Randomness and control in design processes: an empirical study with architecture students

María Victoria Belmonte[a], Eva Millán[a], Manuela Ruiz-Montiel[a], Reyes Badillo[a], Javier Boned[b], Lawrence Mandow[a], José-Luis Pérez-de-la-Cruz[a]

[a]*ETSI Informática, University of Málaga, Campus de Teatinos, 29080. Málaga, Spain*
[b]*ETS Arquitectura, University of Málaga, Plaza de El Ejido, 29080. Málaga, Spain*

Abstract

The aim of this study is to explore designers' preferences between randomness and control in the generation of architectural forms. To this end, a generative computer tool was implemented that allows both random and controlled generation of elements. An assignment was given to fourth-year Architecture students which involved the designing of several megastructures using the tool. Results show that both randomness and control can have their own space and play a complementary role in design. Most students were willing to explore randomness and were able to exploit it to generate good designs. However, some of them have certain degree of preference for more controlled solutions.

Keywords:
architectural design; design studies; randomness.

The use of randomness in design has been considered and analyzed by many researchers, usually by means of case studies (Goldschmidt, 1994) or computer based simulations (Petre et al., 2006). Randomness can help designers in the initial stages of the process or even can be present in the final result for the sake of visual pleasure (Verbeeck, 2006, p. 73).

This paper performs an empirical study of randomness in design processes. More concretely, our research goal is to determine the degree to which novice designers are willing to perform random explorations in a design space, that is, the degree to which they exploit randomness, prefer random to controlled results, and are able to obtain "good" designs by means of partially random processes. To this end, an interactive computer tool has been designed and implemented by the authors and has been offered to a group of fourth-year Architecture students. The students were asked to perform a certain design task, and the resulting work was analyzed in terms of randomness and quality. Another research goal of this work is the evaluation of the computer tool in order to continue this research, and eventually modify it in such a way that it can be used in a more realistic design environment. Therefore, students also had to complete a survey giving their opinions on the task and the tool.

1. Randomness in design

A certain amount of uncertainty and randomness has sometimes been advocated for the first steps of design processes. The intended benefits are twofold: allowing for computational design exploration, and introducing an unintentional influence that forces reinterpretation of the whole design (Verbeeck, 2006). Some well known cases are cited to support this approach. For example, it is said that Alvar Aalto (Quantrill, 1983, p. 5) commonly made random pencil marks and unconscious drawings, from which he developed relevant forms in his architectural design process. Aalto would use these random marks as stimuli in the development of ideas for building forms and designs.

Some experiments have also been carried out that support these ideas. In one of them (Goldschmidt, 1994), an architecture student had to design a kindergarten on a given urban lot. He decided to start his project using a random drawing which then shifted to a structured drawing. In Figure 1, we can see some steps of the design process, from a random start to an elaborated solution.

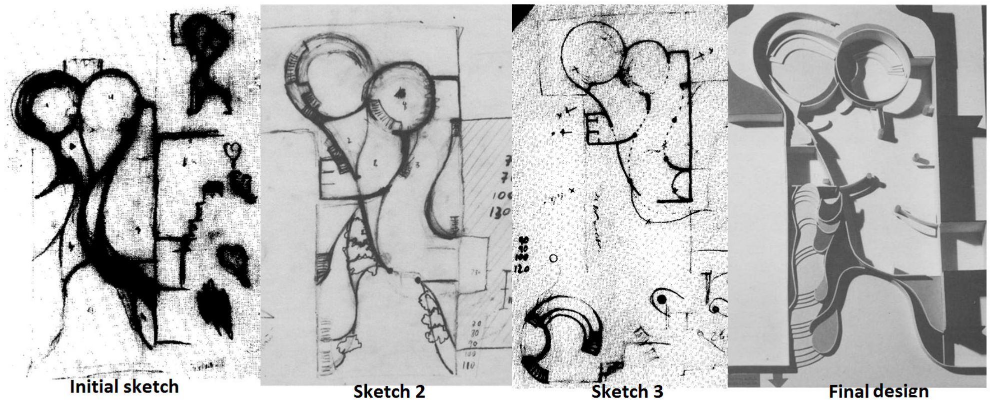

Figure 1: A design from a random drawing (Goldschmidt, 1994)

In other research (Petre et al., 2006) on the exploration of ideas in knitwear design, evidence was gathered on how designers perform their task and then a computational model was implemented that placed motifs and objects partially at random. The program was able to produce interesting designs similar to those generated by human designers.

So far we have taken the concept of *randomness* for granted. However, the concept of randomness is not clearly defined. From a mathematical point of view, Chaitin's randomness (Chaitin, 2001, chapter 8) relates the randomness of an object to the properties of its generating algorithms. Chaitin says that "something is random if it is algorithmically incompressible or irreducible", i.e., if the simplest rules to generate the result are as complex as the result itself. But this is not always the concept of randomness that we use in everyday life. The popular meaning of the term is quite different, and usually it is associated with unpredictability and seen as opposite to "order", and sometimes simple rules can generate what looks to be a totally disordered object. For example, Wolfram (Wolfram, 2002) has extensively studied randomness in nature by means of deterministic, simple cellular automata that compute seemingly random patterns. Hence it could be said that "visual randomness" is not always the outcome of a real random process.

In architecture and visual arts the same reflections also apply. As Verbeeck remarks, "even in its visual complexity, a Jackson Pollock painting can be considered the result of a limited set of rules" (Verbeeck, 2006, p. 57) and he even tries to express Pollock's "action paintings" by means of a shape grammar. However, in these cases deterministic, simple rules are usually applied by an indeterministic algorithm, so a certain degree of "real" randomness is present.

There exist several generative techniques that can be used to integrate randomness and enhance creativity and exploration in design, notably cellular automata, genetic algorithms, L-systems, shape grammars, and swarm intelligence (Singh & Gu, 2012). These techniques can yield involved patterns that are "visually random" by applying simple procedures and rules.

Cellular automata have been proposed as a method to support generative architectural design processes (Herr & Kvan, 2007). An example is the *MODEL* program, that implements the ideas of "Parametric Modeling" in a CAD system (Rubinowicz, 2000) to generate "chaotic" designs and makes use of 3D cellular automata in order to simulate the ideation of complex spatial designs. Genetic algorithms have also been proposed, usually to generate designs that are "optimal" according to some criteria (Caldas, 2008). In the literature we can also find examples of application of L-systems, mainly for image synthesis and modeling (Parish & Muller, 2001), (Palubicki et al., 2009), and of swarm intelligence (Theraulaz & Bonabeau, 1995).

Shape grammars (Stiny, 1980), (Stiny, 2006) (Al-kazzaz & Bridges, 2012) are a well known technique that has been broadly used in design (McCormack et al., 2004) and architectural research (Cagdas, 1996). A shape grammar is completely defined by a set of transformation rules that are sequentially applied to an initial, simple shape to generate a complex design. However, a grammar does not determine its final result, since in every step of the computation there can be many different possibilities: Which rule must be applied? To which fragment of the present shape? The grammar does not set these points and, in the words of Shea, ?when transformations are applied iteratively in random order and at random locations in the design, the grammar defines an infinite language of structural shapes? (Shea, 2004). In this way, shape grammars are especially well suited to generate a certain degree of visual (or real) randomness by following a specified set of rules. For these reasons we will use in this paper shape grammars as generating devices.

2. Methodology

2.1. Participants and Environment

Our study was carried out with students from the course *Teoría e Historia IV* (Theory and History of Architecture–4). This course is compulsory for seventh semester students at the University of Málaga School of Architecture.

A total of 62 students took part in the study. 25 students were female and 37 students were male. Only 60 of them finished the task associated with this study.

The learning objective of *Teoría e Historia IV* is to know and handle the main concepts underlying architectural theory in the second half of the 20th century. One of the topics covered is that of "cells" and "megastructures". In this context, an architectural megastructure is a massive structure or building formed by the repetition of a group of similar shapes (cells). Famous examples of this concept are Moshe Safdie's *Habitat 67* for Expo'67 in Montreal, or the works from Japanese metabolists as Kisho Kurokawa and Kenzo Tange. Each student had to develop an individual project based on these architectural ideas. In academic year of 2012–13 the project was carried out as described below.

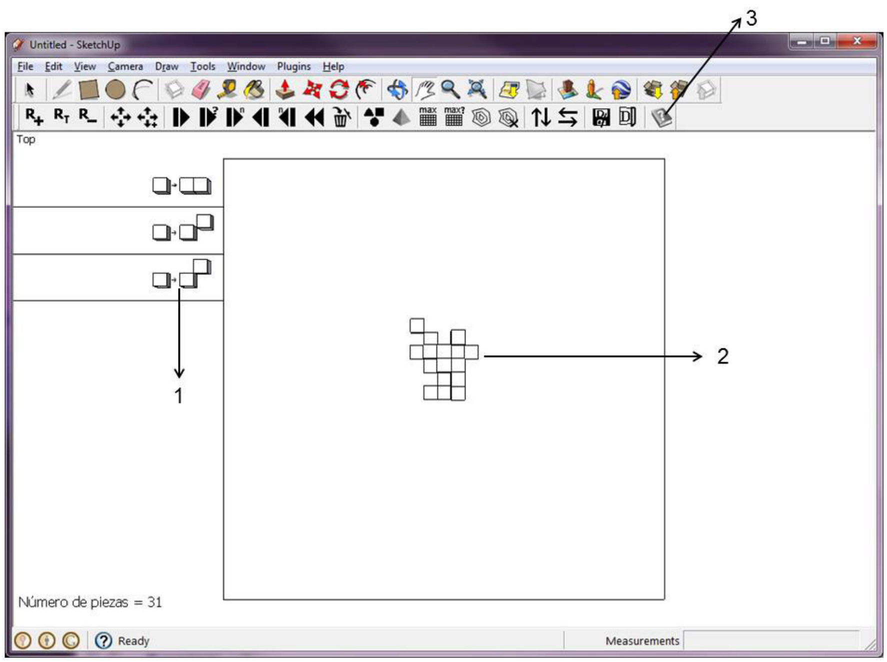

Figure 2: Graphical interface of `MG-Shade`

2.2. Computer tool: MG-Shade

Students were asked to use a computer tool to generate their projects. The tool, named `MG-Shade` (MeGastructures SHApe DEsign), was developed specifically for this study in order to interactively generate design solutions and, in particular, megastructures, and is related to a previous tool implemented by some of the authors (Ruiz-Montiel et al., 2013), which also generates design solutions. `MG-Shade` has been implemented on Trimble SketchUp, a free 3D modeling program that combines a toolset with an intelligent drawing system (`http://www.sketchup.com/`) By means of Ruby plugins, SketchUp can be extended and customized to suit different needs. `MG-Shade` has been created as one of these plugins and its main aim is to design megastructures, eventually using some simple 3D shape grammars.

In Figure 2 we can see a screenshot of the graphical interface of `MG-Shade`. It is based on the interface provided by SketchUp. There are three main regions in the interface:

1. *Rule canvas.* Rules of the selected grammar appear on the left hand side of the canvas.
2. *Design canvas.* The current produced design appears in the center of the canvas. The design must be inside a square, each side being 100 meters..
3. *Toolbar.* It provides Sketchup commands plus others implemented by `MG-Shade`.

The user may perform certain operations on the elements on the design canvas, generally by activating the corresponding icon in the toolbox.

A complete description of `MG-Shade` is beyond the scope of this paper; a user's guide is available on the web (anonymized url) However, some general features should be mentioned in order to understand this study:

- The user must choose between three basic cells: cube, triangular prism and hexagonal prism (height, width, and depth of each cell are always 3m).
- A volumetric constraint can be activated/deactivated. If activated, all cells must lay inside a given square pyramid.
- The total number of cells can also be bound.

As mentioned above, the tool can be used to generate random designs. To this end, `MG-Shade` can be seen as a 3D generative tool that relies on the formalism of shape grammars (Stiny, 1980), (Stiny, 2006). A shape grammar is composed of a set of *rules* and an initial element or shape called the *axiom*. If the left hand side of a rule matches some part of the design, then the rule can be applied to this part. The process goes on until no rule is applicable or a constraint (for example, the volumetric one or the maximum number of elements) is violated. This sequence+ of steps is called a *derivation*. In Figure 3 we can see an example of derivation starting from an axiom (in this case, a cube) and applying a rule stating “add a cube to one free face of an existing cube”. General shape grammars allow both addition and deletion of shapes; however, `MG-Shade` implements *additive* grammars, the rules of which just add new elements. In order to detect all the possible matches between the left hand side of a rule and a design, shape grammars usually allow translations, rotations and scaling (`MG-Shade` does not need to consider scaling).

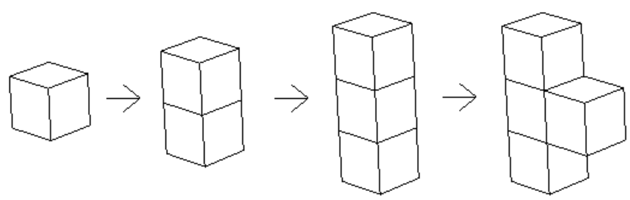

Figure 3: Example of a derivation

The derivation in Figure 3 is *random*, in the sense that many other derivations were possible starting from the same axiom and applying the same set of rules (in fact, the same rule). Randomness can arise due to the following indeterministic choices that must be made throughout a derivation:

- Select the element or subshape that matches the left hand side of a rule.
- Select one of the several rules that can be applied to the selected element or subshape.
- Select one of the several geometric transformations that can be used to match the selected element or subshape with the left hand side of the selected rule.

However, `MG-Shade` is not just a shape grammar interpreter. It provides a set of tools that can control the generation process to a certain or even to an almost absolute degree. To this end, the following features can be used:

- At the start and at any step, the user can explicitly place an element anywhere on the design canvas.
- At any moment s/he can delete an element present in the design.
- At each step, s/he can select the cell to which another cell will be adjoined.
- S/he can select the rule(s) that will be applied in order to add new cells.
- S/he can select the direction of growth (horizontal or vertical).
- S/he can select the number of consecutive applications of the selected rule(s).

To illustrate some of these features and the general operation of `MG-Shade`, let us consider the example shown in Figures 4 and 5. In Figure 4 we can see the initial design canvas, showing a given landscape and no cells. We can also see (left hand side of the figure) the rule canvas, showing all active rules that pertain to triangular prisms. In Figure 5 we can see the final result provided by the interaction between the user and the tool.

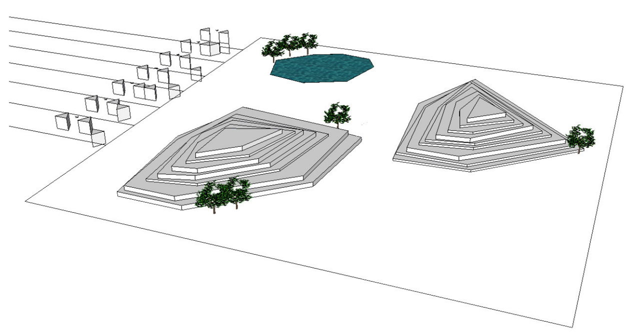

Figure 4: Initial state of a design

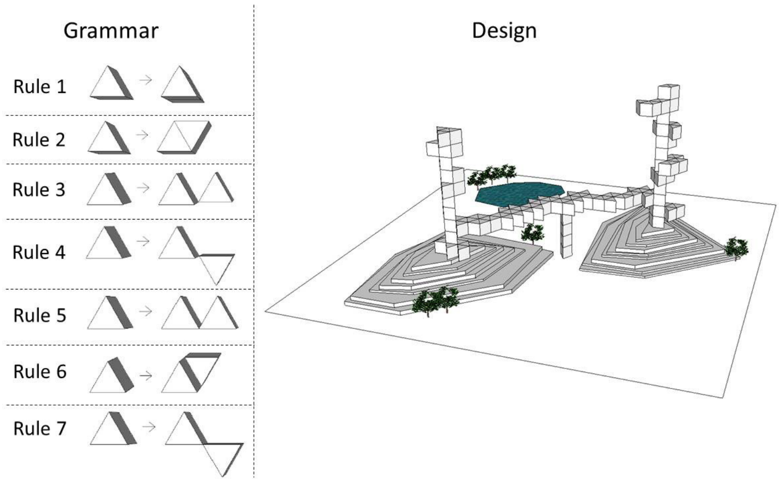

Figure 5: Final state of a design

The sequence to create this megastructure is:

1. Place an axiom (or *seed*) on the top of one of the hills.
2. Add a seed on the top of the other hill.
3. Apply the first rule 20 times. Note that this rule means "add a new prism to a free triangular face of an existing prism". This results in two "towers"
4. Apply the second rule 50 times. Note that this rule means "add a new prism to a free rectangular face of an existing prism".
5. To support the bridge between the two towers, choose a shape and apply the second rule. Repeat this step until you have connected the towers.
6. In order to hold the bridge, build a pile. Choose a shape in the bridge and apply the first rule. Repeat this step until the pile is sustained on the ground.

This sequence of steps is more or less controlled. However, some instructions are executed randomly (for example, instructions numbered 3 and 4), since we do not decide the cells in which the tool applies the selected rule, or the applied transformations. Therefore control plays an important role in this design, but randomness also determines the final outcome to a great extent.

2.3. Student task

In a previous lecture, students were given a theoretical introduction to megastructures. Subsequently, a session was held in the computer room in order to work with `MG-Shade`. The session comprised an introduction to 3D shape grammars and rules, and a tutorial to learn about the use and capabilities of the tool. Once this introduction had been completed, the students were ready to work on their individual assignments.

Each student had to sketch six projects, corresponding to the six combinations cubic/triangular/hexagonal cell vs. volumetric constraint activated/deactivated. To unify all the projects, they all had to be developed from the landscape shown in Figure 4 and the maximum number of cells was set to 800. The intended use of the project was residential, with optional commercial use for the ground floor. Each student had to write a report documenting the creation process and displaying four perspectives for each project. From his/her six projects, each student had to select the "best" one, giving the reasons for their choice. Then s/he could develop the selected one in more detail by using additional graphical resources (textures, text, components, floor sections, ...). From now on, the projects selected by each student among his/her six projects will be referred to as "Type S^+" projects and non selected projects will be referred to as "Type S^-" projects. This amounts to 60 S^+ projects and 297 S^- projects (the sum is not exactly 300 due to some incomplete student's assignment).

Once the students finished their assignments, they were asked to fill in a survey where they could give their opinion about the software. Feedback was required on three main issues: potential use of this software in architectural design, problems found when using it, and possible improvements.

2.4. Task processing

The instructor selected the ten best assignments (six projects each), that were presented by their authors in a public session. From now on, the 60 projects from these ten "best" students will be referred to as "Type I^+" projects, and the 297 projects from the rest of the students will be referred to as "Type I^-" projects.

The selection criteria applied by the instructor to choose the best assignments were as follows:

- Maximum number of shapes: the student tried to maximize the number of shapes in his/her design.
- Feasibility of the design: the student designed structures that could be developed as residential buildings.

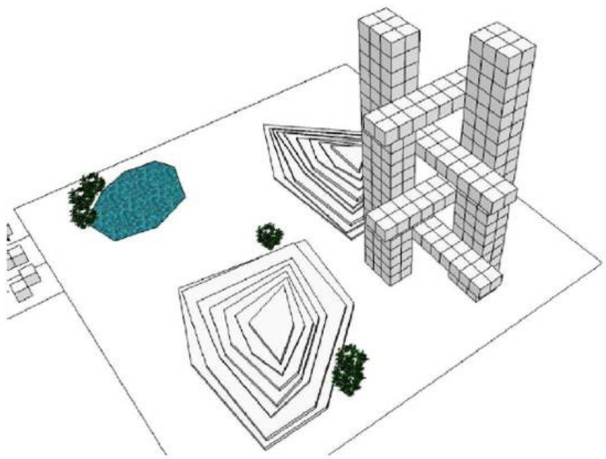

Figure 6: A controlled megastructure project generated by a student.

- Degree of detail: the student proposed specific solutions for perceived problems.

Though these criteria were not explicitly stated in the written assignment, students were verbally informed that, in order for their projects to be considered as *megastructures*, the number of shapes should be as big as possible (up to a maximum of 800). The other two criteria are commonly used in the school to evaluate student's projects.

Independently from this assessment, each of the 357 projects was inspected and graded according to its degree of randomness. Grading was performed by a team of two judges that has to agree on a common score. The scale was as follows:

1 (Almost) total control
2 More control than randomness
3 More randomness than control
4 (Almost) total randomness

Judges took into account both the design process (as described by students in their reports), and the final look of generated projects. Hereafter, the consensus score of each project will be referred as the randomness value (r). Figure 6 displays a project that has been totally controlled ($r = 1$), as shown both by the written report and the visual inspection. In contrast, Figure 7 displays a totally random project ($r = 4$).

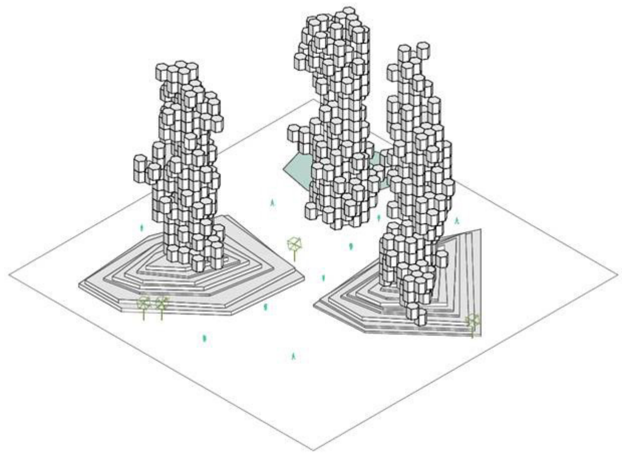

Figure 7: A random megastructure project generated by a student.

2.5. Survey processing

The first part of the survey was composed of eight Likert items, relative to the task and the usability of the tool. Students had to evaluate their degree of agreement with each sentence from 1 to 6. We have used the recommended methodology (Jamieson, 2004) to analyze Likert items, that is, mode, median, inter-quartile range and nominal levels of disagree (degree of agreement of 1, 2 and 3) vs. agree (degree of agreement of 4, 5 and 6).

Additionally, the survey included two free-text items where students could identify the strong and weak points of the software and make any comments they wished.

We have analyzed those two items according to the *constant comparative method* (Corbin & Strauss, 2008), a methodology based on *grounded theory* (Glaser & Strauss, 1967). In the first step, each student's response was decomposed into the ideas it expresses (*answers*). Therefore, there are generally more answers than students, because each student's response usually expresses more than one idea. Then the answers are divided into *categories*. In the *phenomenological reduction phase*, the categories are grouped by subject (*themes*). Finally, in the *triangulation phase*, examples of *supporting quotes* are provided. The main advantage to using this methodology is that the ideas expressed in students' answers emerge from the analysis of the sentences, and are not pre-conceived by researchers.

3. Results

3.1. Randomness Values (r)

In the way described above, an r value was assigned to each of the 357 projects. Relative frequencies for each r value ($r = 1, 2, 3, 4$) are shown in Table 1. Frequencies are computed globally for the total set of projects (group of rows *Total*) and separately for projects of type I^+. For each r value the following frequencies have been computed:

- the frequency with which r appears in any project (column r)
- the frequency with which r is the minimum or maximum value of the projects from the same student (columns r_{min}, r_{max})
- the frequency with which a student selected a project with value r as his/her best design.

The last column "p(sel/r)" contains an estimation of the probability of selecting a project by a student conditioned to the value of r, i.e., the relative frequency of selected projects from projects with a certain r value.

	value	r	r_{min}	r_{max}	r_{sel}	$p(sel/r)$
Total	1	19.33	46.67	1.67	38.33	0.33
	2	27.73	26.67	15.00	28.33	0.17
	3	32.49	21.67	43.33	20.00	0.10
	4	19.33	5.00	40.00	13.33	0.12
I^+	1	40.00	70.00	10.00	60.00	0.25
	2	28.33	10.00	30.00	20.00	0.12
	3	16.67	20.00	30.00	10.00	0.10
	4	15.00	0.00	30.00	10.00	0.11

Table 1: Frequencies (%) of randomness values and probabilities of selection (see text)

Absolute frequencies are graphically displayed in Figures 8 and 9 in the form of histograms of r values for I^+ and I^- projects (Figure 8) and S^+ and S^- projects (Figure 9). In both figures the total height of the bars represent the frequencies of each r value in the total set of designs. In Figure 8 the smaller bars represent absolute frequencies of r values in the set of I^+ designs, while in Figure 9 they represent absolute frequencies of r values in the set of S^+ designs.

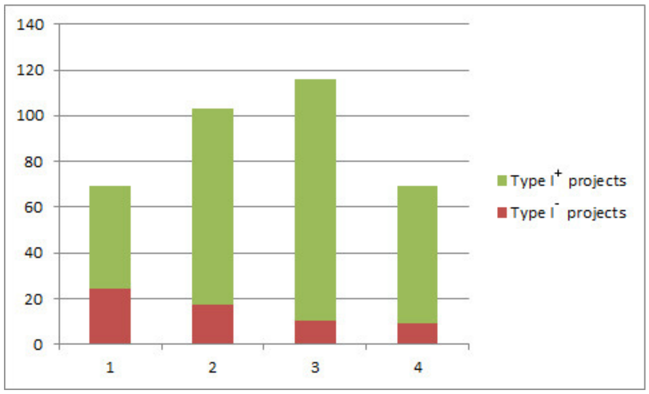

Figure 8: Values of r (I^+ and I^- projects)

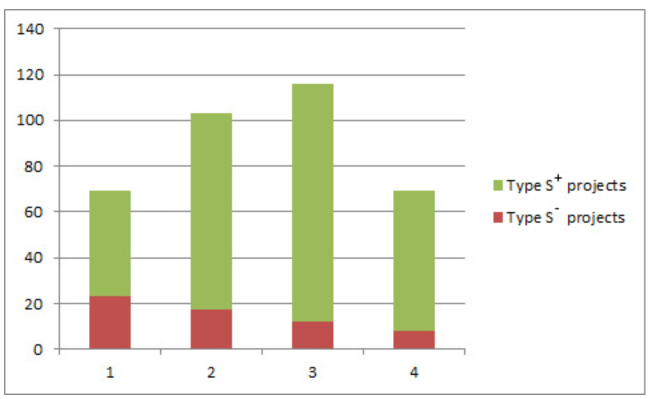

Figure 9: Values of r (S^+ and S^- projects)

In Table 2 some statistics for r values are shown. For each student the following values have been computed or collected:

- The minimum value of r, r_{min}, for his/her six projects.
- The maximum value of r, r_{max}, for his/her six projects.
- The average value of r, r_{avg}, for his/her six projects.
- The r value, r_{sel}, for his/her selected project.

Then averages have been computed for these four values on the total set of projects and on each type I^+ projects.

	r_{min}	r_{avg}	r_{max}	r_{sel}
Total	1.85	2.53	3.22	2.08
I^+	1.50	2.07	2.80	1.70

Table 2: Averages of randomness values

3.2. Student survey

The survey was anonymous, and it was answered by 58 students. As stated, it was composed of eight Likert items, relative to the tool and the practice. Students had to evaluate their degree of agreement with each sentence from 1 to 6. Table 3 summarizes mode, median, inter-quartile range and nominal levels of disagree (degrees of agreement of 1, 2 and 3) vs. agree (degrees of agreement of 4, 5 and 6) for each of the 8 items.

	MEDIAN	MODE	(Q_1, Q_3)	Don't agree	Agree
About the software tool...					
1. I quickly learned how to use the tool	5	5	(4,6)	15.52%	84.48%
2. It was easy for me to use the tool	5	5	(4,6)	18.97%	81.03%
3. The user interface is intuitive	4	4	(3,5)	29.31%	70.69%
4. The tool worked quick enough	4	3	(3,5)	44.83%	55.17%
5. The tutorial was useful and easy to follow	5	5	(4,5)	18.97%	81.03%
About this practice					
6.All in one, it was interesting	4	5	(3,5)	29.31%	70.69%
7.I think that the methodology used was suitable	4	5	(2,5)	32.76%	67.24%
8.It was appropriate for this subject	4	4	(3,5)	27.59%	72.41%

Table 3: Results of the survey

Concerning the two free-text items, there were 97 different answers for the positive aspects, and 86 for the aspects to be improved. Two independent researchers assigned answers to categories (12 in the case of the positive answers, and 20 for the negative ones). The inter-rater agreement between the two researchers was computed using the iota ι statistic (Janson & Olsson, 2001), an extension of the kappa measure to the case of multivariate data and multiple judges. A ι value of 1 indicates perfect agreement. In our case, we obtained ι values of 0.81 and 0.82, which indicates good agreement. Through a negotiation process between the two researchers, answers were assigned to categories.

The results of applying the constant comparative method to our two free text items are shown in Table 4 and Table 5.

	CATEGORIES			THEMES	EXAMPLES OF SUPPORTING QUOTES
	Name	**№answers**	**% answers**		
97 different answers	The tool was quick and easy to use	10	10.20%	ABOUT THE SOFTWARE TOOL (16.32%)	*Using the tool, the creation of modules was quick/easy*
	Good usability	6	6.12%		*The tool was easy to use*
	Novelty	3	3.06%	TECHNICAL ASPECTS OF THE TOOL (18.38%)	*The tool was innovative, entertaining, unique. It surprised me, I was expecting worse results*
	Use of modules	8	8.17%		*It is nice to be able to use modules to create buildings; it is really helpful when your inspiration is low*
	Adaptation to contour maps	2	2.04%		*The possibility to generate contour maps and to adapt the designs to them*
	Being able to design from 3-D	5	5.11%		*It was interesting to begin our projects from a 3-D model and not from floor plans, that is what teachers usually demand from us in spite that we are supposed to be the 2.0 generation*
	Creativity/originality	16	16.33%	ASPECTS RELATIVE TO THE MEGASTRUCTURES GENERATED (33.67%)	*The shapes generated are very interesting... they might seem utopian, but they can get to be feasible with some modifications*
	Diversity	7	7.14%		*It was interesting to see that the tool is able to generate many different solutions for each prism*
	Quality of megastructures	10	10.20%		*The tool provided interesting megastructures that would have been more difficult to design from scratch*
	Randomness	17	17.35%	FOSTERING CREATIVITY (31.63%)	*Given the randomness of the tool, it is not constrained to aspects like logic and order??? therefore the design process is the opposite: beginning from randomness, it is possible to find order and logic in the constructive process*
	Control/order in the randomness	3	3.06%		*What I enjoyed most is that the tool allowed me to quickly create shapes with an adequate balance between randomness and control*
	Good starting points	11	11.22%		*It was nice to have a starting point instead of having to face a blank page*

Table 4: Categories, themes and supporting quotes for positive aspects

4. Discussion

4.1. Analysis of randomness values

Three main points will be analyzed:

1. To what degree do students explore randomness?
2. What degree of randomness is preferred by students?
3. Are students able to obtain "good" designs by means of random processes?

Now we will discuss the results obtained for each one of these points.

1. With respect to the exploration of randomness, we will consider the values shown in the first group of rows in Table 1, labeled *Total*. These

	CATEGORIES			THEMES	EXAMPLES OF SUPPORTING QUOTES
	Name	**№answers**	**% answers**		
86 different answers	Fix bugs in saving/ loading designs	4	4.65%	IMPROVEMENTS OF THE SOFTWARE TOOL (25.57%)	*A bug occurred while saving my design and I could not load it correctly afterwards*
	Better efficiency	5	5.81%		*The tool should work more quickly*
	More possibilities for saving designs	5	5.81%		*Other saving formats (other than .txt) should be allowed*
	Editing contour maps should be easier	3	3.49%		*A simpler way to define my own contour maps*
	Better positioning of the button to go back to the initial structure	5	5.81%		*The button to go back to the initial structure is too close to other buttons so it is easy to press it accidentally*
	Undo button (control+z)	1	1.16%	NEW FUNCTIONALITY FOR SOFTWARE TOOL (13.95%)	*It would be nice to be able to use the control+z command*
	Possibility to use textures	1	1.16%		*The plugin could include tools to modify textures of the building*
	Automatic removal of freestanding modules	7	8.14%		*Freestanding modules should not be allowed in the designs*
	Possibility to use SketchUp commands	2	2.33%		*The use of SketchUp commands should be allowed*
	Automatic generation of multiple megastructures	1	1.16%		*It would be useful to include an automatic generation capability, so that different designs were generated and saved by the tool and then presented to the user*
	More types of prisms	6	6.98%	ASPECTS RELATIVE TO SHAPE GRAMMARS (23.28%)	*Introduce more shapes and rules*
	More variety of rules	2	2.33%		
	Bigger size of modules	4	4.65%		*The size of the modules makes it difficult to generate habitable spaces*
	Additional architectural criteria	2	2.33%		*Additional architectural criteria should be considered*
	Possibility to include user-defined grammars	2	2.33%		*It would be nice to be able to define my own shape grammars*
	Possibility to apply the approach to other domains	2	2.33%		*I would like to apply this to the design of single-family dwellings*
	Possibility to combine different prisms in the same design	2	2.33%		*It would be interesting to be able to combine different figures in the same megastructure*
	More control	18	20.93%	MORE CONTROL WOULD BE DESIRABLE (37.21%)	*More control of the generated shape*
	Better control of randomness	3	3.49%		*Randomness should not result in useless solutions*
	More editing options	11	12.79%		*Possibility to rotate/move/copy prisms*

Table 5: Categories, themes and supporting quotes for aspects to be improved

are the r values for the whole set of designs. We will also consider the first row in Table 2, labeled *Total*, that shows averaged values.

We can see that the average value for r is 2.53 (Table 2). The mode is $r = 3$ since 32.49% of the designs were produced for this value (Table 1). That means that 32.49% of the designs were generated following a more random rather than controlled process. Moreover, the vast majority of the designs (80.67% = 28.85% + 32.49% + 19.33%) were produced using randomness to a certain extent (r = 2, 3 or 4).

The analysis of r_{min} and r_{max} values confirm this. Note that the average value of r_{min} (Table 2) is $r_{min} = 1.85 > 1$. That means that the least random design of each student has, on average, a certain degree of randomness. In fact, in Table 1 we can see that less than half of the students (46.67%) generated a totally controlled design ($r_{min} = 1$); the rest of the students (26.67% + 21.67% + 5.00% = 53.33%) did use a certain degree of randomness (r_{min} = 2, 3 or 4) in all their designs. On the other hand, just one student (1.67%) generated only controlled designs ($r_{max} = 1$). So we can conclude that students fairly explore randomness.

2. With respect to the degree of randomness preferred by the students, we will consider the values showed in the last two columns in Table 1, labeled r_{sel} and $p(\text{sel}/r)$. Column r_{sel} shows frequencies for the set of designs preferred by students, that are also graphically displayed in Figure 9.

   We can see that the average value for r_{sel} is 2.08 (Table 2). The mode is 1 (Table 1) since 38.33% of the preferred designs were produced with this value. That means that 38.33% of the preferred designs were generated following a totally controlled process ($r_{sel} = 1$). These values are smaller than those considered in the aforementioned analysis, that is, preferred designs are not evenly distributed over the set of generated designs, but tend to fall in relatively low values of r. This can be seen more clearly in the last column of Table 1, that shows the probability $p(\text{sel}/r)$ of being preferred for the different values of r. We see that for $r = 1$ the probability is 0.33, that is, if the student generates a totally controlled design, then it will be preferred one in three times. To the contrary, if s/he generates a totally random or more random than controlled design (r= 3, 4), then it will be preferred approximately one in ten times. The histogram of Figure 9 graphically displays the same fact and shows that the distribution of r for S^+ designs is skewed to

the left.
However, note that if we add the frequencies corresponding to $r_{sel} =$ 2, 3 or 4, we obtain a total of 61.66%. Therefore the majority of preferred designs were produced using randomness to a certain extent. The conclusion is that students, in the main, like a certain degree of randomness, but this degree is not the maximum degree of randomness that they are willing to explore.

3. With respect to the analysis of randomness in "good" designs, we will consider that "good" designs are those generated by students selected by the instructor (type I^+ designs), and specifically the preferred ones. Frequencies of r values for these designs are shown in the second group of rows in Table 1, labeled I^+, and graphically displayed in Figure 8. Average values are shown in the second row of Table 2.
The outcome of this analysis is similar to the one carried out for the previous research goal. Average value for $I^+$is $r = 2.07$ and the mode is $r = 1$ with a frequency of 40.00%. On the other hand, the sum of the rest of frequencies, standing for designs in which randomness has been present to a certain extent, is higher (60% = 28.33% + 16.67% + 15%); so the majority of "good" designs present a certain degree of randomness. However, note that, in the subset $I^+ \cap S^+$, r values are smaller (average value is 1.70). Adding the frequencies corresponding to $r_{sel} = 1$ and 2, we obtain a total of 80%, indicating that the instructor showed a preference for more controlled designs when selecting the "good" ones.
The conclusion is that, though a certain degree of randomness is present in many of the "good" designs, the teacher has shown a preference for more controlled designs.

4.2. Analysis of the tool

Since the results presented above depend heavily on the computer tool used by the students, it is necessary to evaluate its performance. In a first approximation, this can be done by analyzing the opinions expressed by students and summarized in Table 3. It shows that:

- With respect to the usability of the software tool, most of the aspects were positively evaluated by students (medians and modes of 4, 5), except for item 4 (the tool worked quickly enough). The nominal levels of agreement/disagreement indicate that most students seemed to agree with every sentence.

- On the other hand, students seemed to enjoy this task: it held their interest (item 6, 70.69%) and they positively valued the methodology (item 7, 67.24%) and its appropriateness for the subject matter (item 8, 72.41%).

The analysis of the two free-text items in the survey is intended to detect good features already provided by the tool, and possible improvements in order to continue our research.

The analysis of Table 4 (Categories, themes and supporting quotes for positive aspects) shows that the most frequently mentioned theme was *Aspects relative to the megastructures generated* (33.67%), and specifically, 16.33% of students mentioned *creativity/originality* as a strong point. An example of a supporting quote for this category is: “The shapes generated are very interesting... they might seem utopian, but they can get to be feasible with some modifications”.

Following very closely, the next most frequently mentioned theme is *Fostering creativity* (31.63%, and in particular, *randomness*, mentioned by 17.35% of the students (note that this is the most frequently mentioned category). An example of a supporting quote for this category is “Given the randomness of the tool, it is not constrained to aspects like logic and order... therefore the design process is the opposite: beginning from randomness, it is possible to find order and logic in the constructive process”.

Another two themes were mentioned by students, but with lower frequency: *Technical aspects of the tool* (18.38%) and *About the software tool* (16.32%).

With respect to the aspects to be improved (Table 5), the most frequently mentioned theme was *more control would be desirable* (37.21%), and specifically the categories *more control* (20.93%) and *more editing options* (12.79%). Examples of supporting quotes are “More control of the generated shape” and “Possibility to rotate/move/copy prisms”.The next most frequently mentioned theme was *Improvements of the software tool* (25.57%) which is almost uniformly distributed throughout the categories, the most frequent being *Better efficiency*, *more possibilities for saving designs* and *better positioning of the button to go back to the initial structure* (5,81%). Examples of supporting quotes are “The tool should work more quickly”, “Other saving formats (other than .txt) should be allowed”, and “The button to go back to the initial structure is too close to other buttons so it is easy to press it accidentally”. Another two themes mentioned by students were *aspects relative to shape grammars* (23.28%) and *new functionalities for software tool* (13.95%).

5. Conclusions

The above discussion shows that most participants in this experiment were willing to explore the design space by applying randomness, confirming some previous results reported in the literature. It also shows that a certain degree of randomness is present in many designs preferred by each student and in some ?good? designs selected by the instructor. In fact, while exploring randomness, students must take into account functional and constructive considerations, and surely that is the reason why they have chosen to develop designs that are not the most random ones. This findings could be of interest when implementing new computer tools for conceptual computer-aided design. Users seems to be open to explore randomness, so the tool should provide a certain amount of that; however, the tool should also allow to control and tame such randomness.

In our own personal view, randomness can have an interesting role in the design process. It can provide support for some of its phases, by generating suggestive solutions that go beyond preconceived ideas or by modifying partial solutions in unexpected ways. It seems clear to us that randomly generated solutions must be further worked out and integrated by the human designer into a coherent whole. From an initial and elementary cell, a certain number of random events occur. These events are guided by the designer, to satisfy a concrete logic. The final result fulfills then a certain set of ideas and constraints. On the other side, a possible drawback of introducing randomness is that, in their search of possible solutions, designers might delegate their own responsibility. All in one, and, regarding this particular experiment, we think that the use of the tool has empowered students. Their role is no longer that of a robot with a disconcerting precision, but that of a motivated designer that freely takes his/her own decisions.

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