. A series of slats 1 m long that are adjustable according to the needs of the user are arranged. Figure 10 shows this strategy created to allow for multiple dispositions with the same 1 × 1 matrix.

The second prototype, *Movements* (Fig. 11), is associated with patterns #3 and #4 expandable coplanar projective space and folding space. The concept *folds* has been studied for the geometry of space, testing with different materials the same folds. Both the origami (folded paper art) technique and the architectural kirigami (paper cut art) technique were tested by students on scale models under the influence of the Toyo Ito reference and Japanese culture. The Spanish architect Emilio Pérez Piñero (Pérez Piñero 1965), who from 1960 to 1971 designed and built coplanar deployable structures and removable and retractable domes, worked experimentally at a scale of 1:1, and referred to the process carried out in the preparation of models and later drawings. In many cases, he first produced models and prototypes and then drew them. This pattern has been contemplated in several prototypes, such as *Botellódromo* and *Movements*.

Wormhole, the third prototype (Fig. 12), is associated with pattern #2 topological space. This project starting from a volume of 1 m^3 led to an organic structure, and generated a mirror of the concept "squaring of the circle" (Duvernoy 2008.) The prototype is associated with topological relations of space (Tepavčević and Stojaković 2014). The sensation of metamorphosis (à la Kafka) or of a second skin and ergonomics, leads the students to create a path of 6 m long, folding to 50 cm after folding (Fig. 9). This prototype allows for the possibility of generating

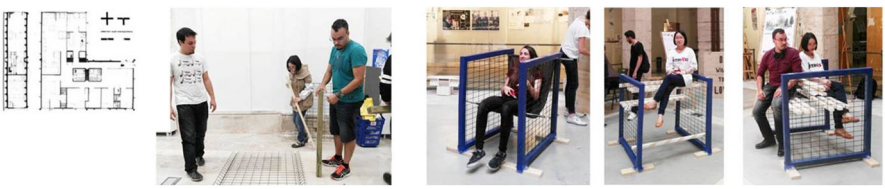


Fig. 10 Pattern 1. Prototype set-mesh

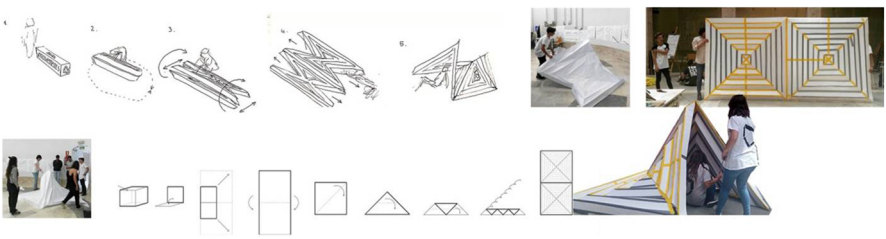


Fig. 11 Pattern 2. Prototype *Movements*

Fig. 12 Pattern 3. Prototype *Wormhole*

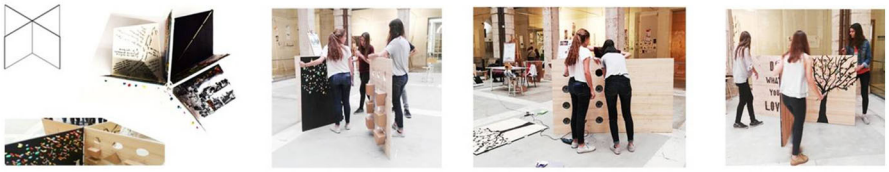


Fig. 13 Pattern 4. Prototype playgrounds

Fig. 14 Final grouping based on the diverse flows of domestic space and activities: intimacy, privacy, quotidian function, familial relations, eating, washing, sleeping or any activity associate with home

multiple paths and arrangements, both horizontal, diagonal and vertical, given the flexibility of the proposed curves.

The prototype *Playgrounds* (Fig. 13) is part of the capsule *Living pod* (http://www.archigram.net/projects_pages/living_pod.html) by the British group Archigram. This prototype is transformed into the intersection of two planes, creating four spaces. The associated programme is the recreational spaces to four generations—a game for all ages. Each space is interconnected contiguously by means of micro-visual perforations or hollows to pass the hands to another geometric space of parallelepipeds or flat pyramids.

The final exhibition with all the prototypes is based on a matrix or a game board (chessboard). The game strategy allows for a constant change of elements. The board performs a double function. First, it takes the domestic space to the public space, the street, taking advantage of the particular function of each prototype. Second, it creates another domestic space that shelters projects, always thinking about the comfort of the user. The process of realisation, both of the prototypes and of the exhibition, was carried out via co-design and collaboration between the teachers and students. In addition, brainstorming and tutorials were carried out with the faculty's architecture laboratory and the provider. The main objective of the exhibition is based on the interconnection of prototypes in the same space. This approach was proposed by the teachers as a possible strategy for the final association of cubic spaces (Fig. 14).

Conclusions

The main results show the evolution of the learning process and the architectural projects of the students, through the development of prototypes, in which it was possible to identify four patterns: cubic Euclidean geometric space, topological space, expandable coplanar projective space and folding space. Also in the development of prototype construction, the incorporation of models to different scales from 1:100 to 1:10 was relevant to the development of prototypes on a 1:1 scale. This allowed first-year students to internalise three important concepts of architecture, mainly concerning experimental housing and its distribution of spaces adapted to change, together with mathematics. First is the united concept of scale and proportion, linked to the ergonomics of the user in a domestic micro architecture as a base point. Second is the incorporation of geometry and form from the distribution of spaces to development in the constructive detail. Third is the concept of groupings by applying the 1 m^3 cube and its subsequent association to a game board (Fig. 14).

The project discussed here with its conclusions and hypotheses should be tested and refined with more case studies of different contexts and prototyping dimensions. Exploring new sets of scales and grouping is also expected in future research. Furthermore, a possible extension to this work could follow several lines. A potential path could be carried out on the basis of the cube but using a material other than wood, or the same volume and different geometries. Applying a similar approach working with metric, dimensions alternative to 1 m^3 as a standardized "a

priori" measure could be applied, for example, a threshold of a door of 80 cm or the minimum radius required for a space to reach with universal accessibility, 150 cm, can also be an interesting extension.

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References

Alexander, Christopher et al. 1977. *A Pattern Language: Towns, Buildings, Construction*. New York: Oxford University Press.

Blumberg, Melvin and Charles Pringle. 1982. The Missing Opportunity in Organizational Research: Some Implications for a Theory of Work Performance. *Academy of Management Review* **7**(4): 560–569.

Cohen, Elisabeth. 1994. Restructuring the Classroom: Conditions for Productive Small Groups. *Review of Educational Research* **64**(1): 1–35.

Cialdini, Robert. 2005. What's the Best Secret Device for Engaging Student Interest? The Answer is in the Title. *Journal of Social and Clinical Psychology* 24(1): 22–29.

De Jorge-Moreno, Justo. 2012. Using Social Network and Dropbox in Blended Learning: An Application to University Education. *Business, Management and Education* 10(2).

Dym, Clive, Alice Agogino, Ozgur Eris, Daniel Frey and Larry Leifer. 2005. Engineering design thinking, teaching and learning. *Journal of Engineering Education* 94(1): 103–120.

Duvernoy, Sylvie. 2008. Leonardo and Theoretical Mathematics. *Nexus Network Journal* 10(1): 39–49. https://doi.org/10.1007/s00004-007-0055-9.

Hejduk, John. 1971. *Education of an Architect: A Point of View*. An exhibition by the at Cooper Union School of Art & Architecture at the museum of Modern Art, New York City. USA.

Heron, John and Reason, Peter. 2008. *Extending epistemology within co-operative inquiry*. Handbook of Action Research. London: Sage.

Ito, Toyo. 2000. *Escritos.* Maite Shigeko Suzuki, trans. Murcia: Colegio Oficial de Aparejadores y Arquitectos Técnicos de Murcia.

Kiatake, Marly and Petreche, Diego. 2012. A case study on the application of the theory of inventive problem solving in architecture. *Architectural Engineering and Design Management* 8(2): 90–102. https://doi.org/10.1080/17452007.2012.659504.

Laban, Rudolf. 1966. *Choreutics*. London: MacDonald and Evans.

LeWitt, Sol. 2001. *Incomplete Open Cubes.* Exhibition catalogue. Hartford, Ct: Wadsworth Atheneum Museum of Art.

Minneman, Scott. 1991. The social construction of a technical reality. Ph.D. dissertation, Stanford University.

Milligan, Andy and Ron Rogers. 2006. Experience design and artefacts after the fact. *CoDesign* 2(2): 89–96.

Pérez Piñero, Emilio. 1965. Folding three-dimensional reticular structure. US US 3185164A. https://www.google.com/patents/US3185164, accessed 11 Nov 2017.

Pinho, Eliana Manuel and Joao Pedro Xavier. 2013. Grid-Based Design in Roman Villas: A Method of Analysis. *Nexus Network Journal* **15**(1): 83–103. https://doi.org/10.1007/s00004-012-0138-0.

Rozhkovskaya, Natasha and Michael Reb. 2015. Is the List of Incomplete Open Cubes Complete? *Nexus Network Journal* **17**(3): 913–9twenty-five https://doi.org/10.1007/s00004-015-0twenty-five4-8.
Rybczynski, Witold. 1986. *Home: A Short Story of an Idea.* New York: Penguin Books.
Sanders, Elizabeth and Pieter Jan Stappers. 2008. Co-creation and the new landscapes of design. *CoDesign* **4**(1): 5–18.
Sleeswijk et al. 2005. Contextmapping: experiences from practice. *CoDesign* **1**(2): 119–149.
Stappers, Pieter Jan. 2007. Doing Design as a Part of Doing Research. Pp. 81–91 in *Design Research Now*, Ralf Michel, ed. Basel: Birkhäuser.
Steen, Marc, Menno Manschot and Nicole De Koning. 2011. Benefits of Co-Design in Service Design Projects. *International Journal of Design* **5**(2): 53–60.
Tepavčević, Bojan and Vesna Stojaković. 2014. Representation of Non-Metric Concepts of Space in Architectural Design Theories. *Nexus Network Journal* **16**(2): 285–297 https://doi.org/10.1007/s00004-014-0194-8.
Welford. John. 2004. *Brainware, The Imaginative Curriculum: Creativity, Taught & Caught*. University of Strathclyde. http://www.jwelford.demon.co.uk/brainwaremap/.

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